Effect of Helium Injection on Diffusion Dominated Air Ingress Accidents in Pebble Bed Reactors

by

Joseph Paul Yurko

Submitted to the Department of Nuclear Engineering
In Partial fulfillment of the requirements for the degree of

Master of Science in Nuclear Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE, 2010

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Abstract

The primary objective of this thesis was to validate the sustained counter air diffusion (SCAD) method at preventing natural circulation onset in diffusion dominated air ingress accidents. The analysis presented in this thesis starts with a vertically oriented rupture of a coaxial pipe. Air enters into the reactor cavity at a rate dictated by diffusion, until the buoyancy force is strong enough to initiate natural convective flow through the reactor. The SCAD method, developed by Yan et al. reduces the buoyancy force in a high temperature gas reactor (HTGR), during the lengthy diffusion phase, by injecting minute amounts of helium into the top of the reactor to set up a counter helium-air diffusion circuit. By delaying the onset of natural circulation, air enters the reactor only at diffusion transport rates, instead of much higher natural convection transport rates. Thus, the air ingress rate is reduced by several orders of magnitude. Without the continuous convective driven supply of "fresh" air the threat of oxidizing graphite components is significantly reduced.

To validate SCAD a small scale simulated Pebble Bed Reactor (PBR) was constructed and a series of air ingress experiments with and without helium injection were conducted. In addition, Computational Fluid Dynamic (CFD) simulations were performed using FLUENT ® to model the experiment and gain further insight into the behavior of the flow field leading up to the onset of natural circulation. In order to have the CFD predicted natural circulation onset time better match the experimentally determined onset time, the initial helium fraction in the numerical model had to be reduced by 15%. This reduction is within the uncertainty of the experimental set-up.

This change helped display an important feature of the behavior of air ingress accidents. With the initial helium fraction in the simulated reactor at 100% the first half of the transient is a very slow completely diffusion dominated transport phase. The second half of the transient had an air transport rate that had an increasing natural convective transport contribution leading up to the onset of natural circulation and complete natural convective transport. Reducing the initial helium fraction by only 15% caused that initial very slow, pure diffusion transport phase to be bypassed and the natural circulation onset time was dictated by the combined effects of free convection and diffusion transport, not simply diffusion. A full scale PBR experiencing a similar accident will have the core entirely filled with helium. Thus, for a vertically oriented double ended guillotine (DEG) large-break loss of coolant accident (LB-LOCA) the subsequent air ingress rate will be dictated by the slow diffusion of air into the reactor cavity, for most of the transient.

For the helium injection tests, even at the at the lowest tested injection rate, both the experiment and the CFD simulation showed that natural circulation was prevented over a time period twice as long as the time to onset. The tests showed that without helium injection, natural circulation started after about 117 minutes on average. With helium injection, natural circulation did not start after 240 minutes when the experiment was terminated. Additional injection tests were run where after 240 minutes the helium injection was terminated, but data continued to be taken. In these tests natural circulation was initiated in approximately 120 minutes after termination of helium injection confirming the helium injection flow was preventing natural circulation from starting. The lowest tested helium injection rate corresponded to 0.01% of the test assembly's total volume per minute, demonstrating how small of a flow rate is needed for the SCAD method to work. Minimal helium injection is not intended to be an emergency core cooling system but rather a system to prevent or delay natural circulation which would result in a large amount of air ingress.

The system response was formulated non-dimensionally to quantify the impact SCAD has on the driving parameters that impact the onset of natural circulation, namely the buoyancy force, mass flow rate, and density ratio between the hot and cold leg. The results showed that SCAD suppresses the buoyancy force and forces a mass flow (transport) rate that causes any changes in the hot leg density to be counter-acted by density changes in the cold leg. The transport rate that is established is orders of magnitude less than the natural circulation transport rate. Using the driving non-dimensional parameters, a methodology was also developed in order to formulate a correlation to estimate the minimum injection rate (MIR) of helium to prevent the onset of natural circulation. In order to properly derive a correlation for the MIR, further experiments and/or simulations are required over different geometrical configurations. The non-dimensional analysis showed that Yan's MIR estimate was conservative for the experimental configuration, and would be conservative for a full scale PBR. Therefore, Yan's MIR calculation was used to provide an order of magnitude estimate for the helium injection rate in a full scale PBR. The resulting MIR of helium for a full scale PBR was 5.36 g/hr, which corresponds to storing only 11.6 kg of helium on-site to prevent the onset of natural circulation for three full months.

The experiment and CFD simulations were performed using an inverted U-tube which simulates a vertically oriented pipe configuration. If the pipe break occurs in a horizontal configuration, the air ingress phenomena could be substantially different depending on the break size and orientation. Thus, this thesis concludes that the method is capable of preventing natural circulation onset as long as air ingress occurs at transport rates comparable to diffusion after the break occurs.

Thesis supervisor: Andrew C. Kadak
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Acknowledgements

I would like to thank my advisor Prof. Kadak for all his help and patience in completing this work. There were many ups and downs as I learned how to operate FLUENT and I want to thank Prof. Kadak for giving me the time to figure out the many issues I had.

I would also like to thank Dr. Xing Yan for his many contributions to this work. Dr. Yan was instrumental in aiding my understanding of how to start this project and provided great help through to its completion.

Many thanks to the Department of Aeronautics/Astronautics 16.62x staff: Prof. Ian Waitz, Prof. Edward Greitzer, Prof. Sheila Widnall, Prof. Jennifer Craig, and especially to the lab staff: Todd Billings, Dave Robertson, and Richard Perdichizzi. Without their help the experimental apparatus would never have been finished. Thank you.

The experiment was a combined effort between me and my 16.62x lab partner Katy Sorenson. Without Katy it never would have been finished. Thanks Katy for all your help.

I would like to acknowledge Dr. Chang Oh of Idaho National Laboratory for providing useful comments and input in understanding the full range of air ingress accident scenarios.

I would also like to express my love and appreciation to my family, my Mom, Dad, and two brothers for putting up with all of this and thank you all for your support as I continue on.

Financial support for this research was provided by the Department of Nuclear Science and Engineering, the Idaho National Laboratory, and the Nuclear Regulatory Commission.

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1. Background

1.1 Pebble Bed Reactor (PBR)

For the past thirty years, many in the world have viewed nuclear energy with skepticism and fear. Safety concerns combined with high cost and large regulatory overhead caused few new nuclear plants to be built. However, with the growing demand for more environmentally-friendly energy, nuclear power is making a come-back. Though there are other "clean" options, there are few choices for large scale constant sources of clean energy other than nuclear power [1]. New light water reactor designs, including the Westinghouse AP1000 and GE's ESBWR, are safer and simpler, thus reducing construction cost and increasing public confidence in the technology.

To further improve nuclear power plant safety and reduce cost, Generation IV plants are currently being researched. One of the most advantageous designs is the Pebble Bed Reactor (PBR) shown in Figure 1[1], which is one type of high temperature gas-cooled reactor (HTGR). The pebble bed reactor is a graphite moderated and reflected thermal neutron spectrum reactor that uses helium as a coolant which operates at a low power density but high outlet temperature. This higher outlet temperature allows for higher thermal efficiency for use in either a direct or indirect gas turbine cycle or an indirect steam cycle for electricity generation. The high outlet temperature compared to light water reactors allows the PBR to be considered for process heat applications such as in oil sands production, thermo-chemical hydrogen production or other uses where high quality heat is needed.

[1] Figure 1 provides an illustration of a PBR plant layout. It does not represent pipe configurations used in the scaled down experiment discussed later.

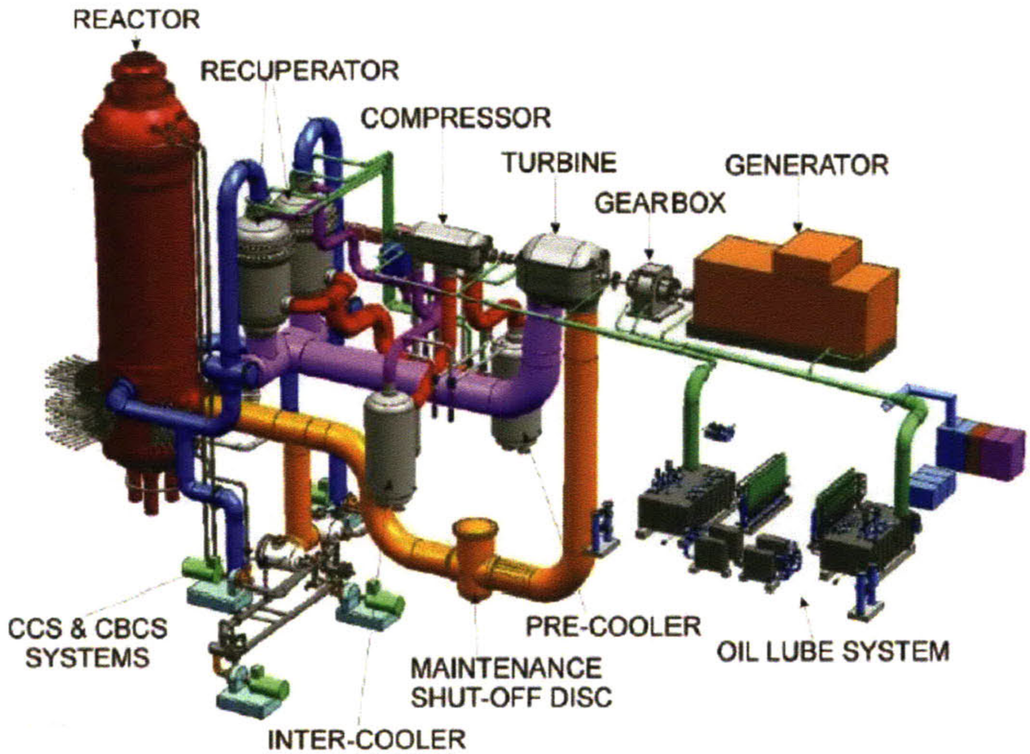

Figure 1: Schematic of a Pebble Bed Reactor [2]

The most important advantage of this technology is a further improvement in safety and an increase in cost effectiveness of the plant due to simplicity in design and higher thermal efficiency. In a PBR, uranium fuel micro-spheres are held in billiard ball sized graphite spheres as shown in Figure 2. This design lowers the power density to the point that a PBR is naturally safe; that is, the core cannot physically meltdown, thus alleviating the greatest public fear of nuclear power. PBRs are more cost-effective because they are not expected to go through costly shut down periods for refueling. Shut downs are avoided by using a process known as on-line refueling. During normal operation, the pebbles cycle through the core. When a pebble's useful operating life is exhausted, it is removed and a new pebble is added during operation. Figure 3 depicts an illustration of the on-line refueling process. Finally, because PBR plant designs are small, smaller units requiring less investment and shorter construction time allow power plants to be functional sooner at less cost.

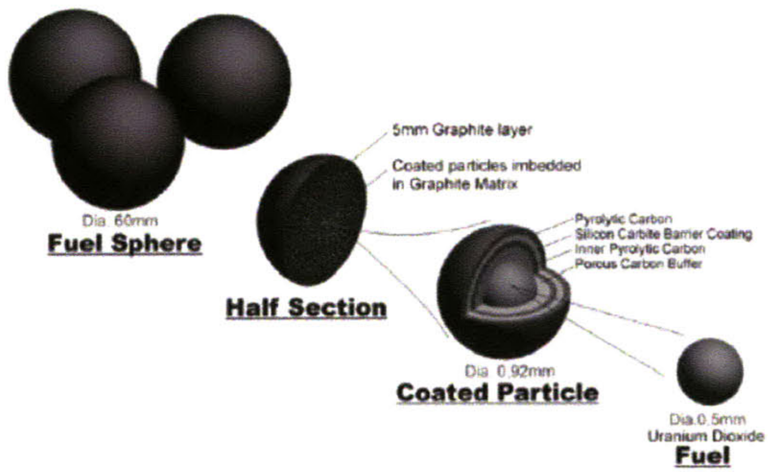

Figure 2: Fuel Elements [2]

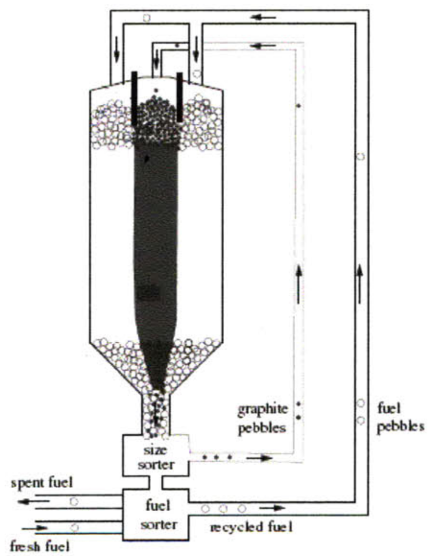

Figure 3: Online Refueling Illustration [3]

The economic case for pebble bed reactors is based on its modular design and construction allowing for factory fabrication of modules with on-site "assembly". The economics of production of a large number of standard smaller units is expected to compete with the overall cost of large base load plants on a cost per kilowatt hour basis.

1.2 Air Ingress Accident Overview

Before the Nuclear Regulatory Commission (NRC) approves a new reactor design, the safety of the plant must be established, which includes performing transient and accident analyses of postulated design basis accidents. One of these more significant design basis events is the rupture of a main coolant pipe and subsequent air ingress. The air ingress transport rate is dependent on the orientation of the break. Vertically oriented pipe breaks, as will be discussed, consist of cold air sitting underneath hotter helium gas. Therefore, the air ingress rate is dictated by diffusion. A horizontal break in a large diameter pipe, however, will have additional convective transport due to density gradients that reduce the natural circulation onset time compared to diffusion driven accidents[2]. This work does not account for any phenomena specific to horizontal flow stratified flow.

Because the SCAD method applies to diffusion driven transport rates, only vertical pipe breaks will be discussed. Diffusion dominated air ingress accidents consist of three phases as shown in Figure 4. The furthest left most illustration in Figure 4 is the first phase, the depressurization stage from approximately 7 MPa in a relativity short time depending on the size of the breach. Here, the helium coolant is forced through the pipe breach, meaning no air can enter the reactor vessel. When the pressure in the reactor core equilibrates with the ambient environment in the reactor cavity or building, the second stage, the diffusion stage, begins. Air enters the reactor through a slow diffusion process. As more air enters the reactor, the buoyancy force increases due to the temperature difference in the hot core and the cold leg (side of the reflector), and eventually the buoyancy force becomes larger than the viscous drag, inducing natural circulation. This last stage is shown in the right most illustration in Figure 4. Air enters the reactor through the breach, gets heated up in the core, cools down in the cold leg, and then exits through the breach.

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[2] Oh, Chang, "Current INL R&D Activities on VHTR Air-Ingress Accident Analysis," Presented at the NGNP Technology Integration Review Process Meeting, March 31, April 1 2009

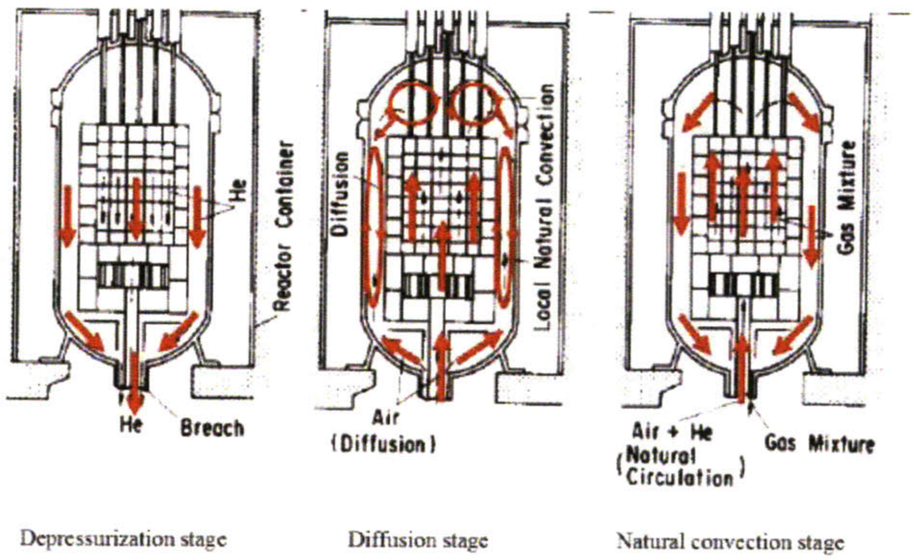

Figure 4: Phases of Air Ingress for Vertically Oriented Breaks [2]

Though the passive safety features inherent to the PBR design ensure that the ultimate reactor temperature rise for such an event is less than the design limit of the silicon carbide coated particles, concern still exists regarding exposure of the graphite pebble and reflector to ambient air which might cause corrosion and possible exothermic reactions heating up the core further. This is a problem because both the outer zone of the pebbles and the lower and side reflectors of the core structure are made out of graphite. Ingress of air will cause the graphite to oxidize, compromising the structural integrity of the lower graphite structure and possibly reaching the fuel pebbles. The natural circulation phase of the air ingress accident provides a continuous supply of "fresh air" to oxidize the graphite components. Natural circulation, therefore, presents the greatest threat to core integrity and must be prevented.

2. Natural Circulation Prevention

2.1 Overview

To maintain the design safety goals of the PBR, air ingress accidents must be prevented or sufficiently low in probability to make them very unlikely events and/or a means to mitigate the consequences of air ingress or to prevent the onset of natural circulation through-flow of air must be developed. Most air ingress analyses indicate that air ingress events proceed on a long time scale after depressurization due to the diffusion process. This allows time for repair of the leak or broken pipe since the activity of the helium coolant is generally very low. Additionally, these analyses assume that the source of the air in the reactor cavity is consumed such that the oxidation reaction is limited and confined to only a small portion of the lower reflector, preventing any damage to the fuel or structural integrity of the lower reflector supporting the pebble bed. Whether these assumptions are correct will be evaluated during the licensing process based on the evidence provided.

The simplest approach to prevent air from entering would be the addition of a helium (or other gas such as nitrogen) injection system upon a break of the primary system boundary. Pressure driven forced convective flow through the reactor will thus prevent air from entering into the core [4]. However, to maintain this condition over long periods of time, for example several months, would require large amounts of helium stored onsite. From an economics point of view, storing large amounts of extra helium (or nitrogen) would add additional complexity to the plant, increasing the initial cost and so this simple approach could become very costly for large reactor sizes and the longer the time of interest becomes. Goals for an air ingress prevention method are thus to not only prevent the onset of natural circulation but also at minimal additional cost and so different prevention approaches must be taken.

2.2 Sustained Counter Air Diffusion (SCAD)

In order to meet the stated prevention method goals, Yan et al. [5] proposed injecting minute amounts of helium gas from the top of the reactor in order to produce sustained counter air diffusion (SCAD). This process counteracts the increasing buoyancy force, effectively halting the development of natural circulation. A steady-state counter air-helium diffusion process is created in SCAD that attempts to effectively have no bulk gas flow through the core. Air is therefore only allowed to enter the reactor through diffusion, which presents negligible risk to core integrity. In their work, an analytical minimum injection rate (MIR) of helium was developed and used in a benchmarked code using data taken from a test facility simulating an air ingress event. Yan et al. then used CFD analysis on a full scale high temperature gas reactor to test their MIR strategy. A two-dimensional axi-symmetric mesh of a 600MWt HTGR was created and an air ingress accident was simulated using FLUENT. Without helium injection the air ingress rate into the reactor was 320 kg/hr. This could be reduced to 1 kg/hr by injecting 0.14 kg/hr of helium. Thus, their numerical results showed that by storing only 300 kg of helium, the air ingress into the reactor could be controlled for three full months.

The MIR equation is derived assuming the bulk flow in the hot leg is effectively zero and that the entering air molar flux then exits out the cold leg. The analytical estimate for MIR as derived by Yan is given by Equation 1.

$$N_{He,h} = \frac{c_h D_h}{L}\left(X^o_{He,h} - X^L_{He,h}\right)$$

$$N_{He,c} = \frac{c_c D_c}{N^* L}\ln\left(\frac{1 - N^* X^L_{He,c}}{1 - N^* X^o_{He,c}}\right)$$

$$N^* = 1 + \frac{N_{He,h}}{S^* N_{He,c}}$$

Equation 1

where: c ≡ molar concentration [mol/m^3],

D ≡ binary mixture mass diffusivity [m^2/s],

L ≡ channel length [m],

N ≡ molar flux [mol/m^2-s],

S* ≡ total flow area ratio of cold to heated channels,

X ≡ molar fraction with superscripts,

Superscripts:

O ≡ top of a particular channel,

L ≡ bottom of a particular channel,

Subscripts:

He ≡ helium,

c ≡ cold channel,

h ≡ hot channel.

Equation 1 must be solved iteratively using the Newton method to determine the individual channel helium molar fluxes for given boundary conditions. The MIR is then the sum of the hot and cold leg helium molar fluxes calculated from Equation 1. It should be noted that the MIR equation was derived assuming steady-state and thus predicts the required helium injection rate to ensure the chosen channel boundary mole fractions are maintained (channel boundary mole fractions refer to the mole fractions at the top and bottom of the hot and cold legs). Therefore, the channel boundary mole fractions just before the onset of natural circulation, as computed from CFD analysis or known from experiments, should be chosen to calculate the MIR for a given configuration.

3. Air Ingress Experiment

3.1 Experimental Overview

To provide a test of the SCAD concept, an experiment was constructed to simulate the onset of air ingress in hot and cold leg system representing a pebble bed core. The objective of the experiment was to numerically predict the onset of natural circulation in a pebble bed configuration using CFD, design an experiment that was appropriately scaled, build the experimental apparatus and then test for onset of natural circulation consistency with numerical predictions. Finally, the configuration was used to test the principle of Sustained Counter Air Diffusion and whether minimal injection of helium did prevent the onset of natural circulation such that it could be used to prevent the phenomenon in real reactors.

3.2 Apparatus Description

The test apparatus was an inverted U-tube with one leg heated with a pebble region and the other cooled, sitting atop a 55-gallon drum. The test apparatus was designed to be a scaled down version of the German NACOK test facility. A detailed description of the apparatus design process is given in Appendix A1. The inverted U-tube configuration was chosen to be consistent with previous air ingress experiments in Japan summarized in Ref. [2] and Ref. [7]. The valves connecting the U-tube to the barrel simulate the rupture of a co-axial pipe with the pipe break directly beneath the core. Figure 5 gives a schematic of the test apparatus giving dimensions and showing the locations of the pebble column, thermocouples, and pitot tubes. The U-tube is connected to the barrel by large valves that are labeled as "big valves". The valves labeled "small valves" are where the helium was injected in order to fill the U-tube with helium.

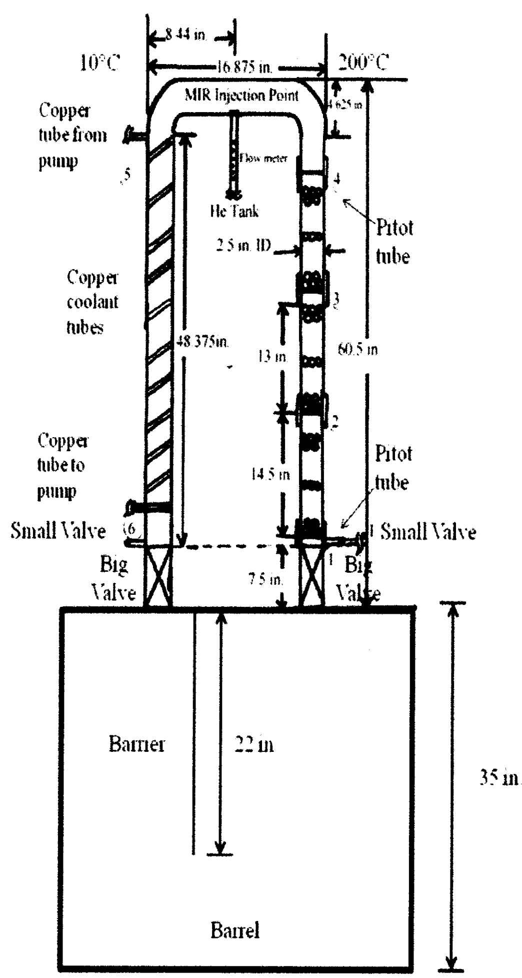

Figure 5: Full Apparatus

Thermocouples were used to monitor the temperatures of each leg, and Pitot tubes were inserted above and below the pebble region to measure the pressure difference across the pebbles. Helium was injected into the middle of the top horizontal cross-over leg, at the injection location shown in Figure 5.

The apparatus was made primarily of copper pipes with an inner diameter of 2.50 in. The hot and cold legs were connected to the horizontal crossover leg with copper elbows, and to the barrel with 2.5 in. full port valves. Opening the full port valves simulated the pipe break, and they will be referred to as the big valves. The purpose of the 55-gallon barrel was to prevent disturbances in the lab from affecting the pressure sensor readings. Electrical metal tubing (EMT) was bent and screwed to the top of the barrel to support the u-tube. A barrier was screwed and sealed to the inside of the top of the barrel to prevent helium from exiting the cold leg and traveling directly back to the hot leg.

Pure-type soda lime glass pebbles with a diameter of 1.2 cm were placed into the hot leg to represent fuel pebbles. The total pebble region was one meter tall and broken up into three equal parts for temperature monitoring purposes. As seen in Figure 5, thermocouples were placed before and after each pebble section at positions 1-4. Each section was supported with a piece of brass that had been water-jetted into a mesh to reduce its resistance. There were approximately 678 pebbles in each section, giving a porosity of 0.418. Due to jostling during the soldering process, the exact packing structure of a PBR could not be recreated; however this is close to the projected porosity in PBRs of 0.395.

The hot leg was heated with three silicone rubber fiberglass insulated flexible heaters, which were wrapped around the pebble sections and secured with metal hose clamps. These three heaters were plugged into a Variac voltage controller, which was adjusted throughout each trial to maintain the desired temperature of 200°C. Copper tubing with a diameter of 0.25 in. was coiled around the outside of the cold leg and fastened with metal hose clamps. Water was pumped through a Neslab FTC-350a refrigerator and into the copper tubing to cool the leg to 10°C. Thermocouples were placed at positions 5 and 6 in

Figure 5 to monitor cold leg temperatures. All thermocouples were inserted such that their sensing tips were in the center of the pipe. The entire u-tube was insulated with several layers of crinkled aluminum foil. There were enough layers that the hot leg could be touched without gloves; the rest of the apparatus was wrapped similarly.

Because of the low flow rate even after circulation starts, a flow meter would have been unreasonable to identify the start of circulation. The flow meters had 0.25 inch openings in the copper tubes which were 2.5 in. in diameter. This small opening would cause significant resistance and likely prevent circulation from ever starting due to the resistance offered. To be able to determine the time for onset of natural circulation, a different indicator was needed. As will be discussed later, CFD results showed the mass flow spike indicating the onset of circulation corresponds to a measurable change in pressure across the pebble region. Thus, Pitot tubes were screwed into the apparatus above and below the pebble region (at positions 1 and 4 in Figure 5) to monitor the pressure difference over this distance. An MKS Instruments, Inc. Baratron was used to sense the pressure and attached to a digital readout. The thermocouple positions were located above and below each heater, and at the top and bottom of the cold leg. High temperature room-temperature vulcanization (RTV) adhesive sealant held the thermocouples in place and sealed the holes. HP Benchlink Datalogger displayed the temperatures from the thermocouples.

The helium supply tank was attached to the apparatus with plastic tubing, and each end of the tube was fastened with a hose clamp. The tube was attached to a small valve to flush and fill the apparatus. The line also included a flow meter at the top of the apparatus during injection. The regulator kept the flow at a pressure of one atmosphere during the filling stage, and was varied according to injection rate during the injection stage.

3.3 Experimental Procedure

3.3.1 Experimental Preparation

To begin each trial, the u-tube was sealed from the outside environment and the walls were heated or cooled as necessary to the desired temperatures. The apparatus was then flushed with helium so that the tank pressure dropped by 200 psi which corresponds to approximately 0.101 kg of helium, or 67 times the mass that would fill the volume of the apparatus at standard temperature and pressure. (In one trial, the apparatus was flushed with 500 psi with similar results.) Because the primary goal of the experiment was to evaluate SCAD, the depressurization phase of the air ingress accident was neglected. Thus, the start of the experiment corresponded to the end of the blowdown phase when the pressure in the reactor equilibrates with containment. The hot and cold legs were heated to near 200° C and 10° C, respectively, and the helium was heated and cooled to these temperatures. At time zero, both the hot and cold leg big valves were open simultaneously allowing air from the 55 gallon drum to flow in. During injection runs, the helium injection started at the same time as the big valves on the end of either leg were opened.

3.3.2 Measurement Description

The appropriate hot and cold leg temperatures were maintained by controlling the power to the heaters and cooler by monitoring the thermocouple data. When the temperature readings would begin to become too high or low, the power to the heater and cooler were adjusted accordingly.

As described previously, the pressure difference across the pebble column was used to monitor the onset of natural circulation. Thus, the differential pressure across the pebble column was monitored and recorded every several minutes and then at faster intervals when the pressure difference was changing relatively quickly. The Baratron pressure value was zeroed to the "cold" air hydrostatic head before the experimental preparation began. When the differential pressure value became negative, a frictional pressure drop was being experienced by the fluid as it flowed upward through the pebble column.

Thus, natural circulation was considered to start when the differential pressure reading became negative.

3.4 Project Results

3.4.1 CFD Results

FLUENT®, commercial CFD software, was used to simulate our setup to ensure that air circulation would start within several hours. A 3-D model was created and is shown in Figure 6. The three separate pebble sections are represented as one continuous pebble column equal to 39 in. in height. The pebble column walls and the walls of the upper heated section of the hot leg were held at 200°C while the cold tube walls were set to 10°C. The walls of the cross-over leg and both big valves were set as adiabatic. The barrel walls were set at 20°C. Appendix A2 provides a summary of the solver settings used in this model (referred to as the original model).

Nitrogen gas was used in place of air in the model to reduce computational complexity. The pebble column was modeled using the FLUENT porous media option. Initially, the upside U-tube was filled with helium at 1 atm and the barrel was filled with nitrogen at 1 atm. The initial temperature in each of the zones were 200°C in the upper heated region and pebble column, 50°C in the cross-over leg, 10°C in the cold tube, and 20°C in both big valves and the barrel.

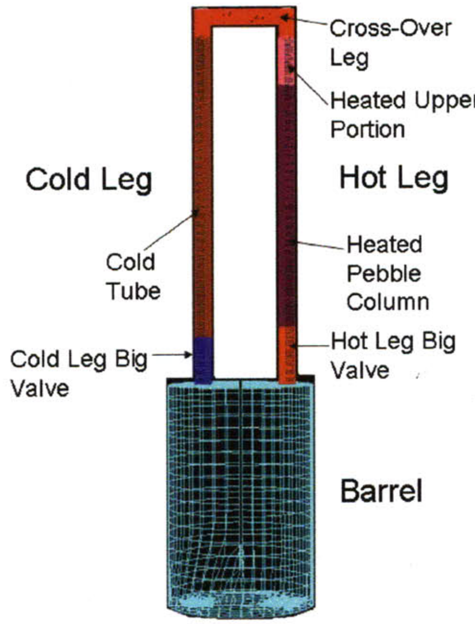

Figure 6: FLUENT Computational Mesh

The FLUENT results are shown in Figures 7 to 9. Figure 7 depicts the nitrogen mole fractions at four different locations in the apparatus: the entrance and exit of the pebble column and the entrance and exit of the cold tube in Figure 6. Figure 8 shows the mass flow rate versus time and Figure 9 gives the pressure difference across the pebbles over time. Natural circulation starts at approximately 280 minutes as indicated by the mass flow spike at that time. The mass flow spike corresponds to the time when the apparatus becomes completely filled with nitrogen, as shown by Figure 7. The pressure difference across the pebble bed was positive, meaning that is the pressure was greater above the pebbles than below during the diffusion phase. At the onset of natural circulation, the pressure difference becomes negative because of the flow through the pebble bed.

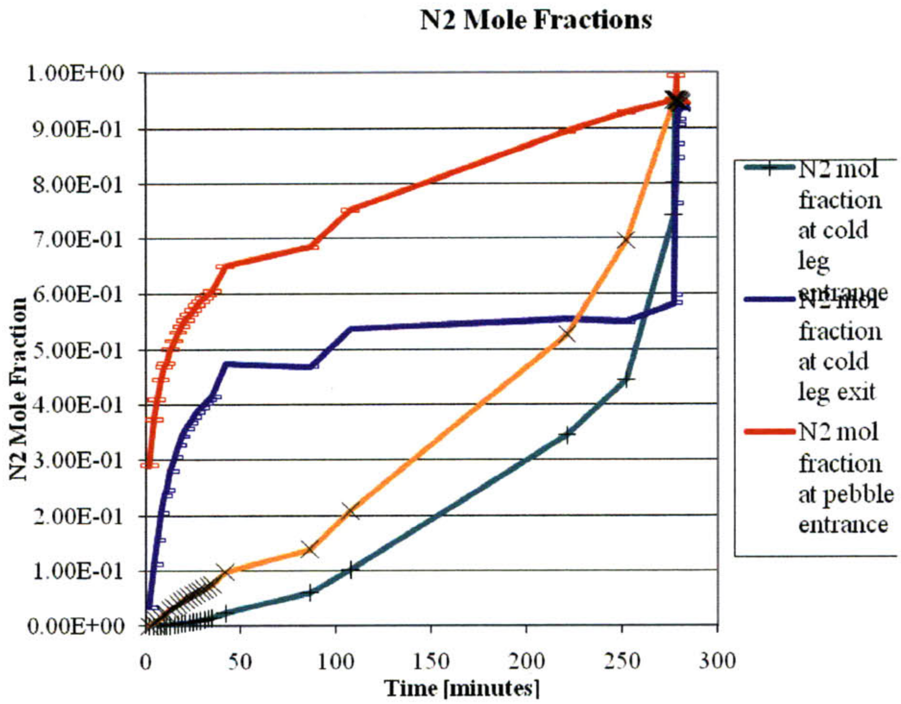

Figure 7: Nitrogen mole fractions at apparatus boundaries

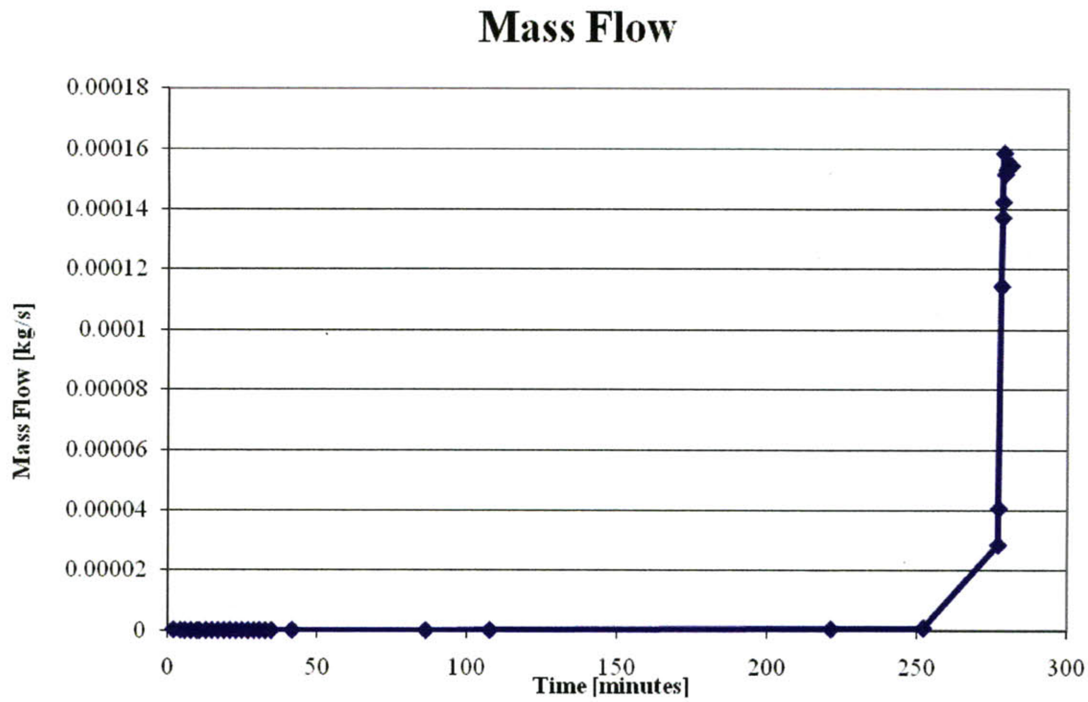

Figure 8: FLUENT results showing mass flow leading up to and at onset of natural circulation

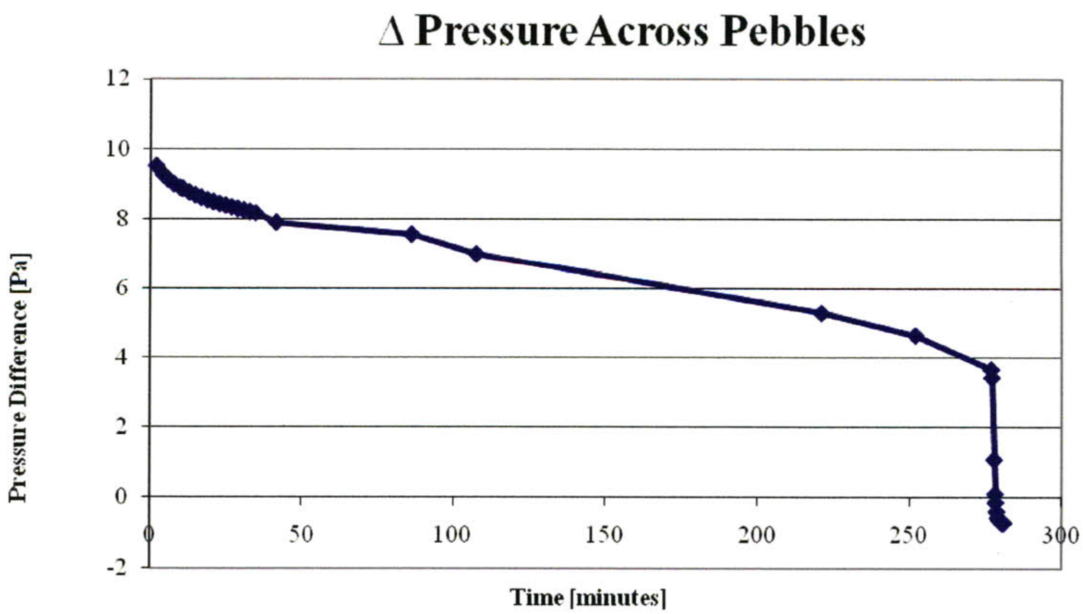

Figure 9: FLUENT results showing change in pressure across pebble region leading up and at onset of natural circulation

3.4.2 Experimental Data

3.4.2.1 Air Only Trials

In order to better appreciate the natural circulation process in this apparatus, several trials were performed. The first trials consisted of heating the air inside the apparatus on the hot leg and cooling the cold leg. Upon opening the two big valves, the pressure across the pebbles immediately dropped, indicating natural convection flow through the pebble column. Once the valves were closed, the differential pressure quickly returned to its original value. Opening any other combination of valves on the apparatus did not cause the same immediate change in the differential pressure reading. The different valve combinations remained open for several minutes and no indication of flow was seen from the pressure reading. The various valve combinations were as follows: opening the hot big valve and cold small valve, the cold big valve and hot small valve, both small valves, and only one big valve. With the two big valves opened natural circulation was indicated almost immediately, whereas none of the other combinations had the immediate natural circulation onset after the different valves were opened. This suggests that there is a correlation between break size and natural circulation onset time. Opening the big valves, immediately establishes a flow path for the hot air to rise, and then fall as the air is cooled in the cold leg. Even though a flow path existed with the small valves open, it was not sufficient to provide a circulation path immediately for the air and thus no flow resulted.

The air-only trials confirmed the use of monitoring the pressure difference across the pebble column as an indicator for the onset of natural circulation. During the heating phase transient, a pressure "bubble" would be created above the pebble column to counteract the buoyancy force to prevent flow, since no flow path existed. When both big valves were opened, the buoyancy force would overcome this pressure "bubble" because of the existence of an open flow path. The pressure difference across the pebbles would almost immediately become negative indicating flow upward through them. Any other combination of opened valves did not show the pressure difference becoming negative, it would remain positive, meaning the pressure "bubble" was in place, and preventing the onset of natural circulation.

3.4.2.2 Non-Injection and Injection Trials

A series of experiments were conducted to gain enough data to support findings on the air ingress phenomena. The first series of tests were aimed at developing a consistent data set on air ingress without helium injection. Five tests were conducted without helium injection which showed consistent behavior in terms of the onset of natural circulation. This was followed by a series of tests in which helium injection of various rates was tested to determine whether it prevented the onset of natural circulation. The last series of injection tests was aimed at establishing a minimum injection rate within the limits of the measuring device. In all 11 tests were run – 6 non-injection and 5 injection.

Figure 10 is a plot of all data taken during the experiment of non-injection and injection trials. Note that the ΔP in Figure 10 is a "zeroed" differential pressure, meaning a value of zero corresponds to the room temperature air hydrostatic head before the start of the experiment. Thus a negative value means a pressure difference across the pebble column greater than the room temperature air hydrostatic head. The absolute pressure difference is then approximately 15 Pa less than the Figure 10 reported value. The important point of Figure 10 is that the differential pressure behavior indicative of natural circulation onset (the ΔP drop) only occurred in non-injection cases. All injection cases did not show that same ΔP drop behavior, therefore natural circulation never started in any of the injection cases.

The average natural circulation onset time for the non-injection trails was 117 minutes with a standard error of 7 minutes. Injection trials were run for at least 240 minutes, approximately twice the length of time that non-injection runs were run. One lasted for 480 minutes. Natural circulation did not start at any injection rate at or above 1 cc/min, the minimum rate we could measure.

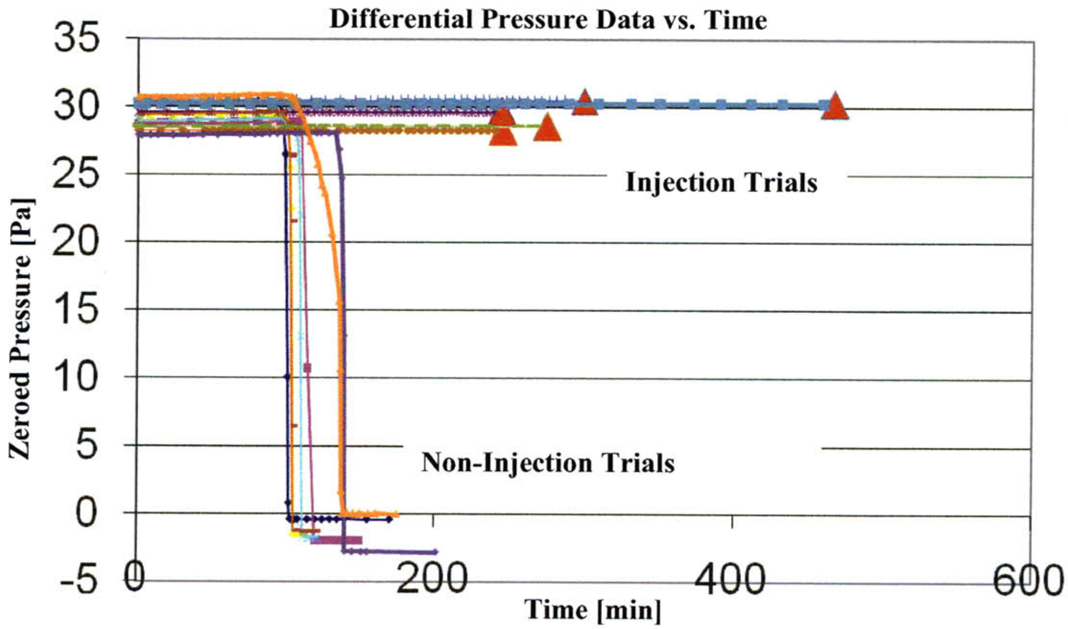

Figure 10: Results of all injection and non-injection trials. Red triangles show the end of the trial in injection runs

In two of the injection runs, data was taken after the injection was turned off. Though the pressure began to drop at different times, the onset time for both was about 120 minutes after injection was turned off as shown in Figure 11. This clearly shows the effectiveness of minimum helium injection as a means to avoid massive air ingress by eliminating or at least significantly delaying natural circulation.

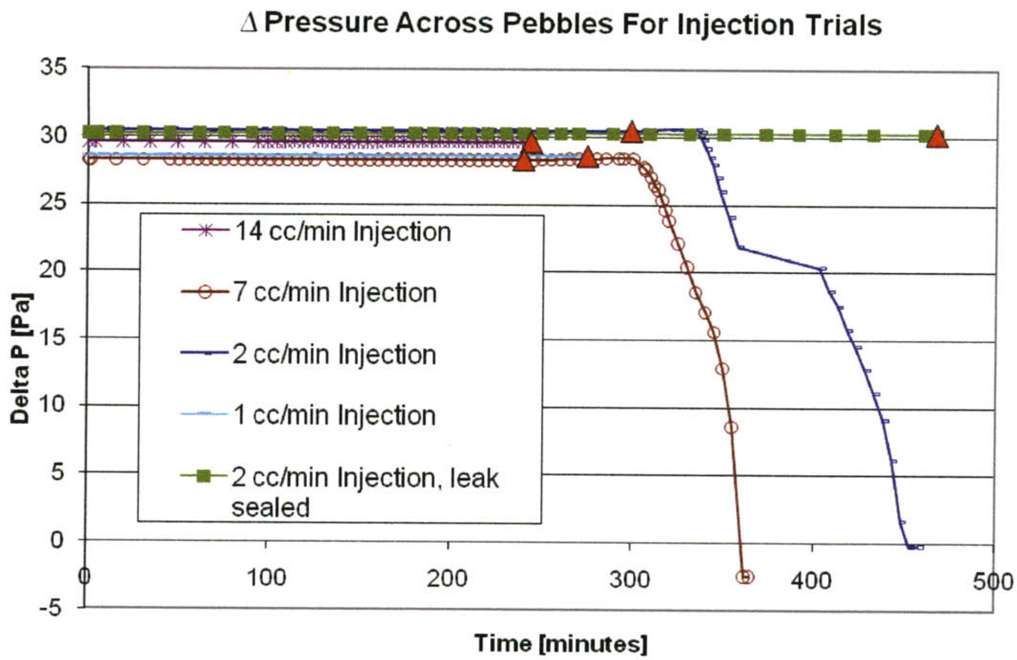

Figure 11: Time until onset in injection trials after injection has been stopped

3.4.2.3 Post-Leak Fixes

After construction on the apparatus was completed, a leak test was performed on the u-tube. No leaks were found in the simple leak test. After multiple trials a second leak test was performed and a leak was found at one of the thermocouple locations. The thermocouples were only sealed by RTV and it is possible that during the filling process the high velocity helium could have dislodged a proper seal. The leak was fixed and several more non-injection cases and an injection case at 2 cc/min were performed. The subsequent non-injection cases had the longest onset times at approximately 140 minutes each. But, one of the trials showed the pressure difference begin decreasing at a similar time as the previous cases, but showed natural circulation onset about the same time as the other post leak fix case. Thus, the case seems to have enveloped the entire spectrum of conditions in the pre and post leak fix cases. Since the onset time difference was only an additional 20 minutes, it was felt then that the leak had a small impact on the results. The 2 cc/min case performed after the leak was sealed was run for about 4 times as long as the average onset time (approximately 480 minutes) and natural circulation was never developed.

4. FLUENT Analysis Discrepancy

Although the experimental data suggests that SCAD does indeed prevent the onset of natural circulation, the FLUENT results over-predicted the natural circulation onset time by over a factor of 2. This point is illustrated by comparing the experimental data, Figure 10, to the FLUENT differential pressure results of Figure 11. The average onset time for the experimental data was about 120 minutes, while the numerical model predicted onset at around 280 minutes. It is important to reconcile the differences in the FLUENT model to allow the CFD results to better reflect the experimental data for a deeper understanding of important phenomenon. The original FLUENT model was created before the experiment was conducted in order to give an estimate for how long the experiment would last. Because of this, the boundary and initial conditions were very simple and ultimately did not accurately reflect those of the experiment. Determining the conditions that were not properly represented will therefore provide further insight into the causes and important parameters that impact the onset of natural circulation. Once the computational model discrepancies are resolved, the evaluation of the validity of SCAD can be more thoroughly examined.

5. Contributions of Current Work

Understanding how to model the development of transient natural convection in a postulated HTGR air ingress accident scenario is important. The flow is dictated by the competing buoyancy effects of thermal and concentration gradients. In general, such flows are classified double-diffusive convective flows with combined heat and mass transfer, and thus this research provided insight into proper modeling techniques for this class of flows in commercial CFD software, specifically FLUENT. The impact of various solver settings, controls, initial, and boundary conditions on the flow field behavior and natural circulation onset were evaluated. The most appropriate settings were therefore determined for this class of flows.

The investigation process into improving the computational model also provided further insight into the mechanisms that affect the onset of natural circulation. The important driving parameters were then quantified in terms of non-dimensional numbers that provided relative strengths between different cases. Looking at the flow field non-dimensionally, provided insight into why the original FLUENT model over predicted the onset time.

The current work also provided further insight into SCAD for a PBR. The effectiveness of SCAD on preventing/delaying natural circulation onset was investigated and compared in non-dimensional terms to provide insight for a full scale PBR case. A methodology was formulated in order to determine an empirical correlation for the minimum injection rate required to prevent the onset of natural circulation. That methodology will be described.

6. Improvements to Previous CFD Model

6.1 Overview

The following discussion describes in detail the various attempts made in trying to improve the computational model to better reflect the experimental data. The different attempts can be broken into two basic classes, boundary conditions and initial condition changes. Boundary condition changes attempted to better reflect the experimental boundary conditions that were not represented by the initial very simple computational model. The boundary condition investigation examined the impact of the porous media model in FLUENT as well as the use of heat flux wall conditions and more accurate temperature wall profile compared to simple constant wall temperature conditions.

Investigating improved initial conditions was an attempt to accurately account for the heating phase that occurred before opening of the big valves to start the experiment. A full heating phase transient was simulated in the u-tube and used then used as the initial conditions for a full transient simulation. The heating phase transient allowed the initial conditions to capture detailed local circulation loops and non-uniform pressure fields that were not accounted for in the original initial conditions. The initial helium fraction in the u-tube was also varied to account for the uncertainty in that there was no way to monitor the helium concentration in the u-tube in the experiment.

The investigation concluded that of the various changes examined only the initial u-tube helium fraction had significant impact on the natural circulation onset time. As will be discussed later, any changes to the original model improved the results only up to the point of more closely following the diffusive transport rate in the hot leg and could not decrease the natural circulation onset time by more than 40 to 50 minutes (so onset occurred around 230 minutes rather than 280 minutes). However, lowering the initial helium fraction only 15% in the u-tube decreased the onset time from approximately 280 minutes to about 126 minutes. Because the initial helium fraction in the u-tube was unknown and was not able to be measured given the budgetary constraints on the experiment, it is felt that these results show that the U tube did not contain 100% helium at the start of the tests. The implications of such initial conditions will be discussed later. Described below are the individual studies that led to the conclusions cited above.

6.2 Boundary Conditions

6.2.1 Porous Media Models

In FLUENT, it would be computationally unreasonable to model the pebble column as an explicit packed bed. Therefore, a porous media model assumption was used to model the pebble column. Previous studies, including Yan's work modeled the prismatic cores as porous media as well. In FLUENT the user must specify the solid material present in the porous media, which impacts the calculation of the heat transfer properties as well as the porosity of the media. The governing momentum equation is modified by including an additional momentum sink term to account for the added resistance of the porous media. There are several different momentum sink models to use. The choice of momentum sink model as well as values used in the model impact the resistance experienced by the flow from the packed bed. Therefore, a sensitivity study was performed on FLUENT's porous media model to determine if the model could be impacting the onset of natural circulation.

The original model used the Power Law model, which was consistent with how Brudieu [2] modeled the pebble column in the NACOK experiments. The Power Law momentum sink model is given by:

$$S = -C_0 |u|^{C_1}$$

Equation 2

where: S ≡ momentum sink term,

u ≡ fluid velocity [m/s],

C_0 and C_1 ≡ pressure loss coefficients [6].

The pressure loss coefficients therefore set the resistance to the flow for the porous zone. The original model used the values determined by Brudieu for 10 mm diameter pebbles, $C_0 = 341$ and $C_1 = 1.6107$. However, the pebbles used in the experiment were 12 mm diameter pebbles. Using the given values would then give an effective pebble column resistance for 10 mm pebbles, which would be greater than the resistance for a bed of 12 mm pebbles. In the original pre-experiment model, it was assumed that the increased resistance would be small and may account for additional losses not accounted for in the model.

To check the porous media model, two additional tests of the effect of porous media model were made. First the viscous loss coefficient model was used instead of the power law model, and in the second the porous media model was not used. In the latter case, the pebbles are effectively removed and an open hot leg exists offering no additional resistance to flow. This would provide a lower bound on the resistance experienced in the hot leg and should bound the onset time prediction, if the porous media model has a substantial impact on the computational results.

In the viscous loss coefficient model, the momentum sink term is given by:

$$S = -\left(\frac{\mu}{K}u + C_2\frac{1}{2}\rho|u|u\right)$$

Equation 3

where: $\mu \equiv$ fluid viscosity [Pa-s],

$K \equiv$ porous media permeability [m^2],

$C_2 \equiv$ inertia loss coefficient [1/m],

$\rho \equiv$ fluid density [kg/m^3].

The inertia loss coefficient accounts for added loss from turbulence present through the porous media. Note that for low velocity flows it will have only a small contribution on the momentum sink term and the momentum sink term is simply Darcy's law through porous media. The permeability and inertia loss coefficient are dependent on the geometry and type of porous media. However, for a packed bed, they are easily calculated from:

$$K = \frac{D_p^2 \varepsilon^3}{150(1-\varepsilon)^2}$$

Equation 4

$$C_2 = \frac{3.5(1-\varepsilon)}{D_p \varepsilon^3}$$

Equation 5

where: $D_p \equiv$ pebble diameter [m],

$\varepsilon \equiv$ pebble bed porosity.

The original FLUENT model assumed the pebble bed porosity of 0.395 while the actual experiment was above 0.4. For the experiment, the calculated values of the permeability and inertia loss coefficient are: K = 1.7067e-7 [m^2] and C_2 = 2734. Since the momentum sink therefore essentially scales with the inverse of the permeability, looking at 1/K for the actual experiment and original FLUENT model gives an idea of how much extra resistance was seen by using the 10 mm pebble assumption. The 1/K value for experiment is: 1/K = 5.86e6 [m^{-2}] while for the original FLUENT model it was: 1/K = 8.91e6 [m^{-2}] (calculated assuming the pebbles were 10 mm with porosity of 0.395).

Thus, the original FLUENT model was about 1.5 times more resistant the actual experimental model.

A FLUENT transient was then re-run with the change to the viscous loss coefficient model as well as the case with no porous media used. The initial conditions and solver settings and schemes were consistent between the original model and the case with no pebbles. The case with the viscous loss model also included changes to solver settings and schemes using higher order schemes and is provided in Appendix A2. The results of the three cases will be compared by examining the behavior of the average helium mole fraction in the cross-over leg. Even though this quantity was not measured, observing its behavior gives insight into the transport rate of nitrogen up the hot leg as well as how that transport rate is changing with time. Looking at the results in this manner therefore assumes once natural circulation starts the cross-over leg helium mole fraction will quickly drop to low values (only a few percent at most).

Figure 12 gives the transient behavior of the average helium mole fraction in the cross-over leg for each case. The original FLUENT case results show that when natural circulation starts at about 280 minutes, there is a sharp drop in the helium mole fraction in the cross over leg from about 15% to about 5%. Also note that later on in the transient the rate of nitrogen transport up the hot leg (and so rate of decrease in helium mole fraction in the cross-over leg) increases. The increased transport rate corresponds to the increasing buoyancy force that arises as the configuration gets closer and closer to the onset of natural circulation. The key point of Figure 12 is that the tested porous media cases have very similar transport rates of nitrogen through the u-tube in the first few hours. The no pebble case curve almost exactly follows the original results, while the viscous loss model curve is slightly faster. The slightly different behavior of the viscous loss model case can be explained from the higher order schemes and settings that were applied to this particular case.

Both modified cases were not run out to the onset of natural circulation because the goal of the investigation was to see if the porous media model was impacting the FLUENT results relative to the experimental data. For the FLUENT results to better match the experimental results, the cross-over leg average helium mole fraction would have to drop to a few percent by about 120 minutes, and not 280 minutes. Since both cases were greater than 80% helium in the cross-over leg by about 2 hours, it was obvious that the porous media model in FLUENT had no major impact on the transport rate of nitrogen during the first few hours and thus do not meaningfully affect the analysis of the onset to natural circulation.

Figure 12: Porous Media Investigation Cross-Over Leg Helium Mole Fraction Comparison

6.2.2 Heat Flux Boundary

The original FLUENT model used a constant wall temperature boundary condition in the hot leg. In reality, however, the power to the externally wrapped heaters was controlled to try and maintain the average gas temperature in the hot leg to be near 200 °C. Thus, higher temperature gas would be located near the walls which could rise at an increased rate than accounted for in the original model. Therefore, to account for this another

FLUENT simulation was run with the pebble column wall set as a heat flux boundary condition.

The experiment consisted of three heaters, and once the hot leg was heated usually the second heater as turned off, so only the bottom and top heaters were required to maintain the temperature. To ease the computational expense, a time-averaged constant wall heat flux was used for the single pebble zone in the computational model. The new heat flux boundary condition model also used the same initial temperature conditions of the original model. A temperature of 200 °C was used in the pebble column. The solver settings and schemes for the heat flux boundary condition case are provided in Appendix A2.

The heat flux simulation did show that the gas was rising faster along the walls, as expected. However, the gas temperature in the pebble column was getting far too high too quickly. Within five minutes, the average temperature in the pebble column was about 330 °C. Continuing to run the transient would have only heated the gas to higher temperatures, and so would have not been accurately modeling the conditions of the experiment. Therefore it was decided that continuing running these simulations was unnecessary.

This exercise therefore suggests if a heat flux boundary condition is desired, accurate temporal and spatial variation in the heat flux is required. In the experiment, with the second heater turned off, even though insulation was wrapped around that part of the hot leg, some heat would have escaped and without knowing the flow rate beforehand it would be very difficult to calculate the heat loss in that portion. Also, adding in proper temporal variation to match the experimental procedure would have complicated the model even further. Using even a simple constant wall heat flux, that is constant in time, required more iterations per time-step and longer processing time per iteration compared to the original model. Therefore to even run the simulation for five minutes of simulation time took considerable longer processing time than the original model. Considering a full scale PBR, using a heat flux boundary condition would then drastically increase the computing time compared to a simple temperature boundary condition, and so this investigation suggests any improvements to modeling would not justify the increased processing time.

6.2.3 Accurate Temperature Profile

The thermocouple data from the experiment showed that the temperature profile in the hot leg was in fact not a constant axial temperature, but rather varied up the hot leg. Using a constant wall temperature boundary condition, the original FLUENT model would not be able to account for this. A user defined function (UDF) was therefore created to accurately describe the thermocouple data from the experiment. The UDF is given in Appendix A4. This UDF was then set as the pebble zone wall boundary condition in a FLUENT case. The initial temperature profile UDF was a cubic best fit line of the thermocouple experimental data.

Results from this updated temperature boundary condition case showed minimal change to the original FLUENT model results. After 40 minutes, the nitrogen transport rate up the hot leg was consistent with the original model. Again, the model was not run until the onset of natural circulation because doing so would have yielded little insight as to why the transport of nitrogen was proceeding slower than it should in the first few hours.

The reason this case was not providing any significant changes is actually very simple. Figure 13 shows the plot of the UDF best fit temperature profile compared to the constant wall temperature condition versus pebble column height. Only the lower third of the pebble column deviated from the constant wall temperature condition by any significant amount, and this deviation made the lower third of the column at a lower temperature. Thus, the more accurate temperature profile would not provide any means to increase the nitrogen transport rate within the first few hours.

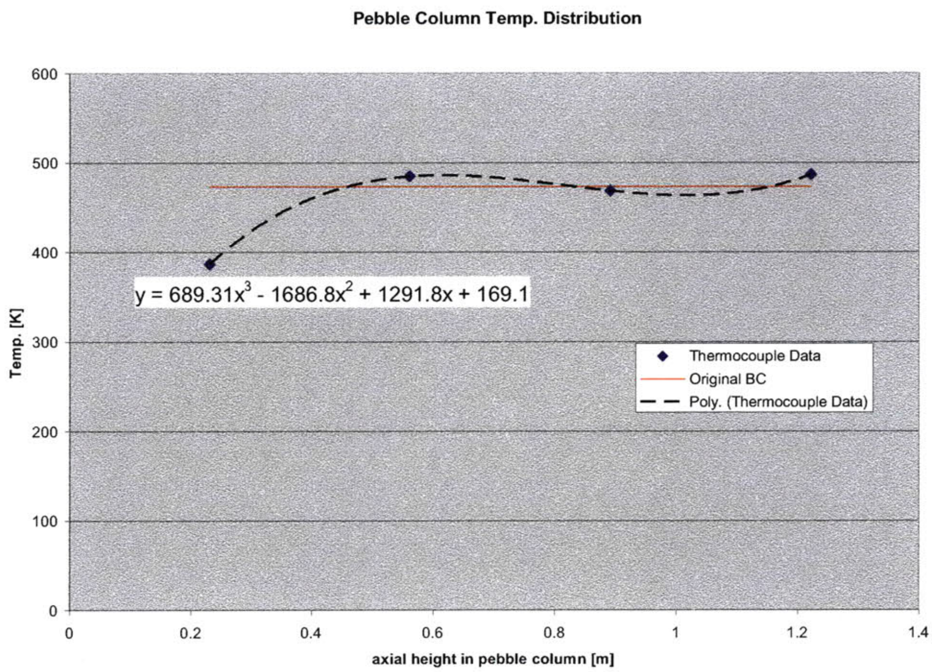

Figure 13: Temperature Profile Comparison

Overall, the investigation into the effect of boundary conditions on the natural circulation onset time showed that more accurate boundary conditions provided little improvement to the computational results. Modifying the boundary conditions had little impact on accelerating the rate of nitrogen transport up the hot leg to allow natural circulation to start sooner, as the experimental data showed. The lack of insight gained from examining the boundary conditions facilitated the investigation of the impact on natural circulation onset from the initial conditions.

6.3 Initial Conditions

6.3.1 Full Heating Phase Transient

The original FLUENT model used very simple initial conditions for pressure, velocity, and temperature inside the u-tube. Again, this was because the original FLUENT model was run before the experiment and so were only very rough estimates for what the initial conditions could be. The original initial pressure field was set to equal pressure everywhere at 1 atm. The original initial velocity field was set to zero everywhere as well. The initial gas temperatures were simply constant temperatures in the different zones.

As described earlier, a heating phase took place before the start of the experiment. The heating phase created the pressure "bubble" described earlier, where the pressure was higher above the pebbles than below. Although, the original FLUENT model, computed a pressure "bubble" early on in the transient, it would not be able to predict any possible over-pressurization that could occur during the heating phase. The over pressurization could have forced out helium out the hot and cold legs when the big valves were opened up that helped draw in air faster due to the depressurization transient.

A heating phase transient simulation was therefore run in FLUENT to account for the dynamics during this period. The experimental heating phase took about an hour, so the simulation lasted for about an hour as well. Single phase helium was used as the working fluid inside the u-tube for the heating phase transient. The u-tube mesh was refined, since the barrel was not part of the simulation, the u-tube could have a much finer mesh than the original at no significant cost to memory. Also, the u-tube bend geometry was improved, from a simple 90° bends in the original mesh, to more accurately representing the curved bends on the apparatus. The improved u-tube mesh is displayed in Figure 14, with the different zones in different colors. To try and setup accurate thermal gradients, the pebble column wall temperature UDF was used as the boundary condition for the pebble column wall as well.

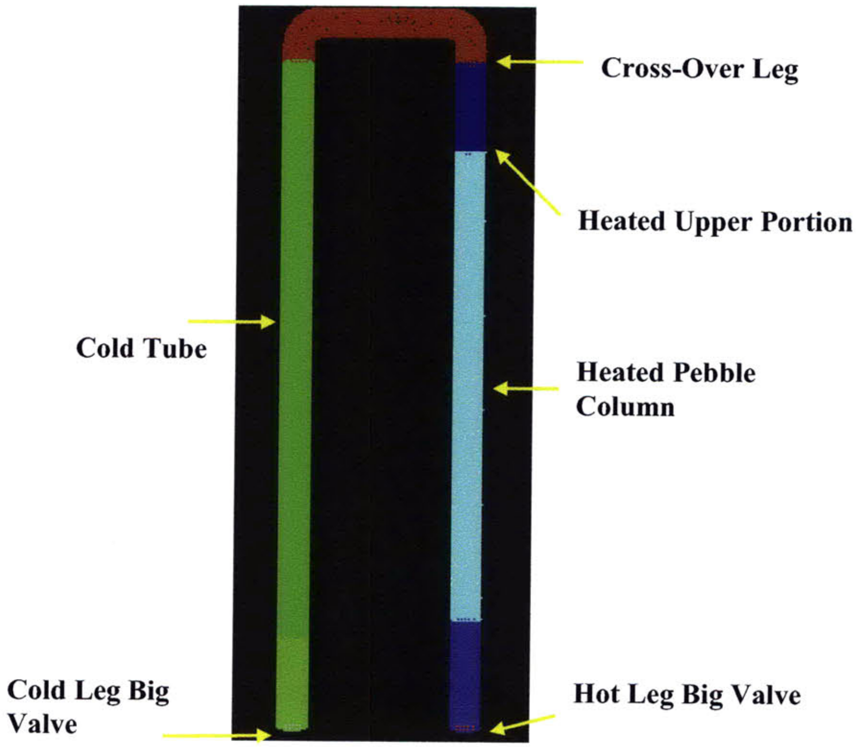

Figure 14: Heating Phase Transient Mesh

Heating phase transient results showed considerable pressurization inside the u-tube. The maximum pressure at the end of the almost one hour simulation was 10.6% higher than atmospheric pressure. The pressure profile followed the trend of the experimental pressure "bubble" where the pressure was higher above the pebbles than below. However, the magnitude was much smaller in the new simulation results, with pressure difference of only about 1 Pa instead of about 15 Pa. The pressure contours inside the u-tube are shown by Figure 15. The maximum pressure, as seen in Figure 15 is located at the bottom of the cold leg. This plot suggests then that the pressure "bubble" effect, where the pressure increases axially up the hot leg forms to counter-act the buoyancy force driving the flow. Inside the cold leg however, the density of the fluid still creates a static head that increases the pressure axially down the cold leg.

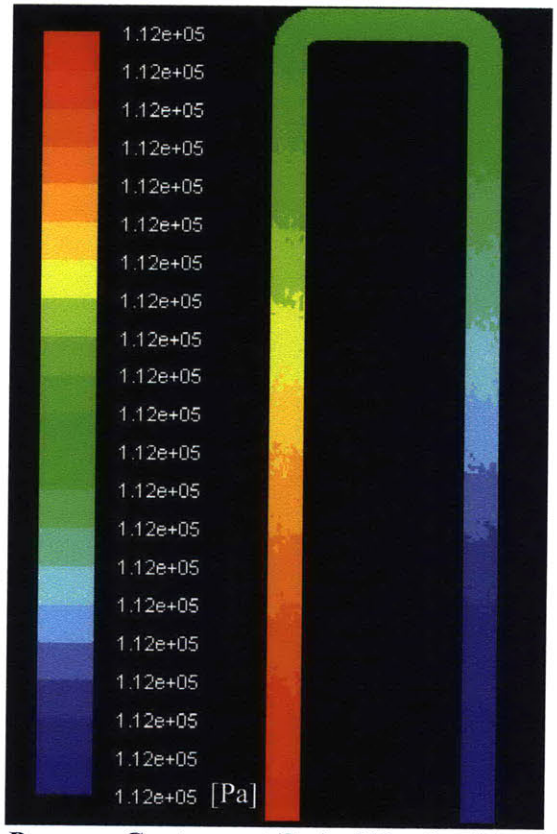

Figure 15: Pressure Contours at End of Heating Phase Transient

The results also exhibit considerable local circulation through the cross-over leg. Smaller local circulation loops also exists at the interface between the hot leg big valve and the pebble column as well as at the big valve interface in the cold leg. However, the velocities of these circulation loops are small relative to the velocity magnitude in the cross-over leg circulation loop. The circulation loop inside the cross-over leg is driven by the temperature gradient that exists between the hot and cold leg. The temperature in the cross-over leg decreases from near the hot leg temperature down to the cold leg temperature. Figure 16 shows the plot of the cross-over leg velocity vectors and Figure 17 shows the temperature contours in the u-tube. The large white arrows in Figure 16 show the direction of the circulation loop. The colder gas is on the bottom side of the cross-over leg and traveling to the right and the hotter gas is above it traveling to the left.

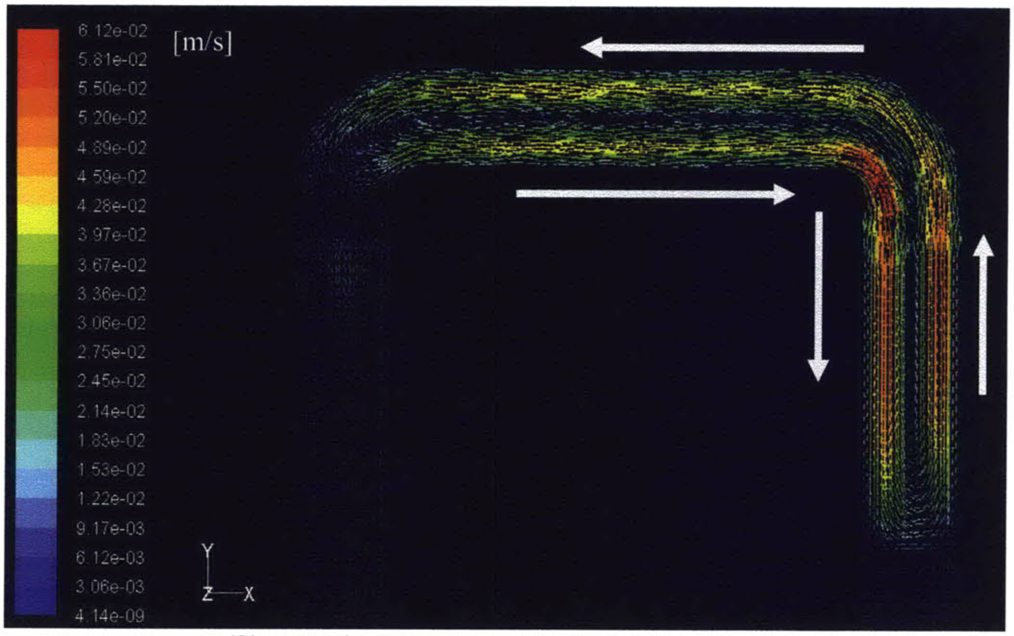

Figure 16: Cross-over Leg Circulation Loop

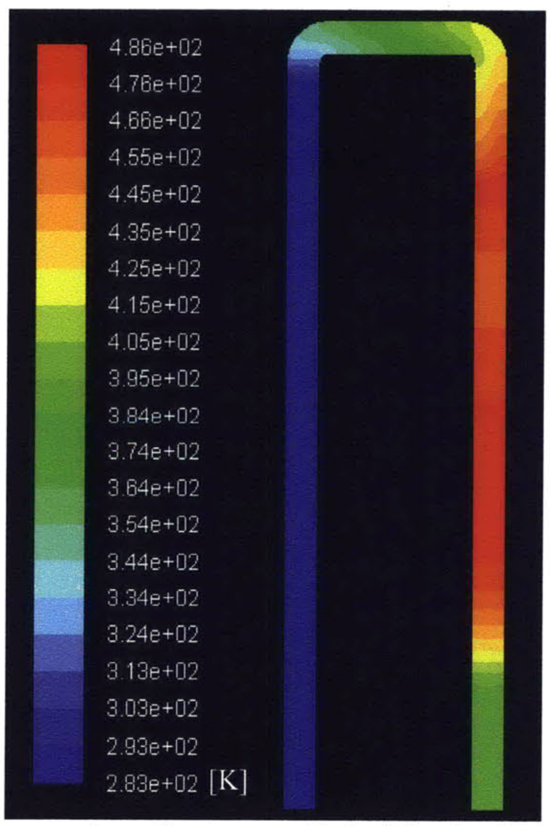

Figure 17: Temperature Contours at End of Heating Phase Transient

6.3.1.1 Effect of Heating Phase Transient

The results of the heating phase transient were then used as the initial conditions for a full transient simulation including nitrogen inside the barrel. The flow field behavior up to about 0.01 seconds was dominated by the over-pressurization in the u-tube that forced flow down through the hot and cold legs. Most of the flow was forced out the cold leg, due to lower resistance in the cold leg than the hot leg. The pressure difference across the pebble column was as high as about 350 Pa during the depressurization portion of the transient. By about 0.01 seconds however, the pressure fluctuations dampened out and the pressure field returned to the pressure field normally computed by FLUENT.

Due to the u-tube over-pressurization, the calculated gas velocity out the cold leg got as high as 55 m/s. It is believed that if there was gas flowing at those speeds out the cold leg it would have been noticeable during the experiment. Also, during the experiment, when the big valves were opened, no pressure fluctuations were indicated across the pebble column and the pressure difference was never more than 15 Pa. Therefore, the experiment suggests that if there was any over-pressurization in the u-tube, it was not nearly as high as that computed by FLUENT during the heating phase transient. Thus, if over-pressurization would impact the results, accounting for such behavior would not be similar to the conditions in the experiment.

6.3.1.2 Effect of Initial Pressure Field

Although the calculated heating phase transient did not accurately reproduce the magnitude of the pressure "bubble" seen in the experiment, it did compute similar trend in the axial change in the pressure up the hot leg. Therefore, to see if the initial pressure field could have an impact on results, the pressure profile from the heating phase transient was scaled to better match the experimental results. Since over-pressurization is not an issue, the pressure field was input with 1 atm at the base of the hot leg. Any simulations run with this as the initial pressure field showed that within a few time-steps the pressure field would dampen out to the usual pressure field. Thus, the initial pressure field does not seem to have any impact on results later on in the transient.

6.3.1.3 Effect of Initial Local Circulation Loops

The effect of initial local circulation loops was evaluated by examining how long it would take FLUENT to predict the circulation loops to develop from a zero velocity field. Since the cross-over leg circulation loop is dictated by the thermal gradient in the cross-over leg, the set up time depends on the set up time for the thermal gradient to be established in the cross-over leg. Cases that used a more realistic temperature profile in the cross-over leg could establish a circulation loop within a few minutes. Cases that set the initial cross-over leg temperature to the hot leg temperature, would take slightly longer. But by 5 to 10 minutes, the circulation loops would be developed. Since the original FLUENT model was more than about 2.5 hours off in the estimate of natural circulation onset, 10 minutes is trivial and therefore, using an initial velocity field of zero everywhere has minimal impact on the natural circulation onset time.

6.3.2 Choice of Operating Density

During the investigation into the pressure field, an interesting point of concern was found for how FLUENT calculates the pressure in buoyant flows. When gravity is enabled in FLUENT, a change of variables is applied to the pressure field, as follows:

$$p' = p - \rho_O g z$$

Equation 6

where: $p' \equiv$ static pressure [Pa],

$p \equiv$ absolute pressure [Pa],

$\rho_o \equiv$ operating density [kg/m^3],

$g \equiv$ gravitational acceleration [m/s^2],

$z \equiv$ coordinate in the direction of gravity [m].

The static pressure is used for boundary conditions and post-processing [6]. This technique avoids round-off error and simplifies the setup of pressure boundary conditions. When this change of variables is applied to the momentum equation in the direction of gravity, the body force is therefore calculated as:

$$(\rho - \rho_o)g$$

Equation 7

In natural convection flows, the gravity body force is the driving mechanism for fluid motion. The choice of operating density, therefore, can impact the relative strength of the buoyant force acting on the fluid. Using the correct operating density is thus important to accurately compute the behavior of the flow field in buoyant driven flows.

In the original model, no operating density was set, so the default operating density was used. In FLUENT, the default operating density is the average fluid density through the space. Since the barrel is roughly 20 times larger in volume than the u-tube, the average density is roughly the nitrogen density at room temperature. With helium inside the u-tube for most of the transient, in the u-tube, the operating density is greater than the density in a specific cell volume. Thus, the direction of the gravity body force will be reversed inside the u-tube. The original model, as described earlier, predicted a similar pressure "bubble" effect, witnessed in the experiment, early in the transient. However, in light of the operating density effect, the pressure field was not the result of correctly predicting a pressure "bubble" to counteract the buoyancy force, but rather resulted from a reversed gravity body force. Thus, the fact the pressure increased axially with elevation in the u-tube was because that was the stable hydrostatic condition in the u-tube.

To check this, a case was run with the operating density set to 0 kg/m^3. The gravity body force will then simply be the density in a particular cell. Figure 18 shows results of the pressure field for the case with operating density of 0 and the original case (default operating density) at similar times (about 10 minutes). The original case is on the right and the peak pressure is in the top of the cross-over leg. However, the case with an operating density set to 0 has the pressure increasing with decreasing elevation with the highest pressure located at the bottom of the barrel. One striking feature of the original case is the almost constant pressure in the barrel. Later cases that used improved solver settings and schemes relative to the original case would also show the pressure increasing with decreasing height in the barrel and the pressure increasing with increasing height in the u-tube. This confirms that the gravity body force is reversed in the original model.

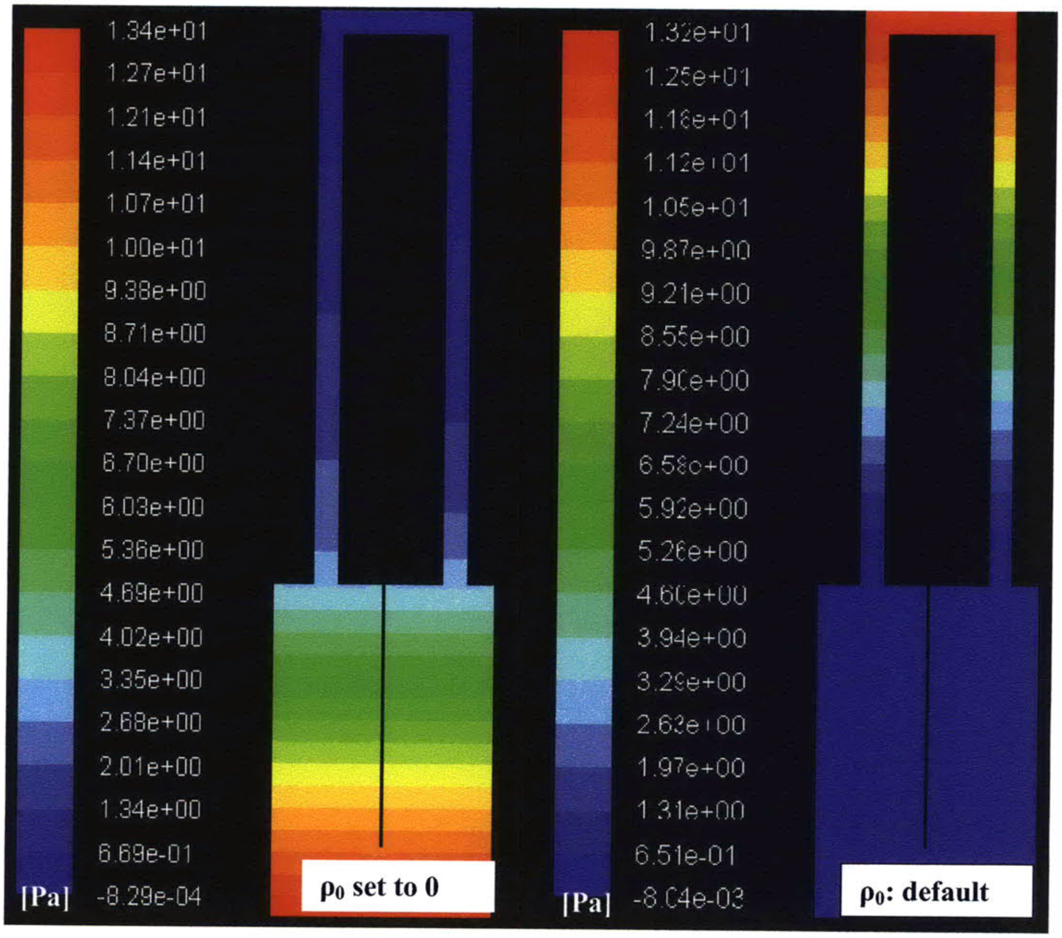

Figure 18: Pressure Profile Comparison Between Different Operating Densities

To see how this pressure field impacts the onset of natural circulation, the case was run for about 220 minutes. The results are compared in Figure 19 against the original model and the loss coefficient case with higher order schemes from section 6.2.1. Again, the average helium mole fraction in the cross-over is used to compare the transport rate of nitrogen between the different cases. As seen in Figure 19, even with the operating density set to 0, there is little difference in the nitrogen transport rate over the first few hours. If the transient had been continued, judging from the results, natural circulation would probably have started about half an hour sooner than the original results. The case with 0 operating density has similar solver settings and schemes to the case with the loss coefficient, than to the original case. Therefore, it makes sense that the original case behaves the least like the other two.

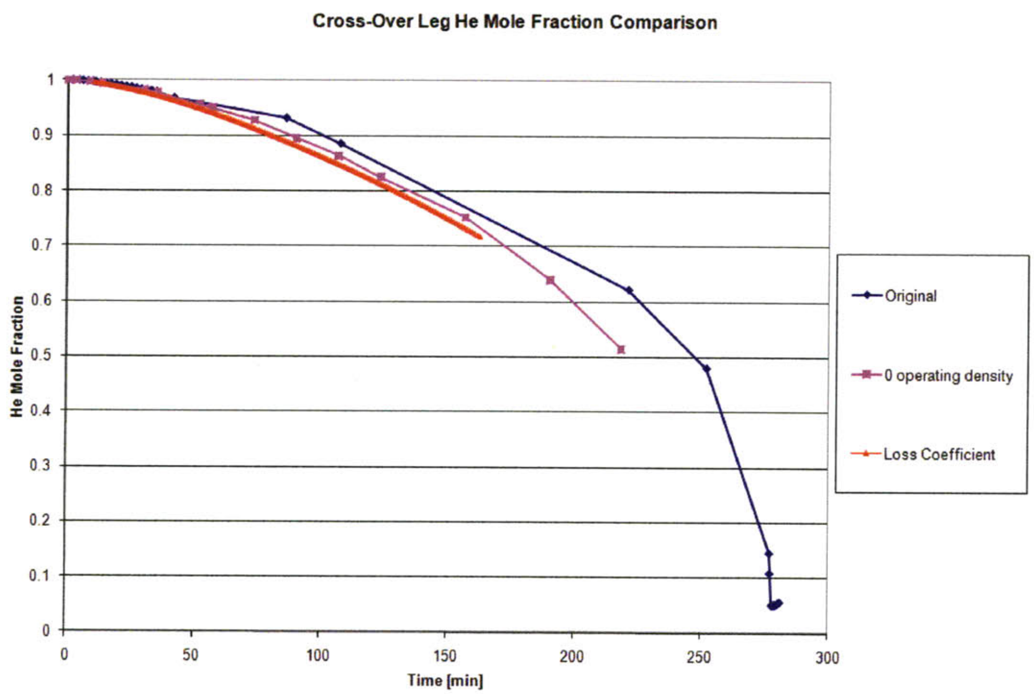

Figure 19: Cross-Over Leg Helium Mole Fraction Comparison

Thus, even though the choice of operating density can have a significant impact on the pressure field behavior, it has minimal impact on the nitrogen transport rate during the first hours of interest. Because of this, it was decided to keep using the default operating density since it better represented the experimental pressure "bubble" during the transient.

6.3.3 Helium Concentration

The original FLUENT model and all previously described cases assumed 100% helium initially in the u-tube. However, during the experiment there was no way of measuring the helium concentration in the u-tube. The filling process, described earlier, simply passed through a certain volume of helium and assumed then that the u-tube was almost entirely helium. The fill valves were small, 0.125 in. diameter valves located above the big valves on both legs. The helium was passed through the hot side fill valve and the gas flowed out the cold side fill valve. It was therefore impossible to know the amount of air purged out through the cold side fill valve.

A case was run using an initial helium fraction of 85% in the u-tube. The gas was assumed to be a uniform gas mixture. In reality, the filling process would have left air concentration gradients through the u-tube. Thus, at the start of the experiment helium-air diffusive transport would have been already occurring locally throughout the u-tube. Using a uniform gas mixture is a simple way to test the impact of higher initial air (or in FLUENT's case nitrogen) content in the u-tube. The initial helium fraction of 85% was chosen because in previous cases it would take about 2 hours for the cross-over leg helium mole fraction to drop 15-20%. It would be interesting to see then if starting at 15% nitrogen already throughout would bypass the first few hours of the transient. The case used simple initial temperature conditions and simple boundary conditions with equal pressure field everywhere and zero velocity field everywhere to start.

The results for the case using 85% helium initially showed that natural circulation started around 126 minutes. Figure 20 shows the plot of the mass flow rate versus time in the hot leg and Figure 21 shows the pebble column pressure difference versus time. Again, the pressure drop across the pebbles corresponds to the mass flow spike in the hot leg. The behavior of the pressure difference does not correspond to the experimentally recorded behavior, but the onset time of natural circulation is within the variation of the experimental data as seen by the dashed red lines of Figure 21. Note the time axis is 20 minutes longer in Figure 21 than 20.

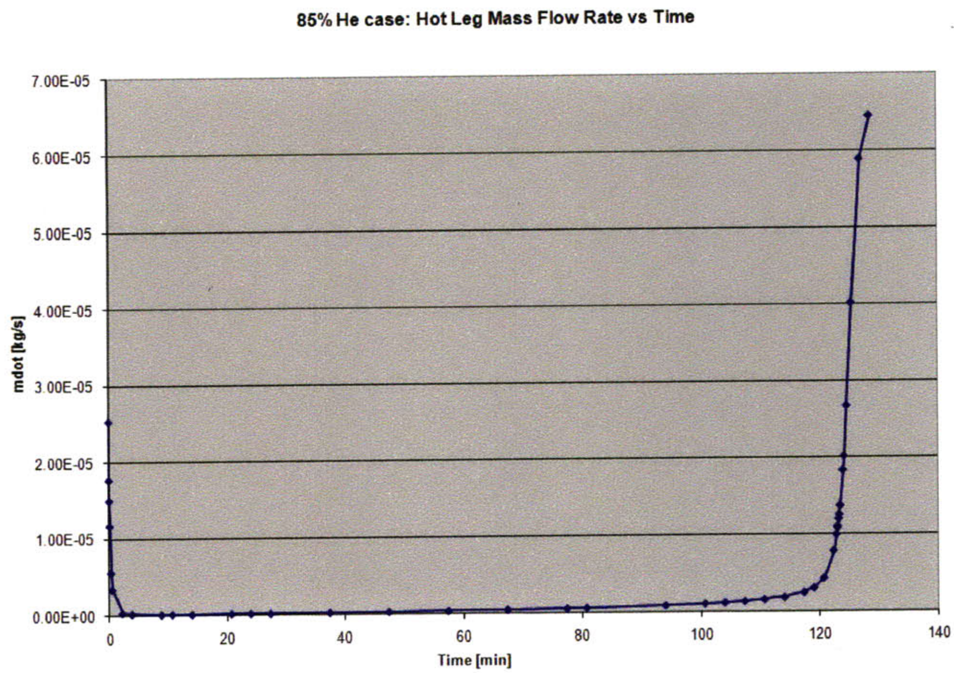

Figure 20: 85% Helium Case Mass Flow Rate

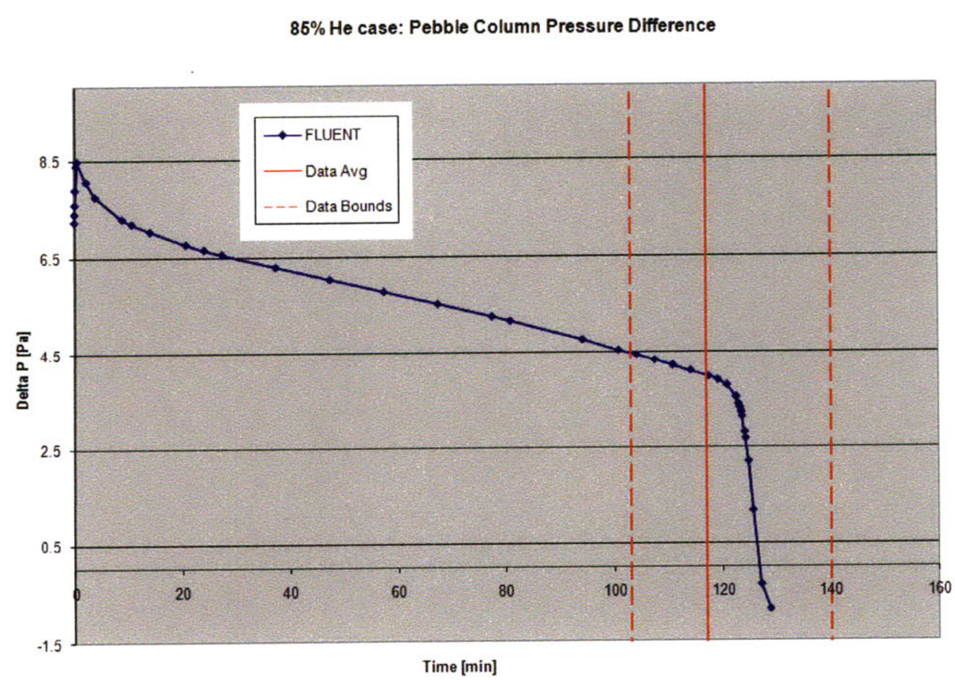

Figure 21: 85% Helium Case Pebble Column Pressure Difference

Reducing the initial helium fraction just 15% in the u-tube causes the onset time to be reduced from 4 hours closer to the 2 hour experimental onset time. Because of this, it is felt that the u-tube was therefore not at 100% helium initially, but at a lower helium fraction. The actual helium fraction distribution in the experiment, although not a uniform gas mixture, must have created an effect similar to having a uniform gas mixture at 85% helium fraction initially.

6.4 Justification for Change

As described previously, there was no way measure the helium concentration in the u-tube. Therefore, it was impossible to tell the difference between 100% helium in the u-tube compared to 90%, 85%, or even 70%. Changing the initial helium fraction is therefore within the uncertainty of the experiment. Also, the computational model shows that indeed the u-tube was mostly helium after the helium filling process. Varying the initial helium fraction was the last change attempted because it was initially assumed that considerable amounts of nitrogen would have to be in the u-tube initially for the onset time to be reduced by an appreciable amount. To get an idea for how only small changes in initial helium fraction can impact the onset time in large ways, the transport rate between cases will be compared.

The average helium mole fraction in the cross-over leg will again be used to compare the different cases. The original FLUENT and the 85% helium case will be compared as well as an additional case that used a higher continuity convergence tolerance than the original model (this case will be referred to as Update A). Again, the solver settings for Update A are given by Appendix A2. Figure 22 shows the average helium mole fraction in the cross-over leg for the different cases, along with the mole fraction computed using a 1-D analytical solution to the diffusion equation. The 1-D diffusion equation was solved using a Matlab script, and is given in Appendix A3. Update A uses the same initial boundary conditions as the original case. Examining Figure 22 shows that Update A follows the behavior of the analytical diffusion solution very well. For almost three-quarters of the transient, Update A follows the diffusive transport trend. Then at some point the buoyancy force begins to boost the transport rate and so Update A diverges from the analytical diffusion equation. The original case actually proceeds at a slower rate than pure diffusion, therefore the solver schemes must have been affecting the transport rate to actually slow down the transport rates in the original model. Obviously, the 85% helium case starts at a lower initial fraction of helium, but as shown in the figure, the transport rate is higher over the initial hour, and steadily increases over the duration of the transient until the onset of natural circulation.

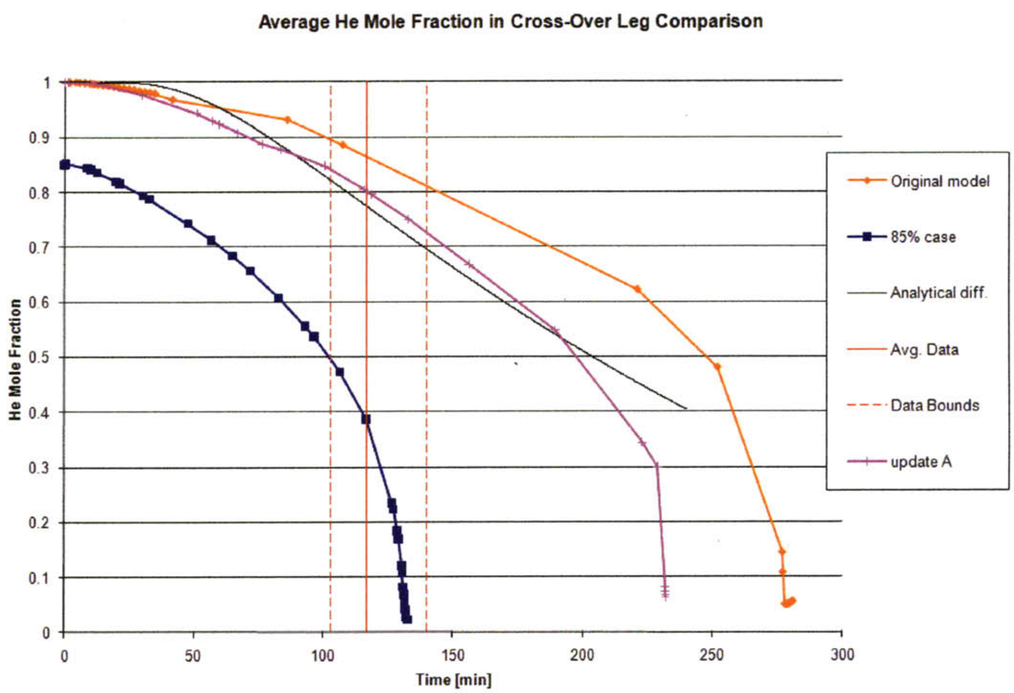

Figure 22: Cross-Over Leg Helium Mole Fraction Comparison

Therefore, any of the changes being made to the original model, were effectively pushing it to converge to the diffusive transport rate for a majority of the transient. That is why none of the previous investigations performed showed any considerable change to the transport rate over the first two hours. The buoyant driven flow for 100% helium initially therefore has negligible contribution over the first several hours, and transport is diffusion dominated. Only much later in the transient, when more nitrogen (and thus air) is in the u-tube, does the buoyant driven flow begin to contribute and increase the transport rate.

The 85% helium initial case however, has a constantly increasing nitrogen rate leading up to natural circulation. This suggests that transport is mixed between diffusive mass transport and thermally driven buoyant flow. By starting with a lower helium fraction initially, the lengthy diffusion dominated transport phase was bypassed and flow is a mixed transport for basically the entire transient. The increased nitrogen transport rate due to mixed transport causes the onset time to then be cut in half compared to pure diffusion transport with 100% helium initially.

Past studies, investigating similar phenomena showed good agreement between experimental data and numerical results, [2] [5] [7] [8]. FLUENT was used by References [2], [5], and [7] to model air ingress in upside down u-tube configurations. Brudieu [2] modeled the large NACOK facility while References [5] and [7] modeled smaller scale experiments. Takeda [8] however used a 1-D finite difference solver to simulate the governing equations of mixture continuity, mixture momentum and species continuity. Even though the 1-D finite approach of Takeda did not have the complexity of FLUENT, the numerical solution predicted the experimental data very well. Thus, it is not unreasonable to feel that numerical methods are more than capable of predicting the natural circulation onset time with reasonable accuracy, as long as the experimental conditions are properly modeled. Modifying the initial helium concentration in the u-tube was within the uncertainty of the experiment. Therefore, it is concluded that decreasing the initial helium concentration only 15% more appropriately modeled the conditions of the experiment which allowed the CFD results to better match the experimental data for natural circulation onset time.

7. Non-Dimensional Analysis

7.1 Formulation

The previous discussion details that there exists three distinct transport phases leading up to natural circulation. The first is diffusion dominated transport, followed by mixed transport between diffusion and buoyant driven convection, and the last being buoyant driven convection dominated transport. Once the last phase is reached, natural circulation through-flow in the apparatus is achieved. Figure 22 displayed this phenomenon in the differences between the Update A case and the 85% helium initial case. Update A, shifts after a majority of the transient from diffusion dominated to mixed, to then natural convection dominated. However, the 85% helium initial case begins at a more mixed transport rate and steadily increases to natural convection dominated. To try and characterize the relative strengths of the buoyant driven convection flow, a non-dimensional analysis was performed.

There are two ways to characterize the problem; the first is considering the mechanisms that determine the onset time of natural circulation. Such a method depends on the mass and heat transfer rates that dictate the properties in the flow field. Another method is similar to a pseudo steady-state approach, where the flow rate is evaluated for a given driving density difference. Thus, this approach does not examine what is causing the driving density difference to change over time, but rather simply characterizes the influence the driving density difference has on the flow rate. The non-dimensional analysis will therefore be formulated in such a manner.

The driving density difference between the hot and cold leg therefore must balance out the viscous forces through the u-tube. Neglecting all viscous losses except through the pebble column and assuming laminar Darcy flow the mass flux through the u-tube is given by:

$$G = \frac{(\bar{\rho}_c - \bar{\rho}_h) g H K}{\bar{\upsilon}_h h}$$

Equation 8

where: G ≡ mass flux,

$\bar{\rho}$ ≡ average density per channel (c and h denote cold and hot leg, respectively),

g ≡ gravitational acceleration,

H ≡ hot leg height,

K ≡ pebble bed permeability,

$\bar{\upsilon}_h = \dfrac{\bar{\mu}_h}{\bar{\rho}_h}$, average kinematic viscosity in the hot leg,

h ≡ height of pebble bed.

The Buckingham Pi theorem was used to determine the non-dimensional parameters. There are eight variables, with a total of three dimensions, so five non-dimensional parameters exist.

7.2 Important Parameters

The five non-dimensional parameters are given by Equations 9-11 and 13-14:

$$\Pi_G = \frac{G^2 K}{\bar{\mu}_h^2}$$

Equation 9

Equation 9, Π_G, gives the ratio between the mass flux to viscous forces through the hot leg.

$$\Pi_B = \frac{KH(\Delta\bar{\rho})g}{\bar{\upsilon}_h \bar{\mu}_h}$$

Equation 10

The non-dimensional buoyancy force, Π_B, relates the driving buoyancy force between the hot and cold legs to the viscous forces in the hot leg. Equation 10 is consistent with Darcy modified Grashof numbers for natural convection in porous media [9].

$$\Pi_{DR} = \frac{\Delta\bar{\rho}}{\bar{\rho}_h}$$

Equation 11

Equation 11, Π_{DR}, gives the density ratio between the driving density difference and the average hot leg density. The density ratio describes the contribution of hot leg density to the driving density difference. A higher driving density difference corresponds to having a higher buoyancy force. The density ratio therefore quantifies the changes in the driving density difference relative to the hot leg. Re-writing the density ratio best explains this concept:

$$\Pi_{DR} = \frac{\Delta\bar{\rho}}{\bar{\rho}_h} = \frac{\bar{\rho}_c - \bar{\rho}_h}{\bar{\rho}_h} = \frac{\bar{\rho}_c}{\bar{\rho}_h} - 1$$

Equation12

As the density in each leg changes over time, if the hot and cold leg densities change at similar rates, the density ratio will remain roughly constant.

The last two non-dimensional parameters are geometry considerations. Equation 13 gives the non-dimensional height and Equation 14 gives the non-dimensional permeability of the pebble bed.

$$\Pi_h = \frac{H}{h}$$

Equation 12

$$\Pi_K = \frac{K}{hH}$$

Equation 13

Following the Buckingham Pi theorem, solving for the mass flux can then be re-formulated as a function of the non-dimensional parameters, given as:

$$\Pi_G = F(\Pi_B, \Pi_{DR}, \Pi_h, \Pi_K)$$

Equation 14

Thus, for given Π_B, Π_{DR}, Π_h, and Π_K, a certain value of Π_G exists. Diffusion dominated transport would then correspond to low values of Π_B and Π_{DR} which gives a low value of Π_G. Mixed transport would correspond to more moderate values of the non-dimensional parameters, since the transport rate corresponds to a combination of both diffusion and buoyant driven flow.

Relating this concept to the onset of natural circulation, the non-dimensional mass flux, Π_G, spikes when the mass flux spikes. Therefore, certain "critical" non-dimensional buoyancy and density ratio values must exist for a given non-dimensional geometry. The "critical" values correspond to the transition from mixed transport to natural convection dominated transport.

7.3 Case Comparison

The 85% helium case non-dimensional parameters are compared to the Update A case non-dimensional parameters. The non-dimensional mass flux is given by Figure 23, the non-dimensional buoyancy by Figure 24, and the density ratio by Figure 25. The first point of interest amongst the different figures is that both cases show parameter value spikes near similar value. Also, both cases show Π_G spiking when Π_B and Π_{DR} also jump up several orders of magnitude. Therefore, both cases seem to be exhibiting similar behavior in the transition from mixed transport to natural convection dominated transport which corresponds to the onset of natural circulation.

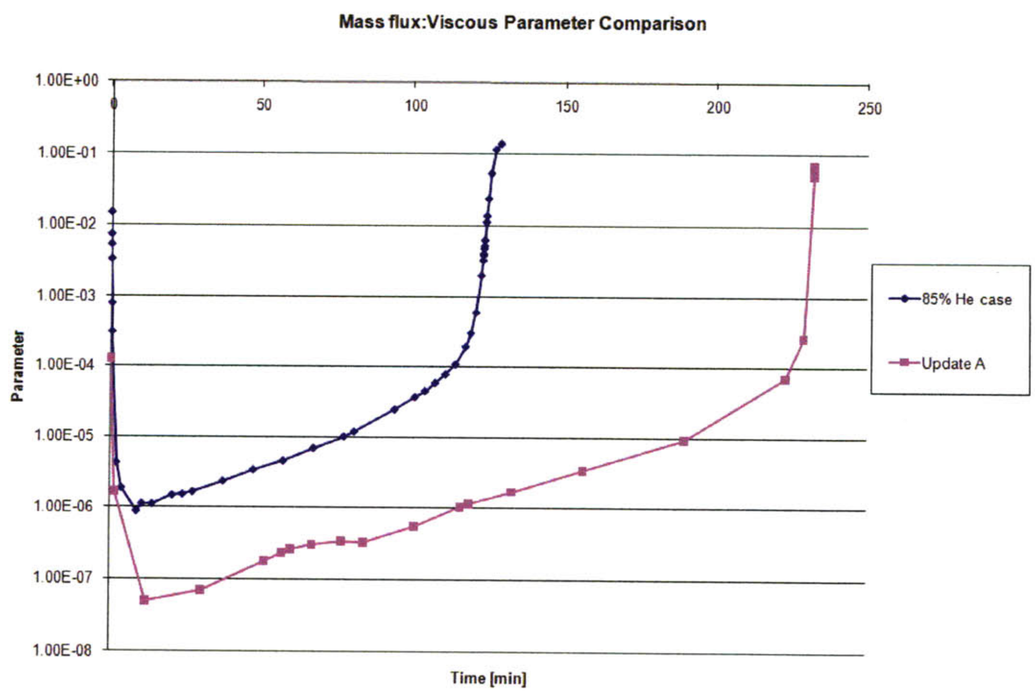

Figure 23: Non-Dimensional Mass Flux

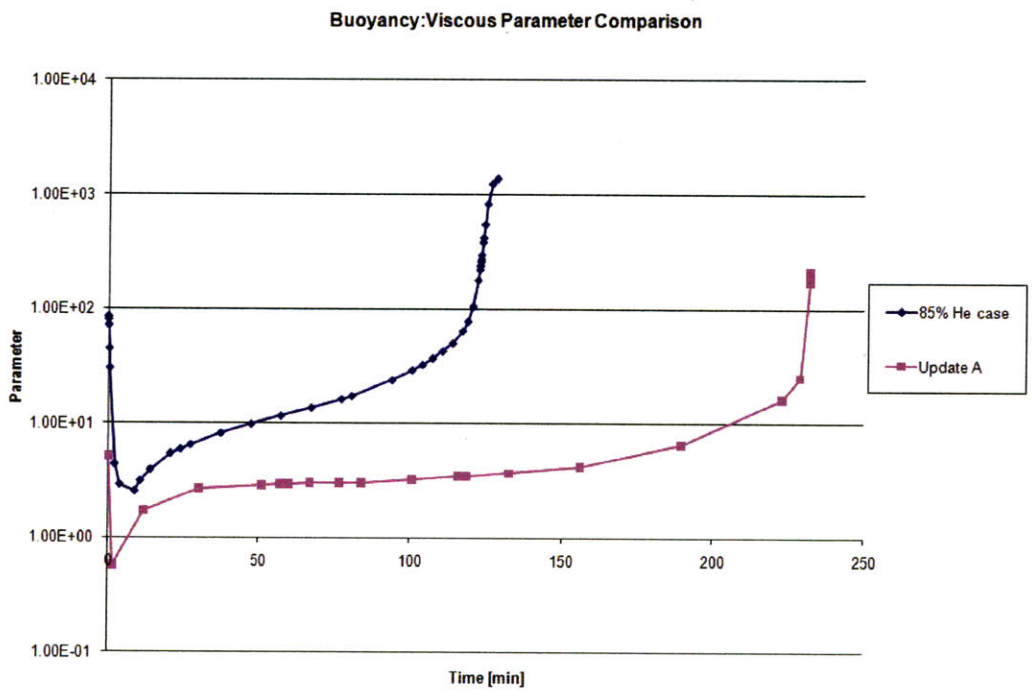

Figure 24: Non-Dimensional Buoyancy Force

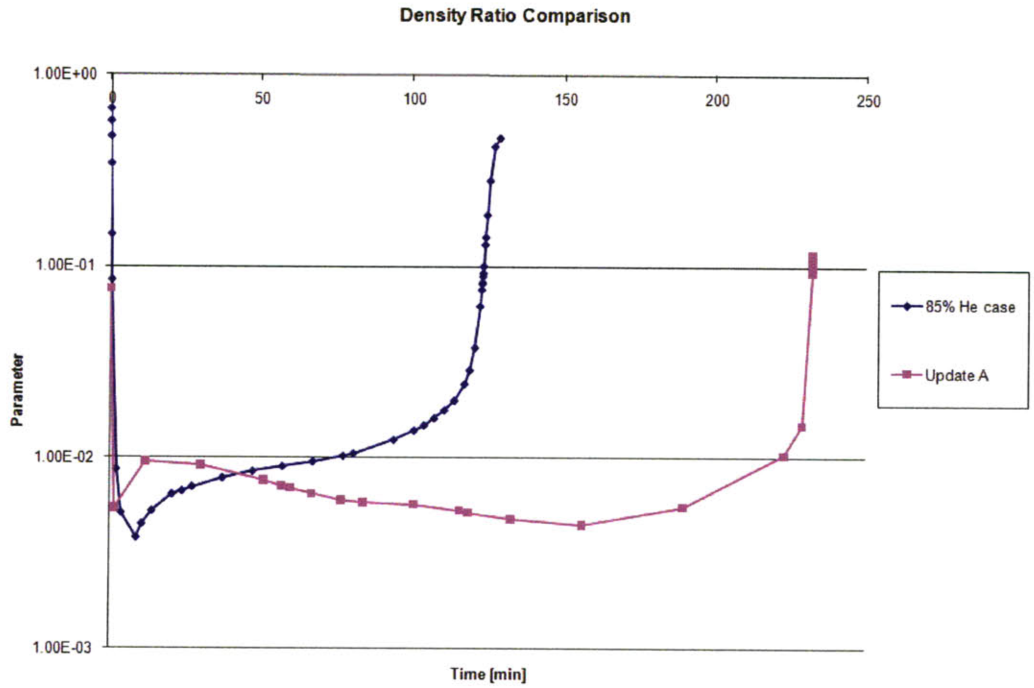

Figure 25: Density Ratio

Figure 23 shows that the mass flux in the 85% helium case is larger early on than in Update A. This is consistent with the previous discussion since Update A does not enter mixed transport until near the end of the transient. The plots of Π_B and Π_{DR} versus time give insight into just why that is happening. At the start of both simulations, the buoyancy force is reduced as air first enters the hot leg, since that increases the average density in the hot leg. After reaching the minimum Π_B value, both cases show a relatively fast increase, but Update A shows a suppression of the buoyancy force where it remains roughly constant for several hours. The density ratio for Update A during that same time interval also decreases, while the 85% helium case does not experience any such behavior.

Comparing the non-dimensional parameter behaviors to Figure 22, at about 180 minutes Update A diverges away from the analytical diffusion solution. Before this time, diffusion transport dominates and this corresponds to the suppression of Π_B and Π_{DR}. After 180 minutes, Π_B and Π_{DR} both begin to increase. Thus, the values of Π_B and Π_{DR}

around this time seem to correspond to the transition from diffusion dominated to mixed transport. The 85% helium case surpasses these transition values sooner in the transient and so bypass the slow lengthy pure diffusion transport phase. Starting with 85% helium in the u-tube therefore provides conditions that allow the system to enter into mixed transport relatively easily. With 100% helium initially however, once the air begins to enter inside, the concentrations suppress the strength of the buoyancy force and density ratio.

8. Injection Modeling

8.1 Injection Case CFD Model

The original FLUENT mesh needed to be modified to accommodate the addition of a helium injection location into the middle of the horizontal cross-over leg. The injection valve was 0.125 inch. diameter, and was approximated as a square injection shape to simplify the geometry generation. Since a square shaped was used, the dimensions were modified to maintain the same flow area. The injection valve was modeled as a mass flow injection face in FLUENT located along the side of the cross-over leg wall. The rest of the geometry remained unchanged.

Near the injection face, very fine volume elements were used. Mesh volumes throughout the rest of the u-tube were then reduced to prevent overly skewed volume meshes at element size transition locations. As a comparison, the mesh used in the 85% helium case, a total of 40943 cells were used, with a minimum cell volume of 1.35e-8 m^3 and a maximum cell volume of 1.98e-4 m^3. The injection case mesh however, used 278443 cells, with a minimum cell volume of 1.76e-11 m^3, and a maximum cell volume of 1.89e-4 m^3. The injection case minimum cell volume corresponds to cells adjacent to the injection face. Both cases have similar maximum cell volume values since the bottom of the barrel was meshed similar in both cases.

A FLUENT case was run using the minimum tested helium injection rate of 1 cc/min or 2.78e-9 kg/s, through the injection face. The same initial conditions were used as the

85% helium case without injection. Solver schemes and under-relaxation factors (URFs) were chosen to aid in convergence so the solver settings were slightly different than the 85% helium case without injection. The solver settings are summarized in Appendix A2.

The simulation was run out to four hours since the experimental data showed that natural circulation did not start during the entire four hour transient with 1 cc/min helium injection. To see what would happen, at about two hours, the injection flow was turned off by setting the injection face to a wall condition rather than a mass flow injection face. In two experimental cases, after injection was turned off, natural circulation began about two hours later. The goal was to see if FLUENT would predict similar behavior.

8.2 CFD Results

Two injection simulations were performed: (1) injection for the entire transient will be referred to as the injection case; (2) stop injection case in which injection flow was shut off after two hours into the transient.

Before discussing the results of the injection cases, it is important to point out that the mass flow rate in the hot leg as reported by FLUENT was negative in sign. At first, when this behavior was witnessed, it was felt that perhaps the injection was forcing flow down the hot leg, due to the pressure gradient. However, upon inspection it was found that the normal vector on the mesh surfaces in the hot leg were defined in the opposite direction from the previous mesh. Thus, when gas traversed the mesh surfaces in the upward direction the dot product between the gas velocity vector and mesh surface normal vector produced a negative sign. Examining velocity vectors in both cases showed indeed that the gas flow was in the upward direction in the hot leg. The "negative" mass flow rate as reported by FLUENT is actually in the positive upward direction. Therefore, both injection case results are consistent with the previous non-injection case results.

The overall conclusion from the two injection simulations is that the SCAD method is indeed preventing the onset of natural circulation. Figure 26 compares average helium mole fraction in the cross-over leg for the 85% helium case with the injection case (at a rate of 1 cc/min) and the stop injection case. The obvious result is that with injection the helium cushion in the cross-over leg is maintained; once the injection flow is turned off the transport rate of nitrogen (air in the actual experiment) increases significantly leading to the onset of natural circulation.

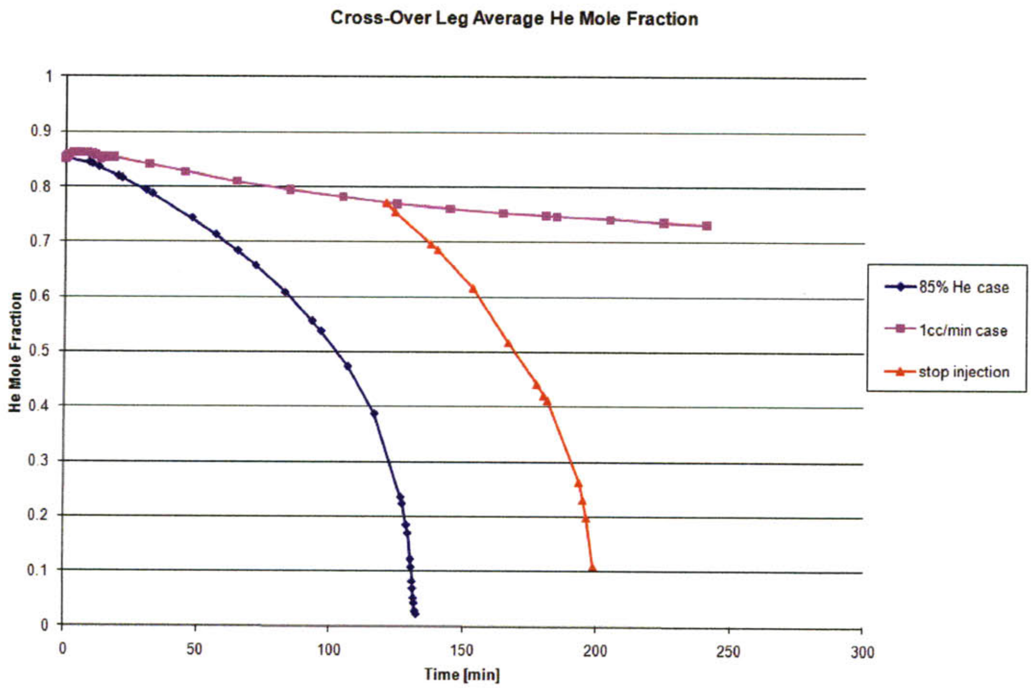

Figure 26: Injection Cases Comparison

As shown by Figure 26 the helium mole fraction in the cross-over leg, for the injection case, decreases at a very slow rate, even slower than the pure diffusion transport rate shown in Figure 22. The behavior also seems to be leveling off to a near constant value of about 73% at the end of the simulation. Figure 27 shows nitrogen mole fraction contours throughout the entire apparatus at various times during the injection case simulation. Red indicates 100% nitrogen, as is the case inside the barrel. The last three times are at about the 2, 3, and 4 hour marks, respectively and show that the nitrogen mole fraction contours are steadying out. The concept of steadying out is consistent with the derivation of SCAD to force a steady-state situation. Figure 27 also shows that SCAD simply prevents the onset of natural circulation; it does not prevent air from entering the apparatus, as described earlier. The nitrogen (air) fraction, reaches a steady value in the core, however the rate that air is replenished is dictated by a reduced transport rate, dictated by diffusion rather than by natural convection, as in the case of natural circulation. The graphite oxidation rate is dictated by the rate that air is replenished in the core, thus even though air will be inside the core, with a greatly diminished air replenishing rate, SCAD maintains the core integrity during air ingress.

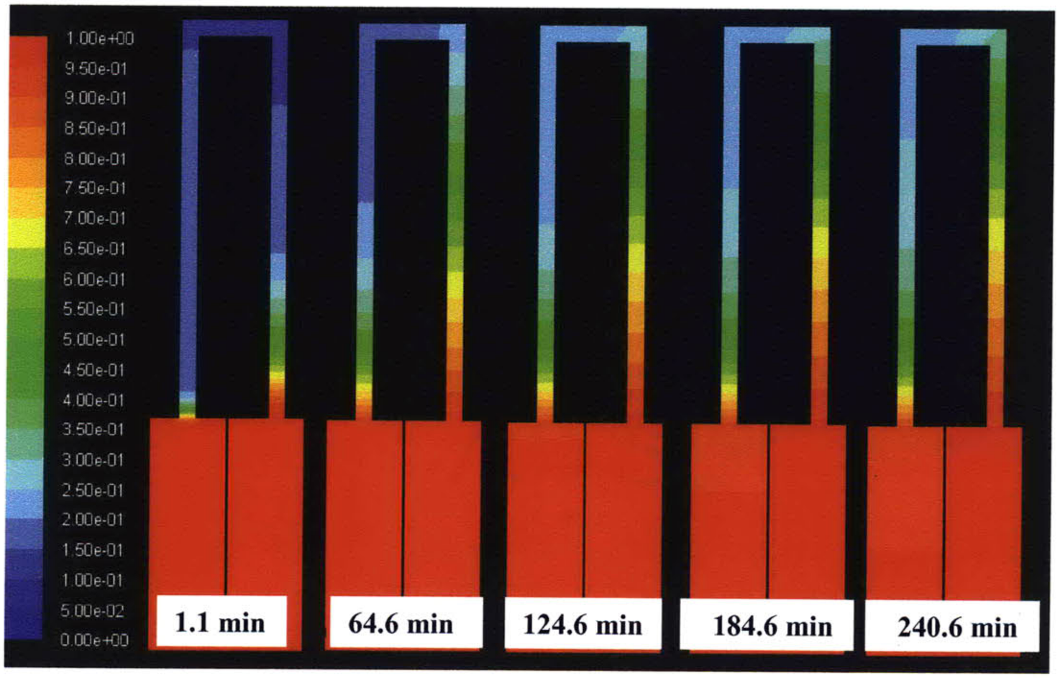

Figure 27: 1 cc/min Injection Case Nitrogen Mole Fraction Contours

The stop injection case was run for an additional 78 minutes after the injection was turned off at 120.66 minutes after the start of the simulation. At the end of the simulation the average helium mole fraction in the cross-over leg was about 11% and the average mass flow rate was of the same order of magnitude as the natural circulation rate in the 85% helium case, at ~10^{-5} kg/s. Figure 26 shows the rapid increase in the nitrogen transport rate after injection is turned off. As a comparison, about 25 minutes after the injection flow was shut off, the average helium mole fraction in the cross-over leg is about 52% in the stop injection case, while at the same time in the injection case, the cross-over leg is about 75% helium. Nitrogen contours throughout the apparatus at various times are given in Figure 28. As expected, with the increased nitrogen transport rate, the u-tube quickly fills with nitrogen leading up to the onset of natural circulation. Due to time constraints and the uncertainty of the odd reported negative mass flow rate, the simulation was ended at that time. But, it is felt that data up to this point shows the impact of SCAD on preventing the onset of natural circulation.

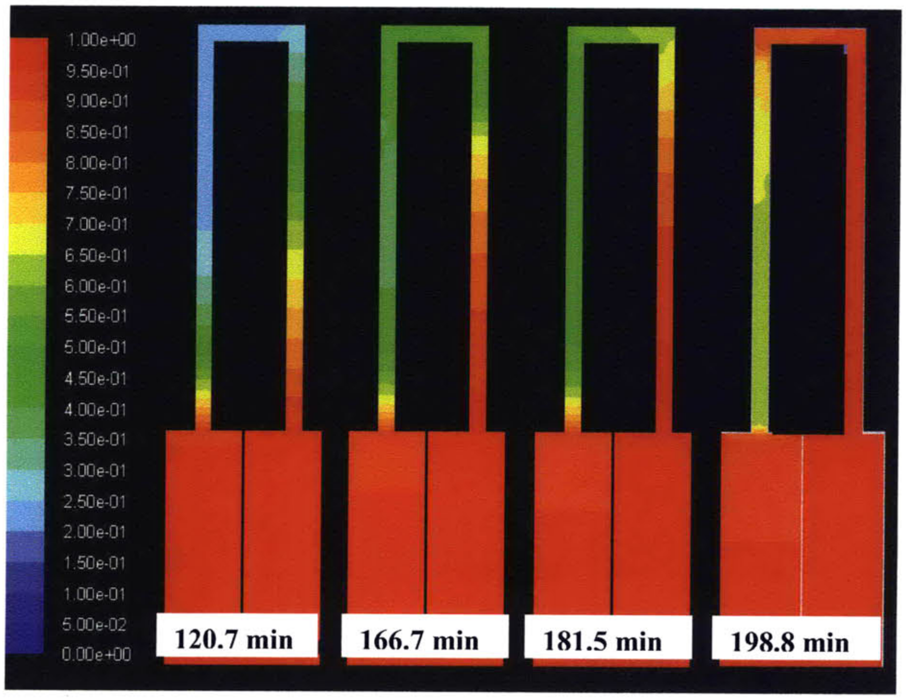

Figure 28: Stop Injection Mole Fraction Contours

In the actual experiment, two tests continued taking data after the injection flow was shut off. These two tests had injection flow for about 4 hours, unlike the 2 hours used in the FLUENT simulation before turning off injection and the FLUENT case was at the lowest experimentally tested injection rate. The tests that continued running after injection flow was shut off used injection rates of 2 cc/min and 7 cc/min. These tests showed natural circulation starting about 2 hours after turning off injection, while FLUENT shows natural circulation about to start at only around 80 minutes after shutting off injection. A possible reason for this difference is discussed in the following section.

8.3 Non-Dimensional Parameters Discussion

Looking at the problem with the same non-dimensional parameters derived earlier allows the relative strength of the driving forces in the injection cases to be compared to the non-injection cases. This approach provides some insight into the behaviors of the different cases.

Figure 29 compares Π_B between the injection cases and non-injection cases, respectively. The first observation for the non-dimensional buoyancy force is that early on in the transient (the first half hour or so) the 85% helium case and the injection case behave nearly the same. Early on, the buoyancy force should be primarily impacted by the nitrogen that enters in from the bottom of the hot leg, since the injected helium must first diffuse from the middle of the cross-over leg. Then as Π_B in the non-injection case continues to increase, the injection case Π_B starts to level off, due to the counter-diffusion of helium down the hot leg. The injection case Π_B then remains roughly constant for the remainder of the transient. Figure 29 also shows update A, the case from earlier that very closely followed the pure diffusion rate in the hot leg, starting with 100% helium in the u-tube. The buoyancy force, in update A, only exceeds the injection case buoyancy force in the last half hour of the transient. This is another example of how in the case with 100% helium initially, the transport rate is from pure diffusion and is very slow.

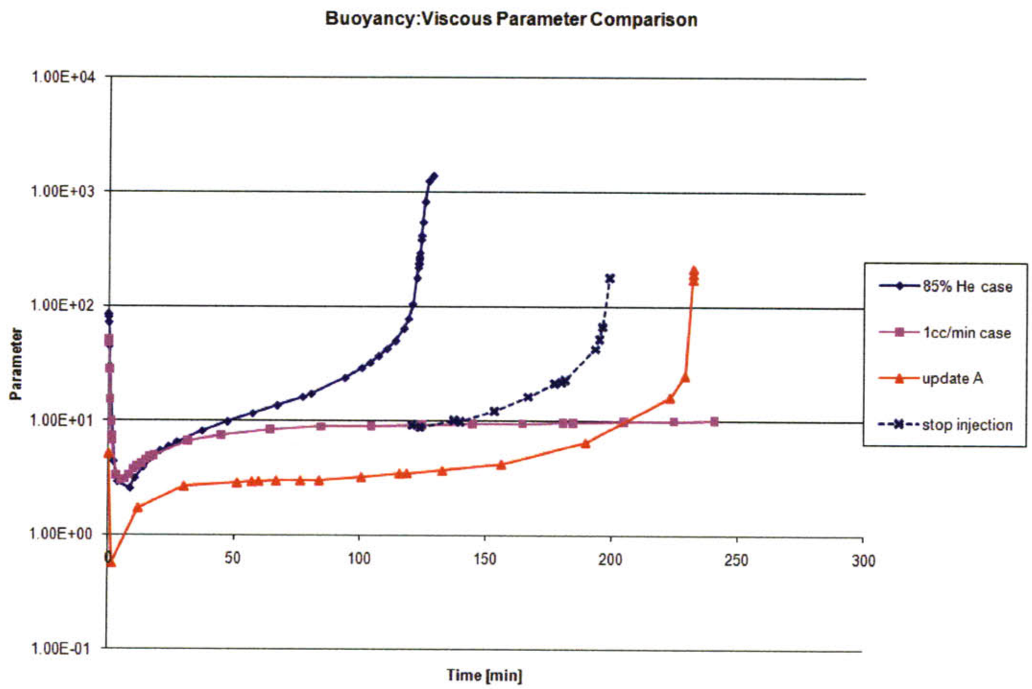

Figure 29: Non-Dimensional Buoyancy Force Comparison

The stop injection case non-dimensional buoyancy force, as shown in Figure 29 remains roughly constant over the first 20 minutes after injection was shut off. After this time however, the driving buoyancy force begins to increase, with a trend similar to the trend seen in update A. It is interesting to note that in update A, the buoyancy force begins to increase around the similar time after the buoyancy force had been roughly constant. The difference is that in the stop injection case, the magnitude of the buoyancy that value started to increase from was about twice that of the value update A.

The density ratio, Π_{DR}, for the different cases is shown in Figure 30. The injection case density ratio, does not drop as low as the 85% helium case, but as the non-dimensional buoyancy force remains roughly constant for most of the transient. The 85% helium case density ratio, follows the trend of its non-dimensional buoyancy force and continuously increases until spiking at the onset of natural circulation. Thus, injection allows the density ratio to be higher earlier on than a non-injection case, but prevents the density ratio from exceeding the critical value. The fact that Π_{DR} remains roughly constant for most of the transient, suggests that the cold and hot leg densities are changing at similar rates. Thus, SCAD tries to force a transport rate that causes the change in hot leg density to be counter-acted by a subsequent change in the cold leg density so that the critical density ratio is never reached. This concept is consistent with Equation 1 in that it solves for a helium injection rate such that the air enters the hot leg via diffusion and exits out the cold leg. The change in hot leg density is therefore "passed" along into the cold leg.

In the stop injection case, the density ratio remains roughly constant for almost half an hour after injection is shut off. After this point it begins to increase rapidly until spiking up near the onset of natural circulation.

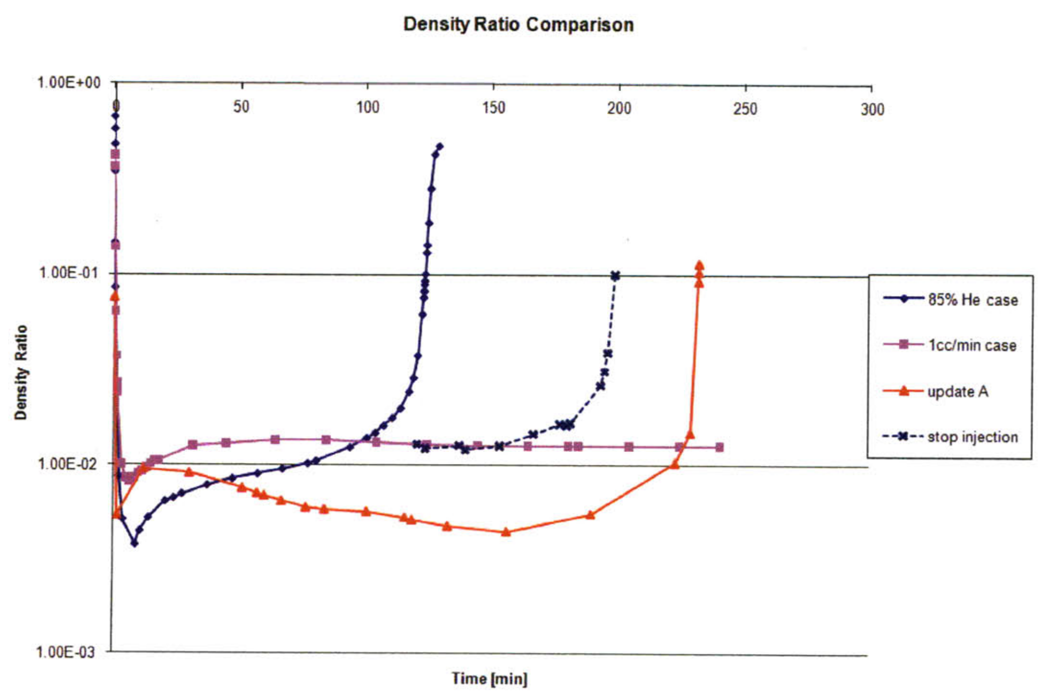

Figure 30: Density Ratio Comparison

The non-dimensional mass flux is shown in Figure 31. The striking feature is that update A exceeds the injection case at about 2 hours, while the Π_B and Π_{DR} values for update A did not exceed the injection case until near the end of the transient. The point of injection is to prevent a large mass flow spike, thereby maintaining transport via diffusion or near diffusion rates. Even though the injection case has higher Π_B and Π_{DR} values than update A, the counter-diffusion of helium and air in the hot leg created by SCAD keeps the mass flow rate at a low rate throughout the transient. The stop injection case confirms this idea because once injection is turned off, the non-dimensional mass flux increases significantly, even though as described earlier, the driving buoyancy and density ratio values remain roughly the same. The Π_B value for the injection case was steadying out to a value similar to the 85% injection case at about 50 minutes. The Π_G value that the stop injection case spikes up to shortly after the injection flow was turned off, is similar to the 85% helium case Π_G value at 50 minutes as well. Thus, the FLUENT results show that once the injection flow is turned off, the driving buoyancy force dictates the flow rate and the mass flux through the hot leg adjusts appropriately. Injecting at a lower rate would thus increase the steady-state buoyancy force, while injecting at a higher rate would decrease the steady-state driving buoyancy force.

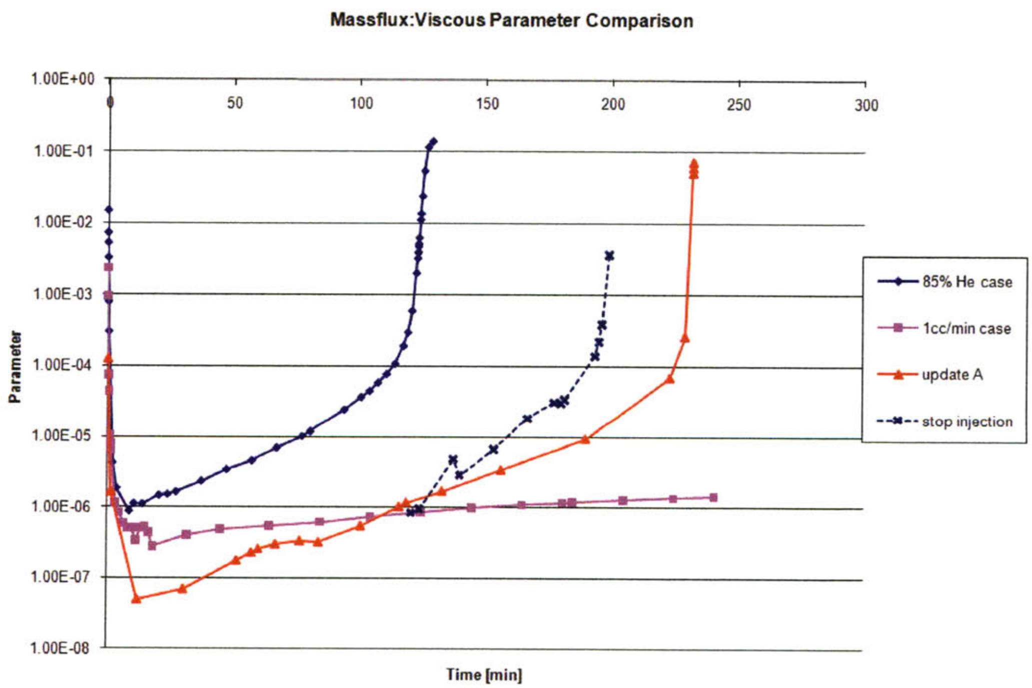

Figure 31: Non-Dimensional Mass Flux Comparison

As mentioned previously, two experimental tests turned off injection flow after 4 hours and at around 2 hours later natural circulation began. FLUENT therefore predicted natural circulation onset after turning off injection faster than seen in the experiment. The two tests, however, used higher injection rates, 2 cc/min and 7 cc/min, than the injection rate used in FLUENT (1 cc/min). Again, the FLUENT injection was chosen because that matched the lowest injection rate experimentally tested. Applying the reasoning from the non-dimensional discussion, using a higher injection rate would drive down the buoyancy force. Thus, when injection flow was turned off, the corresponding mass flow spike, for the 2 cc/min and 7 cc/min tests, would have been less than in the 1 cc/min case modeled by FLUENT.

Figure 11, in section 3.4.2.2 gives insight into this concept. The differential pressure data for the 2 cc/min injection test begins to drop sooner than the 7 cc/min test. But then the 2 cc/min test shows the differential pressure being "held up" until another rapid differential decrease occurs near the onset of natural circulation. The dropping in differential pressure is indicative of fluid starting to flow at a higher rate through the pebble column. The 2 cc/min test begins dropping sooner because it would allow a higher buoyancy force than the 7 cc/min test. The "hold up" behavior suggests then that the air that entered drove down the buoyancy force and more air then had to enter in order for the buoyancy force to increase again. However, the concept that injecting helium at a higher rate reduces the driving buoyancy force makes physical sense and agrees with the available experimental data.

9. MIR Evaluation Methodology

Extending the non-dimensional analysis presented earlier allows a formulation for determining the MIR for a configuration. Yan's injection rate equation, Equation 1, assumed that the bulk flow through the hot leg approached zero, thereby having the molar fluxes of helium and air cancel out. The flow rate through the hot leg (the core) was then controlled only by the concentration gradients in the hot leg. However, in reality some bulk flow would occur due to the buoyancy force and the following methodology allows for the MIR to be determined empirically by handling the flow rate non-dimensionally.

Thus, the following methodology establishes a MIR condition from empirical data or CFD results.

The first step is to perform non-injection simulations for a given geometry (Π_K and Π_h values) to determine the critical Π_G, Π_B, and Π_{DR} values, corresponding to the onset of natural circulation. The second step requires determining a correlation between the mass flux and the driving parameters. To account for the injection flow's impact on the bulk flow rate, an additional variable is introduced into the Buckingham Pi process, the injection mass flow rate, $\dot{m}_{IN}$ which produces an additional Pi group, Π_{IN}. The non-dimensional injection rate was computed to be:

$$\Pi_{IN} = \frac{\dot{m}_{IN}^2}{(\Delta\rho)^2 H^3 K g}$$

Equation 15

Equation 15 is thereby modified to be:

$$\Pi_G = F(\Pi_{IN}, \Pi_B, \Pi_{DR}, \Pi_K, \Pi_h)$$

Equation 16

The correlation given by Equation 17 is what must be determined empirically from data or CFD results. Different injection rates must be run for different geometries and driving temperature differences. The geometry parameters are the permeability, K, total height, H, and core height, h, and thus set the geometry non-dimensional parameters Π_K and Π_h. The driving temperature difference between the hot and cold legs set the driving buoyancy parameters Π_B and Π_{DR}. Running the various simulations will give a time history of the non-dimensional mass flux through the hot leg for each specific configuration. The quasi-steady-state values for the driving parameters for the various configurations can then be used to determine the correlation relating the non-dimensional mass flux to the non-dimensional injection rate, buoyancy force, density ratio, as well as the geometry constraints.

The critical values for Π_G, Π_B, and Π_{DR} for a given geometry (Π_K and Π_h values) are then substituted into Equation 17. By solving for the non-dimensional injection rate, the MIR for a given configuration is then determined. Denoting critical values with a *, the MIR correlation is then:

$$\Pi_{MIR} = G(\Pi_G^*, \Pi_B^*, \Pi_{DR}^*, \Pi_K, \Pi_h)$$

Equation 17

The minimum injection rate value can then be determined from the definition of the non-dimensional value in Equation 16.

The MIR value predicted by Equation 18 allows some bulk flow through the core as dictated by the buoyancy force. The buoyant driven flow is what caused the experiment to differ from the MIR predicted by Equation 1. Originally, the MIR was estimated to be about 7 cc/min; however the fixes in the FLUENT model changed the mole fractions at the boundaries before the onset of natural circulation. The MIR value from Equation 1 was recomputed using values from the 85% helium case. The flow conditions at about 94 minutes were chosen to be the limiting values since mass flow rate after this time begins to increase very quickly leading up to the onset of natural circulation. The recomputed injection rate is about 17 cc/min. Obviously, since the experiment did not observe natural circulation for an injection rate as low as 1 cc/min, Equation 1 can provide a very conservative estimate.

10. Full Scale PBR Considerations

10.1 MIR Order of Magnitude Estimate

To provide an order of magnitude estimate, Equation 1 is used to estimate the MIR value for the full scale PBMR. As described previously, this would give a conservative estimate, but it provides a ballpark number to give an idea of the amount of helium gas that must be stored on site.

The dimensions of the full scale PBMR were taken from Ref. [10]. Equation 1 was solved assuming the same boundary mole fraction values used in the model. The Matlab script used to iteratively solve for the MIR is provided in Appendix A5. The entire system was assumed to be at atmospheric pressure and the hot leg temperature was chosen to be at 1600°C and the cold leg temperature at 280°C, per the analysis in Ref. [7]. With these assumptions, the MIR as estimated by Equation 1 was found to be about 1.5e-6 kg/s, or 5.36 g/hr of helium. If injection flow is required for 3 months, the amount of helium required for storage is only 11.6 kg. This value is very small, and as shown by the previous discussion should be conservative. The truly minute amount of helium required for storage demonstrates the power of the SCAD method at preventing the onset of natural circulation for air ingress accidents with diffusion dominated air ingress accidents.

10.2 Injection System

Air ingress CFD work on the full scale PBMR has been done and reported in Ref. [11] by the PBMR Ltd. Company. The report discussed that air ingress would have little impact on core integrity and that the problem could be easily averted by inert gas injection into the core. The findings of that work are compared to the insights and lessons learned from this current work.

The CFD model in Ref. [11] was far more complicated than the simple geometry consisting of the u-tube in this experiment. The PBMR CFD model included the entire power conversion side of the system. Double-ended guillotine (DEG) breaks were also investigated, but because the hot and cold legs are not coaxial pipes in the latest PBMR design, the entire piping network must be modeled. Having this entire structure can greatly impact the development of natural convection flow since the effective cold leg is not just in the reactor vessel but also the piping network through the power conversion system. The current work modeled the entire system as a simple upside down u-tube, with equal flow areas and no resistances inside the cold leg. Therefore, the current experiment is an absolute worst case scenario if the reactor vessel was completely cut-off from the rest of the piping network of a DEG of a coaxial pipe.

The PBMR report also examined inert gas injection at decreasing the air ingress flow rates. Injection of helium and nitrogen were compared at preventing air ingress. Helium was found to be more effective, and the investigation found that injection rate of nitrogen scaled almost linearly with the air ingress rate. However, the PBMR report looked at injection rates to stop air ingress completely. This is completely different from the goal of the SCAD method. The required injection rates for nitrogen illustrates this difference since injection rates were on the order of 100 g/s depending on the break location. Although this mass flow rate appears very small, it is far larger than the injection rate value estimated by Equation 1. In order to stop air ingress over a 3 month period would therefore require storing around 800,000 kg of nitrogen on site. Storing such an enormous mass of nitrogen gas would not just be a financial burden for the plant but also a logistic problem to fit an additional amount of gas on site.

The non-dimensional analysis presented in section 7, gives insight as to why using nitrogen is less effective than helium at stopping air ingress. Injecting nitrogen is essentially injecting air into the reactor, which is similar to increasing the initial nitrogen fraction in the FLUENT model. The injection flow is thus aiding the air ingress rate at increasing the buoyancy force overtime by artificially increasing the system density faster than it would normally. The only way to then stop air ingress is to pump in enough nitrogen to create forced convection flow out of the system, thereby sustaining a longer depressurization phase. That is why the injection rates investigated by the PBMR report are so much larger than the injection rate values required to maintain SCAD. For this kind of prevention method, helium requires a lower injection rate than nitrogen because it does not artificially increase the density as much as the nitrogen does.

11. Conclusions

This thesis investigated the driving parameters that affect the onset of natural circulation in a pebble bed reactor as well as the prevention of natural circulation through the SCAD method. Commercial CFD software, FLUENT, was used to model an air ingress experiment, which provided insight into the dynamics of the development of the conditions that lead to natural circulation onset. By formulating the problem non-dimensionally, the understanding of just how the SCAD method works at preventing the onset of natural circulation was improved. It was shown that for the transport rates near the order of magnitude of diffusive rates the SCAD method is able to suppress the buoyancy force so that natural circulation is prevented.

The SCAD method offers significant advantages over simply replacing coolant gas inventory to prevent air from entering the reactor core for vertically oriented pipe breaks. As demonstrated by the simple analysis, only a small investment in helium inventory is required to prevent natural circulation onset over a 3 month period. Again it is important to note that the experiment and confirmatory CFD results validate this estimate for air ingress rates comparable to diffusion. Due to the experiment configuration, stratified flow and effects from subsequent lower plenum gas heating due to a large horizontal pipe break could be not addressed. Further analysis is required to evaluate the impact horizontal break phenomena have on the natural circulation onset time in a PBR.

A methodology was developed in order to allow an empirical correlation of the MIR that could validate the injection rate estimated by using Yan's MIR equation. In summary, based on the air ingress experiments which simulated hot and cold leg configurations with and without helium injection, and benchmarked computational fluid dynamics analyses, minimal helium injection appears to be a means to avoid or delay natural circulation after a postulated pipe break in a pebble bed high temperature reactor thus mitigating the consequences of air ingress accidents.

12. Recommendations for Future Work

The methodology presented in this work is performed assuming that outside of the reactor is ambient air at room and atmospheric pressure. In reality, after blowdown the containment gas will be a mixture of helium and air at a temperature and pressure dictated by the containment volume and core coolant inventory. Therefore, the containment pressure, temperature and gas mixture concentration must be varied to determine the impact each has on natural circulation onset time. In addition, graphite oxidation reactions must be accounted for to fully model the accident. This information will be very useful in order to properly size the containment building for a future HTGR.

The MIR correlation must also be determined in order to properly validate the injection rate of a full scale PBR. A fair number of computational simulations or experimental tests are required in order to have enough data to properly correlate the relationship among the driving parameters. Using computational data, due to the time required for a single simulation (several weeks to months, depending on the size of the computational domain) a scaled model will need to be used. The scaling should follow the scaling outlined in this work. To expand upon the current scaling methodology, a correlation for the onset time can be determined if transfer processes are also taken into account in the scaling process. Doing so would allow correlations for both the natural circulation onset time and MIR values to be determined.

When analyzing a full scale PBR, it must be determined if stratified flow in horizontal pipe breaks will drastically alter the natural circulation onset time. Analysis following recent work conducted at INL should be conducted at prototypical PBR geometry sizes to quantify this effect [12]. Results of this analysis show that air ingress is dependent on break size, location and orientation, and the full range of conditions must be evaluated to determine a proper air ingress mitigation process. The work in Ref. [12] showed that the NACOK facility geometry facilitated diffusion controlled natural circulation onset times. Therefore, similar analysis must be performed for a full scale PBR to evaluate if horizontal break phenomena can drastically reduce the natural circulation onset time.

Should such analysis show that a full scale PBR is influenced by horizontal break phenomena the air ingress method must be determined to handle the must faster accident progression not seen by diffusion dominated accidents. However, if the analysis shows that PBR geometry is not affected, then the current methodology and framework would apply for evaluating natural circulation onset and its prevention.

13. References

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14. Appendices

A1. Experimental Apparatus Design Procedure

The German NACOK (**Na**turzug im **Co**re mit **K**orrosion) air ingress test facility was used as the basis for the experimental apparatus. A detailed description of NACOK is given by Ref. [2], but the facility can reach temperatures up to 1200°C and is 7.3 m tall. The main goals for the facility included determining the natural circulation air mass flow rate and its dependence on temperature and geometry, and determining the natural circulation onset time. Figure 32 gives an illustration of the NACOK facility.

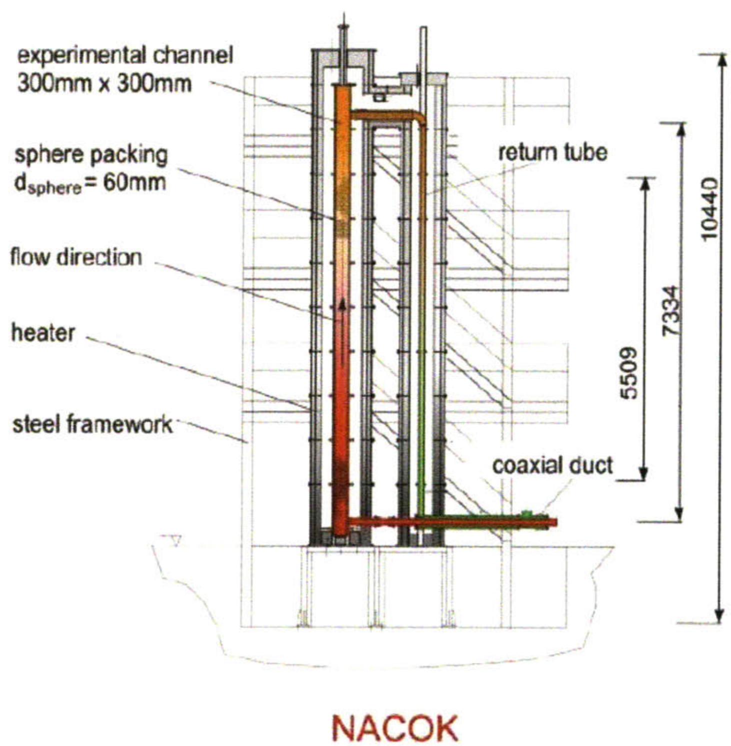

Figure 32: NACOK Test Facility

Since the goal is to evaluate the natural circulation onset time, the phenomena of interest are the transport rate of air during the diffusion phase of the air ingress accident. Therefore, the buoyancy force to viscous drag force must be maintained during the diffusion phase. In fluid flow through porous media, the Bond number, Bo, describes the ratio between buoyancy and surface tension, and the Capillary number, Ca, defines the ratio between viscous forces and surface tension. Taking the ratio between these numbers gives the ratio between the buoyancy force and viscous drag force. This new non-dimensional number is given as:

$$\frac{Bo}{Ca} = \frac{\Delta\rho g K}{\mu u}$$

Equation 18

where:

$\Delta\rho \equiv$ density difference between hot leg and cold leg,

$g \equiv$ gravitational acceleration,

$K \equiv$ permeability of the porous media,

$\mu \equiv$ dynamic viscosity,

$u \equiv$ fluid velocity through the porous media.

The Bo/Ca value for NACOK was evaluated using the test data to determine the average gas velocity through the pebble column. The permeability was computed using the equations in section 6.2.1 and the density difference computed using the temperatures of the hot and cold leg.

To maintain the NACOK Bo/Ca value, FLUENT was used to compute the gas velocity through the pebble column for different u-tube operating temperatures and geometry configurations. The design process was therefore iterative in nature, relying on the FLUENT predicted average gas velocity through the pebble column during the diffusion phase of an air ingress accident. After multiple iterations, the resulting design was the original FLUENT case described throughout this thesis. The Bo/Ca value for the resulting original FLUENT case is given in Table 1.

Table 1: Final Design Characteristics

Bo/Ca NACOK	Bo/Ca Experiment	Total Height	Pebble Section Height	Diffusion Length	Pipe Diameter	Total Volume
8.00	10.77	1.54 m	1 m	2.2 m	6.35 cm	0.00920 m^3 (9209.5 cc)

It is important to note that the scaling methodology considered for the experimental apparatus design is very different from the driving parameters discussed in this thesis. The design process was done very early on in the development of this work while the non-dimensional methodology described in this thesis was the culmination of the experience gained from the experiment and CFD analysis. Thus, the test apparatus design process illustrates the state of knowledge at the beginning of this thesis. Even though this design process was very simplified, it resulted in a very challenging and interested problem that lead to an improved understanding of the various phenomena involved in an air ingress accident.

A2. FLUENT Case Summaries

Summaries for each FLUENT case described in this thesis are given. Each summary includes descriptions of the models used, the boundary condition settings, the solver controls including discretization schemes and URFs, and the material properties.

Original FLUENT Case

```
FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based,  species,
laminar, unsteady)
Release: 6.3.26
Title:

Models
------

   Model                          Settings
   ---------------------------------------------------------
   Space                          3D
   Time                           Unsteady, 1st-Order Implicit
   Viscous                        Laminar
   Heat Transfer                  Enabled
   Solidification and Melting     Disabled
   Radiation                      None
```

```
   Species Transport             Non-Reacting (2 species)
   Coupled Dispersed Phase       Disabled
   Pollutants                    Disabled
   Pollutants                    Disabled
   Soot                          Disabled

Boundary Conditions
-------------------

   Zones

      name                    id   type
      ------------------------------------
      barrel                  2    fluid
      cold_leg                3    fluid
      cold_valve              4    fluid
      cross-over_leg          5    fluid
      hot_top                 6    fluid
      hot_valve               7    fluid
      pebbles                 8    fluid
      wall                    9    wall
      outlet                  10   interior
      cold_exit               11   interior
      cold_enter              12   interior
      hot_exit                13   interior
      pebble_exit             14   interior
      pebble_enter            15   interior
      inlet                   16   interior
      barrel_walls            17   wall
      new_cold_valve          18   wall
      cold_walls              19   wall
      cross_over_walls        20   wall
      hot_top_walls           21   wall
      hot_valve_walls         22   wall
      pebble_walls            23   wall
      default-interior        25   interior
      default-interior:001    1    interior
      default-interior:024    24   interior
      default-interior:026    26   interior
      default-interior:027    27   interior
      default-interior:028    28   interior
      default-interior:029    29   interior

   Boundary Conditions

      barrel

         Condition
Value
         ----------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                      no
         Source Terms                                               ()
         Specify fixed values?                                      no
         Local Coordinate System for Fixed Velocities               no
```

```
          Fixed Values                                                   ()
          Motion Type                                                    0
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          Y-Velocity Of Zone (m/s)                                       0
          Z-Velocity Of Zone (m/s)                                       0
          Rotation speed (rad/s)                                         0
          X-Origin of Rotation-Axis (m)                                  0
          Y-Origin of Rotation-Axis (m)                                  0
          Z-Origin of Rotation-Axis (m)                                  0
          X-Component of Rotation-Axis                                   0
          Y-Component of Rotation-Axis                                   0
          Z-Component of Rotation-Axis                                   1
          Deactivated Thread                                             no
          Porous zone?                                                   no
          Conical porous zone?                                           no
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          Y-Component of Direction-1 Vector                              0
          Z-Component of Direction-1 Vector                              0
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          Y-Component of Direction-2 Vector                              1
          Z-Component of Direction-2 Vector                              0
          X-Component of Cone Axis Vector                                1
          Y-Component of Cone Axis Vector                                0
          Z-Component of Cone Axis Vector                                0
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          Y-Coordinate of Point on Cone Axis (m)                         0
          Z-Coordinate of Point on Cone Axis (m)                         0
          Half Angle of Cone Relative to its Axis (deg)                  0
          Relative Velocity Resistance Formulation?                      yes
          Direction-1 Viscous Resistance (1/m2)                          0
          Direction-2 Viscous Resistance (1/m2)                          0
          Direction-3 Viscous Resistance (1/m2)                          0
          Choose alternative formulation for inertial resistance?        no
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          Direction-2 Inertial Resistance (1/m)                          0
          Direction-3 Inertial Resistance (1/m)                          0
          C0 Coefficient for Power-Law                                   0
          C1 Coefficient for Power-Law                                   0
          Porosity                                                       1
          Solid Material Name
aluminum

      cold_leg

          Condition
Value
          --------------------------------------------------------------
------------
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mixture-template
          Specify source terms?                                          no
          Source Terms                                                   ()
          Specify fixed values?                                          no
          Local Coordinate System for Fixed Velocities                   no
          Fixed Values                                                   ()
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```

```
          Y-Velocity Of Zone (m/s)                                      0
          Z-Velocity Of Zone (m/s)                                      0
          Rotation speed (rad/s)                                        0
          X-Origin of Rotation-Axis (m)                                 0
          Y-Origin of Rotation-Axis (m)                                 0
          Z-Origin of Rotation-Axis (m)                                 0
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          Y-Component of Rotation-Axis                                  0
          Z-Component of Rotation-Axis                                  1
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          Conical porous zone?                                          no
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          Direction-2 Viscous Resistance (1/m2)                         0
          Direction-3 Viscous Resistance (1/m2)                         0
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          Direction-2 Inertial Resistance (1/m)                         0
          Direction-3 Inertial Resistance (1/m)                         0
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          C1 Coefficient for Power-Law                                  0
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          Solid Material Name
aluminum

      cold_valve

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Value
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------------
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mixture-template
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          Specify fixed values?                                         no
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          Fixed Values                                                  ()
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          Z-Velocity Of Zone (m/s)                                      0
          Rotation speed (rad/s)                                        0
```

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         Y-Component of Rotation-Axis                                 0
         Z-Component of Rotation-Axis                                 1
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         Conical porous zone?                                         no
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         Z-Component of Direction-1 Vector                            0
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         Y-Component of Direction-2 Vector                            1
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         Z-Component of Cone Axis Vector                              0
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         Z-Coordinate of Point on Cone Axis (m)                       0
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         Direction-2 Viscous Resistance (1/m2)                        0
         Direction-3 Viscous Resistance (1/m2)                        0
         Choose alternative formulation for inertial resistance?      no
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         Direction-2 Inertial Resistance (1/m)                        0
         Direction-3 Inertial Resistance (1/m)                        0
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         C1 Coefficient for Power-Law                                 0
         Porosity                                                     1
         Solid Material Name
aluminum

      cross-over_leg

         Condition
Value
         -------------------------------------------------------------
------------
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mixture-template
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         Source Terms                                                 ()
         Specify fixed values?                                        no
         Local Coordinate System for Fixed Velocities                 no
         Fixed Values                                                 ()
         Motion Type                                                  0
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         Y-Velocity Of Zone (m/s)                                     0
         Z-Velocity Of Zone (m/s)                                     0
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         Z-Origin of Rotation-Axis (m)                                0
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        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
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        Conical porous zone?                                        no
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        Z-Component of Direction-1 Vector                           0
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        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
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        Direction-2 Viscous Resistance (1/m2)                       0
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        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      hot_top

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
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        Z-Velocity Of Zone (m/s)                                    0
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        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
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        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
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          Conical porous zone?                                        no
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          Y-Component of Direction-1 Vector                           0
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          Y-Component of Direction-2 Vector                           1
          Z-Component of Direction-2 Vector                           0
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          Y-Component of Cone Axis Vector                             0
          Z-Component of Cone Axis Vector                             0
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          Direction-2 Viscous Resistance (1/m2)                       0
          Direction-3 Viscous Resistance (1/m2)                       0
          Choose alternative formulation for inertial resistance?     no
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          Direction-2 Inertial Resistance (1/m)                       0
          Direction-3 Inertial Resistance (1/m)                       0
          C0 Coefficient for Power-Law                                0
          C1 Coefficient for Power-Law                                0
          Porosity                                                    1
          Solid Material Name
aluminum

       hot_valve

          Condition
Value
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          Source Terms                                                ()
          Specify fixed values?                                       no
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```

```
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        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
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        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  yes
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        Direction-2 Viscous Resistance (1/m2)                      0
        Direction-3 Viscous Resistance (1/m2)                      0
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        Direction-1 Inertial Resistance (1/m)                      0
        Direction-2 Inertial Resistance (1/m)                      0
        Direction-3 Inertial Resistance (1/m)                      0
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity                                                   1
        Solid Material Name
aluminum

      pebbles

        Condition
Value
        -------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
---------------------------------------------------------------
        Material Name
mixture-template
        Specify source terms?                                      no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
        Specify fixed values?                                      no
        Local Coordinate System for Fixed Velocities               no
        Fixed Values                                               ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
        Motion Type                                                0
        X-Velocity Of Zone (m/s)                                   0
        Y-Velocity Of Zone (m/s)                                   0
        Z-Velocity Of Zone (m/s)                                   0
        Rotation speed (rad/s)                                     0
        X-Origin of Rotation-Axis (m)                              0
        Y-Origin of Rotation-Axis (m)                              0
        Z-Origin of Rotation-Axis (m)                              0
        X-Component of Rotation-Axis                               0
```

```
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                yes
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                341
        C1 Coefficient for Power-Law
1.6107
        Porosity
0.39500001
        Solid Material Name
glass

      wall

        Condition                                             Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
```

```
      X-Component of Wall Translation (m/s)                0
      Y-Component of Wall Translation (m/s)                0
      Z-Component of Wall Translation (m/s)                0
      External Emissivity                                  1
      External Radiation Temperature (k)                   300
                                                           (0)

(((constant . 0) (profile  )))
      Rotation Speed (rad/s)                               0
      X-Position of Rotation-Axis Origin (m)               0
      Y-Position of Rotation-Axis Origin (m)               0
      Z-Position of Rotation-Axis Origin (m)               0
      X-Component of Rotation-Axis Direction               0
      Y-Component of Rotation-Axis Direction               0
      Z-Component of Rotation-Axis Direction               1
      X-component of shear stress (pascal)                 0
      Y-component of shear stress (pascal)                 0
      Z-component of shear stress (pascal)                 0
      Surface tension gradient (n/m-k)                     0
      Specularity Coefficient                              0

   outlet

      Condition   Value
      -----------------

   cold_exit

      Condition   Value
      -----------------

   cold_enter

      Condition   Value
      -----------------

   hot_exit

      Condition   Value
      -----------------

   pebble_exit

      Condition   Value
      -----------------

   pebble_enter

      Condition   Value
      -----------------

   inlet

      Condition   Value
      -----------------

   barrel_walls
```

```
         Condition                                              Value
         -------------------------------------------------------------
---------------------
         Wall Thickness (m)                                     0
         Heat Generation Rate (w/m3)                            0
         Material Name                                          aluminum
         Thermal BC Type                                        0
         Temperature (k)                                        293
         Heat Flux (w/m2)                                       0
         Convective Heat Transfer Coefficient (w/m2-k)          0
         Free Stream Temperature (k)                            300
         Enable shell conduction?                               no
         Wall Motion                                            0
         Shear Boundary Condition                               0
         Define wall motion relative to adjacent cell zone?     yes
         Apply a rotational velocity to this wall?              no
         Velocity Magnitude (m/s)                               0
         X-Component of Wall Translation                        1
         Y-Component of Wall Translation                        0
         Z-Component of Wall Translation                        0
         Define wall velocity components?                       no
         X-Component of Wall Translation (m/s)                  0
         Y-Component of Wall Translation (m/s)                  0
         Z-Component of Wall Translation (m/s)                  0
         External Emissivity                                    1
         External Radiation Temperature (k)                     300
                                                                (0)

(((constant . 0) (profile )))
         Rotation Speed (rad/s)                                 0
         X-Position of Rotation-Axis Origin (m)                 0
         Y-Position of Rotation-Axis Origin (m)                 0
         Z-Position of Rotation-Axis Origin (m)                 0
         X-Component of Rotation-Axis Direction                 0
         Y-Component of Rotation-Axis Direction                 0
         Z-Component of Rotation-Axis Direction                 1
         X-component of shear stress (pascal)                   0
         Y-component of shear stress (pascal)                   0
         Z-component of shear stress (pascal)                   0
         Surface tension gradient (n/m-k)                       0
         Specularity Coefficient                                0

      new_cold_valve

         Condition                                              Value
         -------------------------------------------------------------
---------------------
         Wall Thickness (m)                                     0
         Heat Generation Rate (w/m3)                            0
         Material Name                                          copper
         Thermal BC Type                                        1
         Temperature (k)                                        300
         Heat Flux (w/m2)                                       0
         Convective Heat Transfer Coefficient (w/m2-k)          0
         Free Stream Temperature (k)                            300
         Enable shell conduction?                               no
```

```
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     cold_walls

        Condition                                           Value
        ------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     0
        Temperature (k)                                     283
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
```

```
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

     cross_over_walls

        Condition                                             Value
        -----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
```

Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

hot_top_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	0
Temperature (k)	473
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

hot_valve_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1

```
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

     pebble_walls

        Condition                                             Value
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       0
        Temperature (k)                                       473
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
```

```
        Define wall velocity components?                  no
        X-Component of Wall Translation (m/s)             0
        Y-Component of Wall Translation (m/s)             0
        Z-Component of Wall Translation (m/s)             0
        External Emissivity                               1
        External Radiation Temperature (k)                300
                                                          (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                            0
        X-Position of Rotation-Axis Origin (m)            0
        Y-Position of Rotation-Axis Origin (m)            0
        Z-Position of Rotation-Axis Origin (m)            0
        X-Component of Rotation-Axis Direction            0
        Y-Component of Rotation-Axis Direction            0
        Z-Component of Rotation-Axis Direction            1
        X-component of shear stress (pascal)              0
        Y-component of shear stress (pascal)              0
        Z-component of shear stress (pascal)              0
        Surface tension gradient (n/m-k)                  0
        Specularity Coefficient                           0

    default-interior

        Condition   Value
        -----------------

    default-interior:001

        Condition   Value
        -----------------

    default-interior:024

        Condition   Value
        -----------------

    default-interior:026

        Condition   Value
        -----------------

    default-interior:027

        Condition   Value
        -----------------

    default-interior:028

        Condition   Value
        -----------------

    default-interior:029

        Condition   Value
        -----------------
```

Solver Controls

Equations

Equation	Solved
Flow	yes
he	yes
Energy	yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.2
Max. Iterations Per Time Step	100

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.80000001
Body Forces	0.69999999
Momentum	0.40000001
he	0.80000001
Energy	0.89999998

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme

Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.576
L-J Energy Parameter	k	constant	10.2
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0

L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	mass-weighted-mixing-law	#f
Viscosity	kg/m-s	mass-weighted-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0
Speed of Sound	m/s	none	#f

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.681
L-J Energy Parameter	k	constant	91.5
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

No Pebbles FLUENT Case

```
FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based,  species,
laminar, unsteady)
Release: 6.3.26
Title:

Models
------

   Model                          Settings
   ---------------------------------------------------------
   Space                          3D
   Time                           Unsteady, 1st-Order Implicit
   Viscous                        Laminar
   Heat Transfer                  Enabled
   Solidification and Melting     Disabled
   Radiation                      None
   Species Transport              Non-Reacting (2 species)
   Coupled Dispersed Phase        Disabled
   Pollutants                     Disabled
   Pollutants                     Disabled
   Soot                           Disabled

Boundary Conditions
-------------------

   Zones

      name                     id   type
      ------------------------------------
      barrel                   2    fluid
      cold_leg                 3    fluid
      cold_valve               4    fluid
      cross-over_leg           5    fluid
      hot_top                  6    fluid
      hot_valve                7    fluid
      pebbles                  8    fluid
      wall                     9    wall
      outlet                   10   interior
      cold_exit                11   interior
      cold_enter               12   interior
      hot_exit                 13   interior
      pebble_exit              14   interior
      pebble_enter             15   interior
      inlet                    16   interior
      barrel_walls             17   wall
      new_cold_valve           18   wall
      cold_walls               19   wall
      cross_over_walls         20   wall
      hot_top_walls            21   wall
      hot_valve_walls          22   wall
      pebble_walls             23   wall
      default-interior         25   interior
      default-interior:001     1    interior
      default-interior:024     24   interior
      default-interior:026     26   interior
```

```
      default-interior:027   27   interior
      default-interior:028   28   interior
      default-interior:029   29   interior

   Boundary Conditions

      barrel

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                             no
         Source Terms                                                      ()
         Specify fixed values?                                             no
         Local Coordinate System for Fixed Velocities                      no
         Fixed Values                                                      ()
         Motion Type                                                       0
         X-Velocity Of Zone (m/s)                                          0
         Y-Velocity Of Zone (m/s)                                          0
         Z-Velocity Of Zone (m/s)                                          0
         Rotation speed (rad/s)                                            0
         X-Origin of Rotation-Axis (m)                                     0
         Y-Origin of Rotation-Axis (m)                                     0
         Z-Origin of Rotation-Axis (m)                                     0
         X-Component of Rotation-Axis                                      0
         Y-Component of Rotation-Axis                                      0
         Z-Component of Rotation-Axis                                      1
         Deactivated Thread                                                no
         Porous zone?                                                      no
         Conical porous zone?                                              no
         X-Component of Direction-1 Vector                                 1
         Y-Component of Direction-1 Vector                                 0
         Z-Component of Direction-1 Vector                                 0
         X-Component of Direction-2 Vector                                 0
         Y-Component of Direction-2 Vector                                 1
         Z-Component of Direction-2 Vector                                 0
         X-Component of Cone Axis Vector                                   1
         Y-Component of Cone Axis Vector                                   0
         Z-Component of Cone Axis Vector                                   0
         X-Coordinate of Point on Cone Axis (m)                            1
         Y-Coordinate of Point on Cone Axis (m)                            0
         Z-Coordinate of Point on Cone Axis (m)                            0
         Half Angle of Cone Relative to its Axis (deg)                     0
         Relative Velocity Resistance Formulation?                         yes
         Direction-1 Viscous Resistance (1/m2)                             0
         Direction-2 Viscous Resistance (1/m2)                             0
         Direction-3 Viscous Resistance (1/m2)                             0
         Choose alternative formulation for inertial resistance?           no
         Direction-1 Inertial Resistance (1/m)                             0
         Direction-2 Inertial Resistance (1/m)                             0
         Direction-3 Inertial Resistance (1/m)                             0
         C0 Coefficient for Power-Law                                      0
         C1 Coefficient for Power-Law                                      0
         Porosity                                                          1
```

```
         Solid Material Name
aluminum

      cold_leg

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum
```

cold_valve

Condition	Value
Material Name	mixture-template
Specify source terms?	no
Source Terms	()
Specify fixed values?	no
Local Coordinate System for Fixed Velocities	no
Fixed Values	()
Motion Type	0
X-Velocity Of Zone (m/s)	0
Y-Velocity Of Zone (m/s)	0
Z-Velocity Of Zone (m/s)	0
Rotation speed (rad/s)	0
X-Origin of Rotation-Axis (m)	0
Y-Origin of Rotation-Axis (m)	0
Z-Origin of Rotation-Axis (m)	0
X-Component of Rotation-Axis	0
Y-Component of Rotation-Axis	0
Z-Component of Rotation-Axis	1
Deactivated Thread	no
Porous zone?	no
Conical porous zone?	no
X-Component of Direction-1 Vector	1
Y-Component of Direction-1 Vector	0
Z-Component of Direction-1 Vector	0
X-Component of Direction-2 Vector	0
Y-Component of Direction-2 Vector	1
Z-Component of Direction-2 Vector	0
X-Component of Cone Axis Vector	1
Y-Component of Cone Axis Vector	0
Z-Component of Cone Axis Vector	0
X-Coordinate of Point on Cone Axis (m)	1
Y-Coordinate of Point on Cone Axis (m)	0
Z-Coordinate of Point on Cone Axis (m)	0
Half Angle of Cone Relative to its Axis (deg)	0
Relative Velocity Resistance Formulation?	yes
Direction-1 Viscous Resistance (1/m2)	0
Direction-2 Viscous Resistance (1/m2)	0
Direction-3 Viscous Resistance (1/m2)	0
Choose alternative formulation for inertial resistance?	no
Direction-1 Inertial Resistance (1/m)	0
Direction-2 Inertial Resistance (1/m)	0
Direction-3 Inertial Resistance (1/m)	0
C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminum

cross-over_leg

```
         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                   no
         Source Terms                                            ()
         Specify fixed values?                                   no
         Local Coordinate System for Fixed Velocities            no
         Fixed Values                                            ()
         Motion Type                                             0
         X-Velocity Of Zone (m/s)                                0
         Y-Velocity Of Zone (m/s)                                0
         Z-Velocity Of Zone (m/s)                                0
         Rotation speed (rad/s)                                  0
         X-Origin of Rotation-Axis (m)                           0
         Y-Origin of Rotation-Axis (m)                           0
         Z-Origin of Rotation-Axis (m)                           0
         X-Component of Rotation-Axis                            0
         Y-Component of Rotation-Axis                            0
         Z-Component of Rotation-Axis                            1
         Deactivated Thread                                      no
         Porous zone?                                            no
         Conical porous zone?                                    no
         X-Component of Direction-1 Vector                       1
         Y-Component of Direction-1 Vector                       0
         Z-Component of Direction-1 Vector                       0
         X-Component of Direction-2 Vector                       0
         Y-Component of Direction-2 Vector                       1
         Z-Component of Direction-2 Vector                       0
         X-Component of Cone Axis Vector                         1
         Y-Component of Cone Axis Vector                         0
         Z-Component of Cone Axis Vector                         0
         X-Coordinate of Point on Cone Axis (m)                  1
         Y-Coordinate of Point on Cone Axis (m)                  0
         Z-Coordinate of Point on Cone Axis (m)                  0
         Half Angle of Cone Relative to its Axis (deg)           0
         Relative Velocity Resistance Formulation?               yes
         Direction-1 Viscous Resistance (1/m2)                   0
         Direction-2 Viscous Resistance (1/m2)                   0
         Direction-3 Viscous Resistance (1/m2)                   0
         Choose alternative formulation for inertial resistance? no
         Direction-1 Inertial Resistance (1/m)                   0
         Direction-2 Inertial Resistance (1/m)                   0
         Direction-3 Inertial Resistance (1/m)                   0
         C0 Coefficient for Power-Law                            0
         C1 Coefficient for Power-Law                            0
         Porosity                                                1
         Solid Material Name
aluminum

      hot_top

         Condition
Value
```

```
          ----------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                       no
          Source Terms                                                ()
          Specify fixed values?                                       no
          Local Coordinate System for Fixed Velocities                no
          Fixed Values                                                ()
          Motion Type                                                 0
          X-Velocity Of Zone (m/s)                                    0
          Y-Velocity Of Zone (m/s)                                    0
          Z-Velocity Of Zone (m/s)                                    0
          Rotation speed (rad/s)                                      0
          X-Origin of Rotation-Axis (m)                               0
          Y-Origin of Rotation-Axis (m)                               0
          Z-Origin of Rotation-Axis (m)                               0
          X-Component of Rotation-Axis                                0
          Y-Component of Rotation-Axis                                0
          Z-Component of Rotation-Axis                                1
          Deactivated Thread                                          no
          Porous zone?                                                no
          Conical porous zone?                                        no
          X-Component of Direction-1 Vector                           1
          Y-Component of Direction-1 Vector                           0
          Z-Component of Direction-1 Vector                           0
          X-Component of Direction-2 Vector                           0
          Y-Component of Direction-2 Vector                           1
          Z-Component of Direction-2 Vector                           0
          X-Component of Cone Axis Vector                             1
          Y-Component of Cone Axis Vector                             0
          Z-Component of Cone Axis Vector                             0
          X-Coordinate of Point on Cone Axis (m)                      1
          Y-Coordinate of Point on Cone Axis (m)                      0
          Z-Coordinate of Point on Cone Axis (m)                      0
          Half Angle of Cone Relative to its Axis (deg)               0
          Relative Velocity Resistance Formulation?                   yes
          Direction-1 Viscous Resistance (1/m2)                       0
          Direction-2 Viscous Resistance (1/m2)                       0
          Direction-3 Viscous Resistance (1/m2)                       0
          Choose alternative formulation for inertial resistance?     no
          Direction-1 Inertial Resistance (1/m)                       0
          Direction-2 Inertial Resistance (1/m)                       0
          Direction-3 Inertial Resistance (1/m)                       0
          C0 Coefficient for Power-Law                                0
          C1 Coefficient for Power-Law                                0
          Porosity                                                    1
          Solid Material Name
aluminum

      hot_valve

          Condition
Value
          ----------------------------------------------------------------
------------
```

```
          Material Name
mixture-template
          Specify source terms?                                          no
          Source Terms                                                   ()
          Specify fixed values?                                          no
          Local Coordinate System for Fixed Velocities                   no
          Fixed Values                                                   ()
          Motion Type                                                    0
          X-Velocity Of Zone (m/s)                                       0
          Y-Velocity Of Zone (m/s)                                       0
          Z-Velocity Of Zone (m/s)                                       0
          Rotation speed (rad/s)                                         0
          X-Origin of Rotation-Axis (m)                                  0
          Y-Origin of Rotation-Axis (m)                                  0
          Z-Origin of Rotation-Axis (m)                                  0
          X-Component of Rotation-Axis                                   0
          Y-Component of Rotation-Axis                                   0
          Z-Component of Rotation-Axis                                   1
          Deactivated Thread                                             no
          Porous zone?                                                   no
          Conical porous zone?                                           no
          X-Component of Direction-1 Vector                              1
          Y-Component of Direction-1 Vector                              0
          Z-Component of Direction-1 Vector                              0
          X-Component of Direction-2 Vector                              0
          Y-Component of Direction-2 Vector                              1
          Z-Component of Direction-2 Vector                              0
          X-Component of Cone Axis Vector                                1
          Y-Component of Cone Axis Vector                                0
          Z-Component of Cone Axis Vector                                0
          X-Coordinate of Point on Cone Axis (m)                         1
          Y-Coordinate of Point on Cone Axis (m)                         0
          Z-Coordinate of Point on Cone Axis (m)                         0
          Half Angle of Cone Relative to its Axis (deg)                  0
          Relative Velocity Resistance Formulation?                      yes
          Direction-1 Viscous Resistance (1/m2)                          0
          Direction-2 Viscous Resistance (1/m2)                          0
          Direction-3 Viscous Resistance (1/m2)                          0
          Choose alternative formulation for inertial resistance?        no
          Direction-1 Inertial Resistance (1/m)                          0
          Direction-2 Inertial Resistance (1/m)                          0
          Direction-3 Inertial Resistance (1/m)                          0
          C0 Coefficient for Power-Law                                   0
          C1 Coefficient for Power-Law                                   0
          Porosity                                                       1
          Solid Material Name
aluminum

      pebbles

          Condition
Value
          -------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-------------------------------------------------------------
```

```
         Material Name
mixture-template
         Specify source terms?                                    no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
         Specify fixed values?                                    no
         Local Coordinate System for Fixed Velocities             no
         Fixed Values                                             ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
         Motion Type                                              0
         X-Velocity Of Zone (m/s)                                 0
         Y-Velocity Of Zone (m/s)                                 0
         Z-Velocity Of Zone (m/s)                                 0
         Rotation speed (rad/s)                                   0
         X-Origin of Rotation-Axis (m)                            0
         Y-Origin of Rotation-Axis (m)                            0
         Z-Origin of Rotation-Axis (m)                            0
         X-Component of Rotation-Axis                             0
         Y-Component of Rotation-Axis                             0
         Z-Component of Rotation-Axis                             1
         Deactivated Thread                                       no
         Porous zone?                                             no
         Conical porous zone?                                     no
         X-Component of Direction-1 Vector                        1
         Y-Component of Direction-1 Vector                        0
         Z-Component of Direction-1 Vector                        0
         X-Component of Direction-2 Vector                        0
         Y-Component of Direction-2 Vector                        1
         Z-Component of Direction-2 Vector                        0
         X-Component of Cone Axis Vector                          1
         Y-Component of Cone Axis Vector                          0
         Z-Component of Cone Axis Vector                          0
         X-Coordinate of Point on Cone Axis (m)                   1
         Y-Coordinate of Point on Cone Axis (m)                   0
         Z-Coordinate of Point on Cone Axis (m)                   0
         Half Angle of Cone Relative to its Axis (deg)            0
         Relative Velocity Resistance Formulation?                no
         Direction-1 Viscous Resistance (1/m2)                    0
         Direction-2 Viscous Resistance (1/m2)
4830000
         Direction-3 Viscous Resistance (1/m2)                    0
         Choose alternative formulation for inertial resistance?  no
         Direction-1 Inertial Resistance (1/m)                    0
         Direction-2 Inertial Resistance (1/m)                    0
         Direction-3 Inertial Resistance (1/m)                    0
         C0 Coefficient for Power-Law                             0
         C1 Coefficient for Power-Law                             0
         Porosity
0.39500001
         Solid Material Name
glass

      wall
```

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)
(((constant . 0) (profile)))	
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

outlet

Condition	Value

cold_exit

Condition	Value

cold_enter

Condition	Value

```
hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                                      Value
   -------------------------------------------------------------------
---------------------
   Wall Thickness (m)                                             0
   Heat Generation Rate (w/m3)                                    0
   Material Name                                                  aluminum
   Thermal BC Type                                                0
   Temperature (k)                                                293
   Heat Flux (w/m2)                                               0
   Convective Heat Transfer Coefficient (w/m2-k)                  0
   Free Stream Temperature (k)                                    300
   Enable shell conduction?                                       no
   Wall Motion                                                    0
   Shear Boundary Condition                                       0
   Define wall motion relative to adjacent cell zone?             yes
   Apply a rotational velocity to this wall?                      no
   Velocity Magnitude (m/s)                                       0
   X-Component of Wall Translation                                1
   Y-Component of Wall Translation                                0
   Z-Component of Wall Translation                                0
   Define wall velocity components?                               no
   X-Component of Wall Translation (m/s)                          0
   Y-Component of Wall Translation (m/s)                          0
   Z-Component of Wall Translation (m/s)                          0
   External Emissivity                                            1
   External Radiation Temperature (k)                             300
                                                                  (0)

(((constant . 0) (profile  )))
   Rotation Speed (rad/s)                                         0
   X-Position of Rotation-Axis Origin (m)                         0
   Y-Position of Rotation-Axis Origin (m)                         0
   Z-Position of Rotation-Axis Origin (m)                         0
   X-Component of Rotation-Axis Direction                         0
   Y-Component of Rotation-Axis Direction                         0
```

Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

new_cold_valve

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

cold_walls

Condition	Value
Wall Thickness (m)	0

```
        Heat Generation Rate (w/m3)                              0
        Material Name                                            copper
        Thermal BC Type                                          0
        Temperature (k)                                          283
        Heat Flux (w/m2)                                         0
        Convective Heat Transfer Coefficient (w/m2-k)            0
        Free Stream Temperature (k)                              300
        Enable shell conduction?                                 no
        Wall Motion                                              0
        Shear Boundary Condition                                 0
        Define wall motion relative to adjacent cell zone?       yes
        Apply a rotational velocity to this wall?                no
        Velocity Magnitude (m/s)                                 0
        X-Component of Wall Translation                          1
        Y-Component of Wall Translation                          0
        Z-Component of Wall Translation                          0
        Define wall velocity components?                         no
        X-Component of Wall Translation (m/s)                    0
        Y-Component of Wall Translation (m/s)                    0
        Z-Component of Wall Translation (m/s)                    0
        External Emissivity                                      1
        External Radiation Temperature (k)                       300
                                                                 (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                   0
        X-Position of Rotation-Axis Origin (m)                   0
        Y-Position of Rotation-Axis Origin (m)                   0
        Z-Position of Rotation-Axis Origin (m)                   0
        X-Component of Rotation-Axis Direction                   0
        Y-Component of Rotation-Axis Direction                   0
        Z-Component of Rotation-Axis Direction                   1
        X-component of shear stress (pascal)                     0
        Y-component of shear stress (pascal)                     0
        Z-component of shear stress (pascal)                     0
        Surface tension gradient (n/m-k)                         0
        Specularity Coefficient                                  0

     cross_over_walls

        Condition                                                Value
        --------------------------------------------------------------
---------------------
        Wall Thickness (m)                                       0
        Heat Generation Rate (w/m3)                              0
        Material Name                                            copper
        Thermal BC Type                                          1
        Temperature (k)                                          300
        Heat Flux (w/m2)                                         0
        Convective Heat Transfer Coefficient (w/m2-k)            0
        Free Stream Temperature (k)                              300
        Enable shell conduction?                                 no
        Wall Motion                                              0
        Shear Boundary Condition                                 0
        Define wall motion relative to adjacent cell zone?       yes
        Apply a rotational velocity to this wall?                no
        Velocity Magnitude (m/s)                                 0
```

```
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

     hot_top_walls

        Condition                                               Value
        ----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         0
        Temperature (k)                                         473
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
```

```
        X-Position of Rotation-Axis Origin (m)            0
        Y-Position of Rotation-Axis Origin (m)            0
        Z-Position of Rotation-Axis Origin (m)            0
        X-Component of Rotation-Axis Direction            0
        Y-Component of Rotation-Axis Direction            0
        Z-Component of Rotation-Axis Direction            1
        X-component of shear stress (pascal)              0
        Y-component of shear stress (pascal)              0
        Z-component of shear stress (pascal)              0
        Surface tension gradient (n/m-k)                  0
        Specularity Coefficient                           0

     hot_valve_walls

        Condition                                         Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                0
        Heat Generation Rate (w/m3)                       0
        Material Name                                     copper
        Thermal BC Type                                   1
        Temperature (k)                                   300
        Heat Flux (w/m2)                                  0
        Convective Heat Transfer Coefficient (w/m2-k)     0
        Free Stream Temperature (k)                       300
        Enable shell conduction?                          no
        Wall Motion                                       0
        Shear Boundary Condition                          0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?         no
        Velocity Magnitude (m/s)                          0
        X-Component of Wall Translation                   1
        Y-Component of Wall Translation                   0
        Z-Component of Wall Translation                   0
        Define wall velocity components?                  no
        X-Component of Wall Translation (m/s)             0
        Y-Component of Wall Translation (m/s)             0
        Z-Component of Wall Translation (m/s)             0
        External Emissivity                               1
        External Radiation Temperature (k)                300
                                                          (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                            0
        X-Position of Rotation-Axis Origin (m)            0
        Y-Position of Rotation-Axis Origin (m)            0
        Z-Position of Rotation-Axis Origin (m)            0
        X-Component of Rotation-Axis Direction            0
        Y-Component of Rotation-Axis Direction            0
        Z-Component of Rotation-Axis Direction            1
        X-component of shear stress (pascal)              0
        Y-component of shear stress (pascal)              0
        Z-component of shear stress (pascal)              0
        Surface tension gradient (n/m-k)                  0
        Specularity Coefficient                           0

     pebble_walls
```

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	0
Temperature (k)	473
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)
(((constant . 0) (profile)))	
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

default-interior

Condition	Value

default-interior:001

Condition	Value

default-interior:024

Condition	Value

default-interior:026

Condition	Value

default-interior:027

Condition	Value

default-interior:028

Condition	Value

default-interior:029

Condition	Value

Solver Controls

Equations

Equation	Solved
Flow	yes
he	yes
Energy	yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.2
Max. Iterations Per Time Step	100

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.80000001
Body Forces	0.69999999
Momentum	0.40000001
he	0.80000001
Energy	0.89999998

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.576
L-J Energy Parameter	k	constant	10.2
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	mass-weighted-mixing-law	#f
Viscosity	kg/m-s	mass-weighted-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0
Speed of Sound	m/s	none	#f

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f

Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.681
L-J Energy Parameter	k	constant	91.5
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225

Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Loss Coefficient FLUENT Case

FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

```
name                       id   type
------------------------------------
barrel                     2    fluid
cold_leg                   3    fluid
cold_valve                 4    fluid
cross-over_leg             5    fluid
hot_top                    6    fluid
hot_valve                  7    fluid
pebbles                    8    fluid
wall                       9    wall
outlet                     10   interior
cold_exit                  11   interior
cold_enter                 12   interior
hot_exit                   13   interior
pebble_exit                14   interior
pebble_enter               15   interior
inlet                      16   interior
barrel_walls               17   wall
new_cold_valve             18   wall
cold_walls                 19   wall
cross_over_walls           20   wall
hot_top_walls              21   wall
hot_valve_walls            22   wall
pebble_walls               23   wall
default-interior           25   interior
default-interior:001       1    interior
default-interior:024       24   interior
default-interior:026       26   interior
default-interior:027       27   interior
default-interior:028       28   interior
default-interior:029       29   interior
```

Boundary Conditions

barrel

```
         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                         no
         Source Terms                                                  ()
         Specify fixed values?                                         no
         Local Coordinate System for Fixed Velocities                  no
         Fixed Values                                                  ()
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
```

```
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum

      cold_leg

         Condition
Value
         --------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
```

```
          Conical porous zone?                                          no
          X-Component of Direction-1 Vector                             1
          Y-Component of Direction-1 Vector                             0
          Z-Component of Direction-1 Vector                             0
          X-Component of Direction-2 Vector                             0
          Y-Component of Direction-2 Vector                             1
          Z-Component of Direction-2 Vector                             0
          X-Component of Cone Axis Vector                               1
          Y-Component of Cone Axis Vector                               0
          Z-Component of Cone Axis Vector                               0
          X-Coordinate of Point on Cone Axis (m)                        1
          Y-Coordinate of Point on Cone Axis (m)                        0
          Z-Coordinate of Point on Cone Axis (m)                        0
          Half Angle of Cone Relative to its Axis (deg)                 0
          Relative Velocity Resistance Formulation?                     yes
          Direction-1 Viscous Resistance (1/m2)                         0
          Direction-2 Viscous Resistance (1/m2)                         0
          Direction-3 Viscous Resistance (1/m2)                         0
          Choose alternative formulation for inertial resistance?       no
          Direction-1 Inertial Resistance (1/m)                         0
          Direction-2 Inertial Resistance (1/m)                         0
          Direction-3 Inertial Resistance (1/m)                         0
          C0 Coefficient for Power-Law                                  0
          C1 Coefficient for Power-Law                                  0
          Porosity                                                      1
          Solid Material Name
aluminum

      cold_valve

          Condition
Value
          -------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                         no
          Source Terms                                                  ()
          Specify fixed values?                                         no
          Local Coordinate System for Fixed Velocities                  no
          Fixed Values                                                  ()
          Motion Type                                                   0
          X-Velocity Of Zone (m/s)                                      0
          Y-Velocity Of Zone (m/s)                                      0
          Z-Velocity Of Zone (m/s)                                      0
          Rotation speed (rad/s)                                        0
          X-Origin of Rotation-Axis (m)                                 0
          Y-Origin of Rotation-Axis (m)                                 0
          Z-Origin of Rotation-Axis (m)                                 0
          X-Component of Rotation-Axis                                  0
          Y-Component of Rotation-Axis                                  0
          Z-Component of Rotation-Axis                                  1
          Deactivated Thread                                            no
          Porous zone?                                                  no
          Conical porous zone?                                          no
          X-Component of Direction-1 Vector                             1
          Y-Component of Direction-1 Vector                             0
```

```
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    yes
        Direction-1 Viscous Resistance (1/m2)                        0
        Direction-2 Viscous Resistance (1/m2)                        0
        Direction-3 Viscous Resistance (1/m2)                        0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                        0
        Direction-2 Inertial Resistance (1/m)                        0
        Direction-3 Inertial Resistance (1/m)                        0
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity                                                     1
        Solid Material Name
aluminum

      cross-over_leg

        Condition
Value
        ------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                        no
        Source Terms                                                 ()
        Specify fixed values?                                        no
        Local Coordinate System for Fixed Velocities                 no
        Fixed Values                                                 ()
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 no
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
```

```
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum

      hot_top

         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
```

```
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    yes
        Direction-1 Viscous Resistance (1/m2)                        0
        Direction-2 Viscous Resistance (1/m2)                        0
        Direction-3 Viscous Resistance (1/m2)                        0
        Choose alternative formulation for inertial resistance?      no
        Direction-1 Inertial Resistance (1/m)                        0
        Direction-2 Inertial Resistance (1/m)                        0
        Direction-3 Inertial Resistance (1/m)                        0
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity                                                     1
        Solid Material Name
aluminum

      hot_valve

        Condition
Value
        --------------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                        no
        Source Terms                                                 ()
        Specify fixed values?                                        no
        Local Coordinate System for Fixed Velocities                 no
        Fixed Values                                                 ()
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 no
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
```

```
          Z-Coordinate of Point on Cone Axis (m)                        0
          Half Angle of Cone Relative to its Axis (deg)                 0
          Relative Velocity Resistance Formulation?                     yes
          Direction-1 Viscous Resistance (1/m2)                         0
          Direction-2 Viscous Resistance (1/m2)                         0
          Direction-3 Viscous Resistance (1/m2)                         0
          Choose alternative formulation for inertial resistance?       no
          Direction-1 Inertial Resistance (1/m)                         0
          Direction-2 Inertial Resistance (1/m)                         0
          Direction-3 Inertial Resistance (1/m)                         0
          C0 Coefficient for Power-Law                                  0
          C1 Coefficient for Power-Law                                  0
          Porosity                                                      1
          Solid Material Name
aluminum

       pebbles

          Condition
Value
          -------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
----------------------------------------------------------------
          Material Name
mixture-template
          Specify source terms?                                         no
          Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
          Specify fixed values?                                         no
          Local Coordinate System for Fixed Velocities                  no
          Fixed Values                                                  ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
          Motion Type                                                   0
          X-Velocity Of Zone (m/s)                                      0
          Y-Velocity Of Zone (m/s)                                      0
          Z-Velocity Of Zone (m/s)                                      0
          Rotation speed (rad/s)                                        0
          X-Origin of Rotation-Axis (m)                                 0
          Y-Origin of Rotation-Axis (m)                                 0
          Z-Origin of Rotation-Axis (m)                                 0
          X-Component of Rotation-Axis                                  0
          Y-Component of Rotation-Axis                                  0
          Z-Component of Rotation-Axis                                  1
          Deactivated Thread                                            no
          Porous zone?                                                  yes
          Conical porous zone?                                          no
          X-Component of Direction-1 Vector                             1
          Y-Component of Direction-1 Vector                             0
          Z-Component of Direction-1 Vector                             0
          X-Component of Direction-2 Vector                             0
          Y-Component of Direction-2 Vector                             1
          Z-Component of Direction-2 Vector                             0
```

```
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
        X-Coordinate of Point on Cone Axis (m)                     1
        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  no
        Direction-1 Viscous Resistance (1/m2)                      0
        Direction-2 Viscous Resistance (1/m2)
4830000
        Direction-3 Viscous Resistance (1/m2)                      0
        Choose alternative formulation for inertial resistance?    no
        Direction-1 Inertial Resistance (1/m)                      0
        Direction-2 Inertial Resistance (1/m)                      0
        Direction-3 Inertial Resistance (1/m)                      0
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity
0.39500001
        Solid Material Name
glass

      wall

        Condition                                              Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                     0
        Heat Generation Rate (w/m3)                            0
        Material Name                                          copper
        Thermal BC Type                                        1
        Temperature (k)                                        300
        Heat Flux (w/m2)                                       0
        Convective Heat Transfer Coefficient (w/m2-k)          0
        Free Stream Temperature (k)                            300
        Enable shell conduction?                               no
        Wall Motion                                            0
        Shear Boundary Condition                               0
        Define wall motion relative to adjacent cell zone?     yes
        Apply a rotational velocity to this wall?              no
        Velocity Magnitude (m/s)                               0
        X-Component of Wall Translation                        1
        Y-Component of Wall Translation                        0
        Z-Component of Wall Translation                        0
        Define wall velocity components?                       no
        X-Component of Wall Translation (m/s)                  0
        Y-Component of Wall Translation (m/s)                  0
        Z-Component of Wall Translation (m/s)                  0
        External Emissivity                                    1
        External Radiation Temperature (k)                     300
                                                               (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                 0
        X-Position of Rotation-Axis Origin (m)                 0
        Y-Position of Rotation-Axis Origin (m)                 0
```

```
   Z-Position of Rotation-Axis Origin (m)                      0
   X-Component of Rotation-Axis Direction                      0
   Y-Component of Rotation-Axis Direction                      0
   Z-Component of Rotation-Axis Direction                      1
   X-component of shear stress (pascal)                        0
   Y-component of shear stress (pascal)                        0
   Z-component of shear stress (pascal)                        0
   Surface tension gradient (n/m-k)                            0
   Specularity Coefficient                                     0

outlet

   Condition   Value
   -----------------

cold_exit

   Condition   Value
   -----------------

cold_enter

   Condition   Value
   -----------------

hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                                   Value
   -----------------------------------------------------------------
---------------------
   Wall Thickness (m)                                          0
   Heat Generation Rate (w/m3)                                 0
   Material Name                                               aluminum
   Thermal BC Type                                             0
   Temperature (k)                                             293
   Heat Flux (w/m2)                                            0
   Convective Heat Transfer Coefficient (w/m2-k)               0
```

Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

new_cold_valve

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0

```
        Z-Component of Wall Translation (m/s)                    0
        External Emissivity                                      1
        External Radiation Temperature (k)                       300
                                                                 (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                   0
        X-Position of Rotation-Axis Origin (m)                   0
        Y-Position of Rotation-Axis Origin (m)                   0
        Z-Position of Rotation-Axis Origin (m)                   0
        X-Component of Rotation-Axis Direction                   0
        Y-Component of Rotation-Axis Direction                   0
        Z-Component of Rotation-Axis Direction                   1
        X-component of shear stress (pascal)                     0
        Y-component of shear stress (pascal)                     0
        Z-component of shear stress (pascal)                     0
        Surface tension gradient (n/m-k)                         0
        Specularity Coefficient                                  0

     cold_walls

        Condition                                                Value
        ----------------------------------------------------------------
--------------------
        Wall Thickness (m)                                       0
        Heat Generation Rate (w/m3)                              0
        Material Name                                            copper
        Thermal BC Type                                          0
        Temperature (k)                                          283
        Heat Flux (w/m2)                                         0
        Convective Heat Transfer Coefficient (w/m2-k)            0
        Free Stream Temperature (k)                              300
        Enable shell conduction?                                 no
        Wall Motion                                              0
        Shear Boundary Condition                                 0
        Define wall motion relative to adjacent cell zone?       yes
        Apply a rotational velocity to this wall?                no
        Velocity Magnitude (m/s)                                 0
        X-Component of Wall Translation                          1
        Y-Component of Wall Translation                          0
        Z-Component of Wall Translation                          0
        Define wall velocity components?                         no
        X-Component of Wall Translation (m/s)                    0
        Y-Component of Wall Translation (m/s)                    0
        Z-Component of Wall Translation (m/s)                    0
        External Emissivity                                      1
        External Radiation Temperature (k)                       300
                                                                 (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                   0
        X-Position of Rotation-Axis Origin (m)                   0
        Y-Position of Rotation-Axis Origin (m)                   0
        Z-Position of Rotation-Axis Origin (m)                   0
        X-Component of Rotation-Axis Direction                   0
        Y-Component of Rotation-Axis Direction                   0
        Z-Component of Rotation-Axis Direction                   1
```

```
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

    cross_over_walls

        Condition                                               Value
        -----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         1
        Temperature (k)                                         300
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

    hot_top_walls

        Condition                                               Value
        -----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
```

Material Name	copper
Thermal BC Type	0
Temperature (k)	473
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

hot_valve_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1

```
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

     pebble_walls

        Condition                                               Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         0
        Temperature (k)                                         473
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
```

```
      Y-Position of Rotation-Axis Origin (m)                    0
      Z-Position of Rotation-Axis Origin (m)                    0
      X-Component of Rotation-Axis Direction                    0
      Y-Component of Rotation-Axis Direction                    0
      Z-Component of Rotation-Axis Direction                    1
      X-component of shear stress (pascal)                      0
      Y-component of shear stress (pascal)                      0
      Z-component of shear stress (pascal)                      0
      Surface tension gradient (n/m-k)                          0
      Specularity Coefficient                                   0

   default-interior

      Condition   Value
      -----------------

   default-interior:001

      Condition   Value
      -----------------

   default-interior:024

      Condition   Value
      -----------------

   default-interior:026

      Condition   Value
      -----------------

   default-interior:027

      Condition   Value
      -----------------

   default-interior:028

      Condition   Value
      -----------------

   default-interior:029

      Condition   Value
      -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes
```

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.0099999998
Max. Iterations Per Time Step	100

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.80000001
Body Forces	0.69999999
Momentum	0.40000001
he	0.80000001
Energy	0.89999998

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	PISO
Skewness-Neighbour Coupling	yes
Skewness Correction	1
Neighbour Correction	1

Discretization Scheme

Variable	Scheme
Pressure	PRESTO!
Density	Third-Order MUSCL
Momentum	Third-Order MUSCL
he	Third-Order MUSCL
Energy	Third-Order MUSCL

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.576
L-J Energy Parameter	k	constant	10.2
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

```
    Property                          Units    Method
Value(s)
    ------------------------------------------------------------------
------------------
    Mixture Species                            names
((he n2) () ())
    Density                           kg/m3    ideal-gas
#f
    Cp (Specific Heat)                j/kg-k   mixing-law
#f
    Thermal Conductivity              w/m-k    mass-weighted-mixing-law
#f
    Viscosity                         kg/m-s   mass-weighted-mixing-law
#f
    Mass Diffusivity                  m2/s     kinetic-theory
#f
    Thermal Diffusion Coefficient     kg/m-s   kinetic-theory
#f
    Thermal Expansion Coefficient     1/k      constant
0
    Speed of Sound                    m/s      none
#f

  Material: (nitrogen . mixture-template) (fluid)

    Property                      Units       Method            Value(s)
    ------------------------------------------------------------------
    Cp (Specific Heat)            j/kg-k      kinetic-theory    #f
    Thermal Conductivity          w/m-k       kinetic-theory    #f
    Viscosity                     kg/m-s      kinetic-theory    #f
    Molecular Weight              kg/kgmol    constant          28.013399
    L-J Characteristic Length     angstrom    constant          3.681
    L-J Energy Parameter          k           constant          91.5
    Degrees of Freedom                        constant          5
    Speed of Sound                m/s         none              #f

  Material: nitrogen (fluid)

    Property                          Units      Method      Value(s)
    ----------------------------------------------------------------
    Density                           kg/m3      constant    1.138
    Cp (Specific Heat)                j/kg-k     constant    1040.67
    Thermal Conductivity              w/m-k      constant    0.0242
    Viscosity                         kg/m-s     constant    1.663e-05
    Molecular Weight                  kg/kgmol   constant    28.0134
    L-J Characteristic Length         angstrom   constant    3.621
    L-J Energy Parameter              k          constant    97.53
    Thermal Expansion Coefficient     1/k        constant    0
    Degrees of Freedom                           constant    0
    Speed of Sound                    m/s        none        #f

  Material: oxygen (fluid)

    Property                          Units      Method      Value(s)
    ----------------------------------------------------------------
    Density                           kg/m3      constant    1.2999
    Cp (Specific Heat)                j/kg-k     constant    919.31
```

Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Heat Flux FLUENT Case

FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type
barrel	2	fluid
cold_leg	3	fluid
cold_valve	4	fluid
cross-over_leg	5	fluid
hot_top	6	fluid
hot_valve	7	fluid
pebbles	8	fluid
wall	9	wall
outlet	10	interior
cold_exit	11	interior
cold_enter	12	interior
hot_exit	13	interior
pebble_exit	14	interior
pebble_enter	15	interior
inlet	16	interior
barrel_walls	17	wall
new_cold_valve	18	wall
cold_walls	19	wall
cross_over_walls	20	wall
hot_top_walls	21	wall
hot_valve_walls	22	wall
pebble_walls	23	wall
default-interior	25	interior
default-interior:001	1	interior
default-interior:024	24	interior
default-interior:026	26	interior
default-interior:027	27	interior
default-interior:028	28	interior
default-interior:029	29	interior

Boundary Conditions

barrel

```
        Condition
Value
        --------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                        no
        Source Terms                                                 ()
        Specify fixed values?                                        no
        Local Coordinate System for Fixed Velocities                 no
        Fixed Values                                                 ()
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 no
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    yes
        Direction-1 Viscous Resistance (1/m2)                        0
        Direction-2 Viscous Resistance (1/m2)                        0
        Direction-3 Viscous Resistance (1/m2)                        0
        Choose alternative formulation for inertial resistance?      no
        Direction-1 Inertial Resistance (1/m)                        0
        Direction-2 Inertial Resistance (1/m)                        0
        Direction-3 Inertial Resistance (1/m)                        0
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity                                                     1
        Solid Material Name
aluminum

      cold_leg

        Condition
Value
```

```
        ------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ()
        Motion Type                                                 0
        X-Velocity Of Zone (m/s)                                    0
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      cold_valve

        Condition
Value
        ------------------------------------------------------------
------------
```

```
          Material Name
mixture-template
          Specify source terms?                                        no
          Source Terms                                                 ()
          Specify fixed values?                                        no
          Local Coordinate System for Fixed Velocities                 no
          Fixed Values                                                 ()
          Motion Type                                                  0
          X-Velocity Of Zone (m/s)                                     0
          Y-Velocity Of Zone (m/s)                                     0
          Z-Velocity Of Zone (m/s)                                     0
          Rotation speed (rad/s)                                       0
          X-Origin of Rotation-Axis (m)                                0
          Y-Origin of Rotation-Axis (m)                                0
          Z-Origin of Rotation-Axis (m)                                0
          X-Component of Rotation-Axis                                 0
          Y-Component of Rotation-Axis                                 0
          Z-Component of Rotation-Axis                                 1
          Deactivated Thread                                           no
          Porous zone?                                                 no
          Conical porous zone?                                         no
          X-Component of Direction-1 Vector                            1
          Y-Component of Direction-1 Vector                            0
          Z-Component of Direction-1 Vector                            0
          X-Component of Direction-2 Vector                            0
          Y-Component of Direction-2 Vector                            1
          Z-Component of Direction-2 Vector                            0
          X-Component of Cone Axis Vector                              1
          Y-Component of Cone Axis Vector                              0
          Z-Component of Cone Axis Vector                              0
          X-Coordinate of Point on Cone Axis (m)                       1
          Y-Coordinate of Point on Cone Axis (m)                       0
          Z-Coordinate of Point on Cone Axis (m)                       0
          Half Angle of Cone Relative to its Axis (deg)                0
          Relative Velocity Resistance Formulation?                    yes
          Direction-1 Viscous Resistance (1/m2)                        0
          Direction-2 Viscous Resistance (1/m2)                        0
          Direction-3 Viscous Resistance (1/m2)                        0
          Choose alternative formulation for inertial resistance?      no
          Direction-1 Inertial Resistance (1/m)                        0
          Direction-2 Inertial Resistance (1/m)                        0
          Direction-3 Inertial Resistance (1/m)                        0
          C0 Coefficient for Power-Law                                 0
          C1 Coefficient for Power-Law                                 0
          Porosity                                                     1
          Solid Material Name
aluminum

       cross-over_leg

          Condition
Value
          --------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                        no
```

```
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ()
        Motion Type                                                 0
        X-Velocity Of Zone (m/s)                                    0
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      hot_top

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
```

```
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum

      hot_valve

         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
```

```
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

     pebbles

        Condition
Value
        ------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
---------------------------------------------------------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
```

```
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
         Z-Component of Rotation-Axis                                  1
         Deactivated Thread                                            no
         Porous zone?                                                  yes
         Conical porous zone?                                          no
         X-Component of Direction-1 Vector                             1
         Y-Component of Direction-1 Vector                             0
         Z-Component of Direction-1 Vector                             0
         X-Component of Direction-2 Vector                             0
         Y-Component of Direction-2 Vector                             1
         Z-Component of Direction-2 Vector                             0
         X-Component of Cone Axis Vector                               1
         Y-Component of Cone Axis Vector                               0
         Z-Component of Cone Axis Vector                               0
         X-Coordinate of Point on Cone Axis (m)                        1
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
         Relative Velocity Resistance Formulation?                     no
         Direction-1 Viscous Resistance (1/m2)
5860000
         Direction-2 Viscous Resistance (1/m2)
5860000
         Direction-3 Viscous Resistance (1/m2)
5860000
         Choose alternative formulation for inertial resistance?       no
         Direction-1 Inertial Resistance (1/m)                         2734
         Direction-2 Inertial Resistance (1/m)                         2734
         Direction-3 Inertial Resistance (1/m)                         2734
         C0 Coefficient for Power-Law                                  0
         C1 Coefficient for Power-Law                                  0
         Porosity
0.40000001
         Solid Material Name
glass

      wall

         Condition                                               Value
         --------------------------------------------------------------
---------------------
         Wall Thickness (m)                                      0
         Heat Generation Rate (w/m3)                             0
         Material Name                                           copper
         Thermal BC Type                                         1
```

```
        Temperature (k)                                         300
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

     outlet

        Condition   Value
        -----------------

     cold_exit

        Condition   Value
        -----------------

     cold_enter

        Condition   Value
        -----------------

     hot_exit

        Condition   Value
        -----------------

     pebble_exit
```

```
   Condition   Value
   ----------------

pebble_enter

   Condition   Value
   ----------------

inlet

   Condition   Value
   ----------------

barrel_walls

   Condition                                                    Value
   -------------------------------------------------------------------------
--------------------
   Wall Thickness (m)                                           0
   Heat Generation Rate (w/m3)                                  0
   Material Name                                                aluminum
   Thermal BC Type                                              0
   Temperature (k)                                              293
   Heat Flux (w/m2)                                             0
   Convective Heat Transfer Coefficient (w/m2-k)                0
   Free Stream Temperature (k)                                  300
   Enable shell conduction?                                     no
   Wall Motion                                                  0
   Shear Boundary Condition                                     0
   Define wall motion relative to adjacent cell zone?           yes
   Apply a rotational velocity to this wall?                    no
   Velocity Magnitude (m/s)                                     0
   X-Component of Wall Translation                              1
   Y-Component of Wall Translation                              0
   Z-Component of Wall Translation                              0
   Define wall velocity components?                             no
   X-Component of Wall Translation (m/s)                        0
   Y-Component of Wall Translation (m/s)                        0
   Z-Component of Wall Translation (m/s)                        0
   External Emissivity                                          1
   External Radiation Temperature (k)                           300
                                                                (0)

(((constant . 0) (profile  )))
   Rotation Speed (rad/s)                                       0
   X-Position of Rotation-Axis Origin (m)                       0
   Y-Position of Rotation-Axis Origin (m)                       0
   Z-Position of Rotation-Axis Origin (m)                       0
   X-Component of Rotation-Axis Direction                       0
   Y-Component of Rotation-Axis Direction                       0
   Z-Component of Rotation-Axis Direction                       1
   X-component of shear stress (pascal)                         0
   Y-component of shear stress (pascal)                         0
   Z-component of shear stress (pascal)                         0
   Surface tension gradient (n/m-k)                             0
   Specularity Coefficient                                      0
```

new_cold_valve

```
Condition                                              Value
--------------------------------------------------------------------------------
Wall Thickness (m)                                     0
Heat Generation Rate (w/m3)                            0
Material Name                                          copper
Thermal BC Type                                        1
Temperature (k)                                        300
Heat Flux (w/m2)                                       0
Convective Heat Transfer Coefficient (w/m2-k)          0
Free Stream Temperature (k)                            300
Enable shell conduction?                               no
Wall Motion                                            0
Shear Boundary Condition                               0
Define wall motion relative to adjacent cell zone?     yes
Apply a rotational velocity to this wall?              no
Velocity Magnitude (m/s)                               0
X-Component of Wall Translation                        1
Y-Component of Wall Translation                        0
Z-Component of Wall Translation                        0
Define wall velocity components?                       no
X-Component of Wall Translation (m/s)                  0
Y-Component of Wall Translation (m/s)                  0
Z-Component of Wall Translation (m/s)                  0
External Emissivity                                    1
External Radiation Temperature (k)                     300
                                                       (0)

(((constant . 0) (profile )))
Rotation Speed (rad/s)                                 0
X-Position of Rotation-Axis Origin (m)                 0
Y-Position of Rotation-Axis Origin (m)                 0
Z-Position of Rotation-Axis Origin (m)                 0
X-Component of Rotation-Axis Direction                 0
Y-Component of Rotation-Axis Direction                 0
Z-Component of Rotation-Axis Direction                 1
X-component of shear stress (pascal)                   0
Y-component of shear stress (pascal)                   0
Z-component of shear stress (pascal)                   0
Surface tension gradient (n/m-k)                       0
Specularity Coefficient                                0
```

cold_walls

```
Condition                                              Value
--------------------------------------------------------------------------------
Wall Thickness (m)                                     0
Heat Generation Rate (w/m3)                            0
Material Name                                          copper
Thermal BC Type                                        0
Temperature (k)                                        283
Heat Flux (w/m2)                                       0
Convective Heat Transfer Coefficient (w/m2-k)          0
Free Stream Temperature (k)                            300
```

```
        Enable shell conduction?                           no
        Wall Motion                                        0
        Shear Boundary Condition                           0
        Define wall motion relative to adjacent cell zone? yes
        Apply a rotational velocity to this wall?          no
        Velocity Magnitude (m/s)                           0
        X-Component of Wall Translation                    1
        Y-Component of Wall Translation                    0
        Z-Component of Wall Translation                    0
        Define wall velocity components?                   no
        X-Component of Wall Translation (m/s)              0
        Y-Component of Wall Translation (m/s)              0
        Z-Component of Wall Translation (m/s)              0
        External Emissivity                                1
        External Radiation Temperature (k)                 300
                                                           (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                             0
        X-Position of Rotation-Axis Origin (m)             0
        Y-Position of Rotation-Axis Origin (m)             0
        Z-Position of Rotation-Axis Origin (m)             0
        X-Component of Rotation-Axis Direction             0
        Y-Component of Rotation-Axis Direction             0
        Z-Component of Rotation-Axis Direction             1
        X-component of shear stress (pascal)               0
        Y-component of shear stress (pascal)               0
        Z-component of shear stress (pascal)               0
        Surface tension gradient (n/m-k)                   0
        Specularity Coefficient                            0

     cross_over_walls

        Condition                                          Value
        --------------------------------------------------------------
--------------------
        Wall Thickness (m)                                 0
        Heat Generation Rate (w/m3)                        0
        Material Name                                      copper
        Thermal BC Type                                    1
        Temperature (k)                                    300
        Heat Flux (w/m2)                                   0
        Convective Heat Transfer Coefficient (w/m2-k)      0
        Free Stream Temperature (k)                        300
        Enable shell conduction?                           no
        Wall Motion                                        0
        Shear Boundary Condition                           0
        Define wall motion relative to adjacent cell zone? yes
        Apply a rotational velocity to this wall?          no
        Velocity Magnitude (m/s)                           0
        X-Component of Wall Translation                    1
        Y-Component of Wall Translation                    0
        Z-Component of Wall Translation                    0
        Define wall velocity components?                   no
        X-Component of Wall Translation (m/s)              0
        Y-Component of Wall Translation (m/s)              0
        Z-Component of Wall Translation (m/s)              0
```

```
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

     hot_top_walls

        Condition                                               Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         0
        Temperature (k)                                         473
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
```

```
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     hot_valve_walls

        Condition                                           Value
        -----------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     1
        Temperature (k)                                     300
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     pebble_walls

        Condition                                           Value
        -----------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
```

```
          Thermal BC Type                                       1
          Temperature (k)                                       473
          Heat Flux (w/m2)                                      8889.0596
          Convective Heat Transfer Coefficient (w/m2-k)         0
          Free Stream Temperature (k)                           300
          Enable shell conduction?                              no
          Wall Motion                                           0
          Shear Boundary Condition                              0
          Define wall motion relative to adjacent cell zone?    yes
          Apply a rotational velocity to this wall?             no
          Velocity Magnitude (m/s)                              0
          X-Component of Wall Translation                       1
          Y-Component of Wall Translation                       0
          Z-Component of Wall Translation                       0
          Define wall velocity components?                      no
          X-Component of Wall Translation (m/s)                 0
          Y-Component of Wall Translation (m/s)                 0
          Z-Component of Wall Translation (m/s)                 0
          External Emissivity                                   1
          External Radiation Temperature (k)                    300
                                                                (0)

(((constant . 0) (profile  )))
          Rotation Speed (rad/s)                                0
          X-Position of Rotation-Axis Origin (m)                0
          Y-Position of Rotation-Axis Origin (m)                0
          Z-Position of Rotation-Axis Origin (m)                0
          X-Component of Rotation-Axis Direction                0
          Y-Component of Rotation-Axis Direction                0
          Z-Component of Rotation-Axis Direction                1
          X-component of shear stress (pascal)                  0
          Y-component of shear stress (pascal)                  0
          Z-component of shear stress (pascal)                  0
          Surface tension gradient (n/m-k)                      0
          Specularity Coefficient                               0

       default-interior

          Condition   Value
          -----------------

       default-interior:001

          Condition   Value
          -----------------

       default-interior:024

          Condition   Value
          -----------------

       default-interior:026

          Condition   Value
          -----------------

       default-interior:027
```

```
      Condition   Value
      -----------------

   default-interior:028

      Condition   Value
      -----------------

   default-interior:029

      Condition   Value
      -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes

   Numerics

      Numeric                        Enabled
      ---------------------------------------
      Absolute Velocity Formulation  yes

   Unsteady Calculation Parameters


      -------------------------------------------
      Time Step (s)                  0.15000001
      Max. Iterations Per Time Step  200

   Relaxation

      Variable      Relaxation Factor
      -------------------------------
      Pressure      0.30000001
      Density       1
      Body Forces   1
      Momentum      0.69999999
      he            1
      Energy        1

   Linear Solver

                    Solver     Termination   Residual Reduction
      Variable      Type       Criterion     Tolerance
      -----------------------------------------------------------
      Pressure      V-Cycle    0.1
      X-Momentum    Flexible   0.1           0.7
      Y-Momentum    Flexible   0.1           0.7
```

Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	PRESTO!
Density	Third-Order MUSCL
Momentum	Third-Order MUSCL
he	Third-Order MUSCL
Energy	Third-Order MUSCL

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001

L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	ideal-gas-mixing-law	#f
Viscosity	kg/m-s	ideal-gas-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0
Speed of Sound	m/s	none	#f

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0

Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Accurate Temperature Boundary Condition FLUENT Case

FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type

```
      barrel                    2     fluid
      cold_leg                  3     fluid
      cold_valve                4     fluid
      cross-over_leg            5     fluid
      hot_top                   6     fluid
      hot_valve                 7     fluid
      pebbles                   8     fluid
      wall                      9     wall
      outlet                    10    interior
      cold_exit                 11    interior
      cold_enter                12    interior
      hot_exit                  13    interior
      pebble_exit               14    interior
      pebble_enter              15    interior
      inlet                     16    interior
      barrel_walls              17    wall
      new_cold_valve            18    wall
      cold_walls                19    wall
      cross_over_walls          20    wall
      hot_top_walls             21    wall
      hot_valve_walls           22    wall
      pebble_walls              23    wall
      default-interior          25    interior
      default-interior:001      1     interior
      default-interior:024      24    interior
      default-interior:026      26    interior
      default-interior:027      27    interior
      default-interior:028      28    interior
      default-interior:029      29    interior

   Boundary Conditions

      barrel

         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                    no
         Source Terms                                             ()
         Specify fixed values?                                    no
         Local Coordinate System for Fixed Velocities             no
         Fixed Values                                             ()
         Motion Type                                              0
         X-Velocity Of Zone (m/s)                                 0
         Y-Velocity Of Zone (m/s)                                 0
         Z-Velocity Of Zone (m/s)                                 0
         Rotation speed (rad/s)                                   0
         X-Origin of Rotation-Axis (m)                            0
         Y-Origin of Rotation-Axis (m)                            0
         Z-Origin of Rotation-Axis (m)                            0
         X-Component of Rotation-Axis                             0
         Y-Component of Rotation-Axis                             0
         Z-Component of Rotation-Axis                             1
         Deactivated Thread                                       no
```

```
          Porous zone?                                              no
          Conical porous zone?                                      no
          X-Component of Direction-1 Vector                         1
          Y-Component of Direction-1 Vector                         0
          Z-Component of Direction-1 Vector                         0
          X-Component of Direction-2 Vector                         0
          Y-Component of Direction-2 Vector                         1
          Z-Component of Direction-2 Vector                         0
          X-Component of Cone Axis Vector                           1
          Y-Component of Cone Axis Vector                           0
          Z-Component of Cone Axis Vector                           0
          X-Coordinate of Point on Cone Axis (m)                    1
          Y-Coordinate of Point on Cone Axis (m)                    0
          Z-Coordinate of Point on Cone Axis (m)                    0
          Half Angle of Cone Relative to its Axis (deg)             0
          Relative Velocity Resistance Formulation?                 yes
          Direction-1 Viscous Resistance (1/m2)                     0
          Direction-2 Viscous Resistance (1/m2)                     0
          Direction-3 Viscous Resistance (1/m2)                     0
          Choose alternative formulation for inertial resistance?   no
          Direction-1 Inertial Resistance (1/m)                     0
          Direction-2 Inertial Resistance (1/m)                     0
          Direction-3 Inertial Resistance (1/m)                     0
          C0 Coefficient for Power-Law                              0
          C1 Coefficient for Power-Law                              0
          Porosity                                                  1
          Solid Material Name
aluminum

      cold_leg

          Condition
Value
          ---------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                     no
          Source Terms                                              ()
          Specify fixed values?                                     no
          Local Coordinate System for Fixed Velocities              no
          Fixed Values                                              ()
          Motion Type                                               0
          X-Velocity Of Zone (m/s)                                  0
          Y-Velocity Of Zone (m/s)                                  0
          Z-Velocity Of Zone (m/s)                                  0
          Rotation speed (rad/s)                                    0
          X-Origin of Rotation-Axis (m)                             0
          Y-Origin of Rotation-Axis (m)                             0
          Z-Origin of Rotation-Axis (m)                             0
          X-Component of Rotation-Axis                              0
          Y-Component of Rotation-Axis                              0
          Z-Component of Rotation-Axis                              1
          Deactivated Thread                                        no
          Porous zone?                                              no
          Conical porous zone?                                      no
          X-Component of Direction-1 Vector                         1
```

```
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      cold_valve

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ()
        Motion Type                                                 0
        X-Velocity Of Zone (m/s)                                    0
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
```

```
          Y-Component of Direction-2 Vector                          1
          Z-Component of Direction-2 Vector                          0
          X-Component of Cone Axis Vector                            1
          Y-Component of Cone Axis Vector                            0
          Z-Component of Cone Axis Vector                            0
          X-Coordinate of Point on Cone Axis (m)                     1
          Y-Coordinate of Point on Cone Axis (m)                     0
          Z-Coordinate of Point on Cone Axis (m)                     0
          Half Angle of Cone Relative to its Axis (deg)              0
          Relative Velocity Resistance Formulation?                  yes
          Direction-1 Viscous Resistance (1/m2)                      0
          Direction-2 Viscous Resistance (1/m2)                      0
          Direction-3 Viscous Resistance (1/m2)                      0
          Choose alternative formulation for inertial resistance?    no
          Direction-1 Inertial Resistance (1/m)                      0
          Direction-2 Inertial Resistance (1/m)                      0
          Direction-3 Inertial Resistance (1/m)                      0
          C0 Coefficient for Power-Law                               0
          C1 Coefficient for Power-Law                               0
          Porosity                                                   1
          Solid Material Name
aluminum

      cross-over_leg

          Condition
Value
          --------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                      no
          Source Terms                                               ()
          Specify fixed values?                                      no
          Local Coordinate System for Fixed Velocities               no
          Fixed Values                                               ()
          Motion Type                                                0
          X-Velocity Of Zone (m/s)                                   0
          Y-Velocity Of Zone (m/s)                                   0
          Z-Velocity Of Zone (m/s)                                   0
          Rotation speed (rad/s)                                     0
          X-Origin of Rotation-Axis (m)                              0
          Y-Origin of Rotation-Axis (m)                              0
          Z-Origin of Rotation-Axis (m)                              0
          X-Component of Rotation-Axis                               0
          Y-Component of Rotation-Axis                               0
          Z-Component of Rotation-Axis                               1
          Deactivated Thread                                         no
          Porous zone?                                               no
          Conical porous zone?                                       no
          X-Component of Direction-1 Vector                          1
          Y-Component of Direction-1 Vector                          0
          Z-Component of Direction-1 Vector                          0
          X-Component of Direction-2 Vector                          0
          Y-Component of Direction-2 Vector                          1
          Z-Component of Direction-2 Vector                          0
          X-Component of Cone Axis Vector                            1
```

```
          Y-Component of Cone Axis Vector                             0
          Z-Component of Cone Axis Vector                             0
          X-Coordinate of Point on Cone Axis (m)                      1
          Y-Coordinate of Point on Cone Axis (m)                      0
          Z-Coordinate of Point on Cone Axis (m)                      0
          Half Angle of Cone Relative to its Axis (deg)               0
          Relative Velocity Resistance Formulation?                   yes
          Direction-1 Viscous Resistance (1/m2)                       0
          Direction-2 Viscous Resistance (1/m2)                       0
          Direction-3 Viscous Resistance (1/m2)                       0
          Choose alternative formulation for inertial resistance?     no
          Direction-1 Inertial Resistance (1/m)                       0
          Direction-2 Inertial Resistance (1/m)                       0
          Direction-3 Inertial Resistance (1/m)                       0
          C0 Coefficient for Power-Law                                0
          C1 Coefficient for Power-Law                                0
          Porosity                                                    1
          Solid Material Name
aluminum

      hot_top

          Condition
Value
          -------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                       no
          Source Terms                                                ()
          Specify fixed values?                                       no
          Local Coordinate System for Fixed Velocities                no
          Fixed Values                                                ()
          Motion Type                                                 0
          X-Velocity Of Zone (m/s)                                    0
          Y-Velocity Of Zone (m/s)                                    0
          Z-Velocity Of Zone (m/s)                                    0
          Rotation speed (rad/s)                                      0
          X-Origin of Rotation-Axis (m)                               0
          Y-Origin of Rotation-Axis (m)                               0
          Z-Origin of Rotation-Axis (m)                               0
          X-Component of Rotation-Axis                                0
          Y-Component of Rotation-Axis                                0
          Z-Component of Rotation-Axis                                1
          Deactivated Thread                                          no
          Porous zone?                                                no
          Conical porous zone?                                        no
          X-Component of Direction-1 Vector                           1
          Y-Component of Direction-1 Vector                           0
          Z-Component of Direction-1 Vector                           0
          X-Component of Direction-2 Vector                           0
          Y-Component of Direction-2 Vector                           1
          Z-Component of Direction-2 Vector                           0
          X-Component of Cone Axis Vector                             1
          Y-Component of Cone Axis Vector                             0
          Z-Component of Cone Axis Vector                             0
          X-Coordinate of Point on Cone Axis (m)                      1
```

```
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
         Relative Velocity Resistance Formulation?                     yes
         Direction-1 Viscous Resistance (1/m2)                         0
         Direction-2 Viscous Resistance (1/m2)                         0
         Direction-3 Viscous Resistance (1/m2)                         0
         Choose alternative formulation for inertial resistance?       no
         Direction-1 Inertial Resistance (1/m)                         0
         Direction-2 Inertial Resistance (1/m)                         0
         Direction-3 Inertial Resistance (1/m)                         0
         C0 Coefficient for Power-Law                                  0
         C1 Coefficient for Power-Law                                  0
         Porosity                                                      1
         Solid Material Name
aluminum

      hot_valve

         Condition
Value
         --------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                         no
         Source Terms                                                  ()
         Specify fixed values?                                         no
         Local Coordinate System for Fixed Velocities                  no
         Fixed Values                                                  ()
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
         Z-Component of Rotation-Axis                                  1
         Deactivated Thread                                            no
         Porous zone?                                                  no
         Conical porous zone?                                          no
         X-Component of Direction-1 Vector                             1
         Y-Component of Direction-1 Vector                             0
         Z-Component of Direction-1 Vector                             0
         X-Component of Direction-2 Vector                             0
         Y-Component of Direction-2 Vector                             1
         Z-Component of Direction-2 Vector                             0
         X-Component of Cone Axis Vector                               1
         Y-Component of Cone Axis Vector                               0
         Z-Component of Cone Axis Vector                               0
         X-Coordinate of Point on Cone Axis (m)                        1
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
```

```
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum

      pebbles

         Condition
Value
         --------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
----------------------------------------------------------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              yes
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
```

```
         Z-Component of Cone Axis Vector                             0
         X-Coordinate of Point on Cone Axis (m)                      1
         Y-Coordinate of Point on Cone Axis (m)                      0
         Z-Coordinate of Point on Cone Axis (m)                      0
         Half Angle of Cone Relative to its Axis (deg)               0
         Relative Velocity Resistance Formulation?                   no
         Direction-1 Viscous Resistance (1/m2)
5860000
         Direction-2 Viscous Resistance (1/m2)
5860000
         Direction-3 Viscous Resistance (1/m2)
5860000
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                       2734
         Direction-2 Inertial Resistance (1/m)                       2734
         Direction-3 Inertial Resistance (1/m)                       2734
         C0 Coefficient for Power-Law                                0
         C1 Coefficient for Power-Law                                0
         Porosity
0.40000001
         Solid Material Name
glass

      wall

         Condition                                              Value
         --------------------------------------------------------------
---------------------
         Wall Thickness (m)                                     0
         Heat Generation Rate (w/m3)                            0
         Material Name                                          copper
         Thermal BC Type                                        1
         Temperature (k)                                        300
         Heat Flux (w/m2)                                       0
         Convective Heat Transfer Coefficient (w/m2-k)          0
         Free Stream Temperature (k)                            300
         Enable shell conduction?                               no
         Wall Motion                                            0
         Shear Boundary Condition                               0
         Define wall motion relative to adjacent cell zone?     yes
         Apply a rotational velocity to this wall?              no
         Velocity Magnitude (m/s)                               0
         X-Component of Wall Translation                        1
         Y-Component of Wall Translation                        0
         Z-Component of Wall Translation                        0
         Define wall velocity components?                       no
         X-Component of Wall Translation (m/s)                  0
         Y-Component of Wall Translation (m/s)                  0
         Z-Component of Wall Translation (m/s)                  0
         External Emissivity                                    1
         External Radiation Temperature (k)                     300
                                                                (0)

(((constant . 0) (profile  )))
         Rotation Speed (rad/s)                                 0
         X-Position of Rotation-Axis Origin (m)                 0
         Y-Position of Rotation-Axis Origin (m)                 0
```

```
   Z-Position of Rotation-Axis Origin (m)                0
   X-Component of Rotation-Axis Direction                0
   Y-Component of Rotation-Axis Direction                0
   Z-Component of Rotation-Axis Direction                1
   X-component of shear stress (pascal)                  0
   Y-component of shear stress (pascal)                  0
   Z-component of shear stress (pascal)                  0
   Surface tension gradient (n/m-k)                      0
   Specularity Coefficient                               0

outlet

   Condition   Value
   -----------------

cold_exit

   Condition   Value
   -----------------

cold_enter

   Condition   Value
   -----------------

hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                             Value
   ---------------------------------------------------------------
---------------------
   Wall Thickness (m)                                    0
   Heat Generation Rate (w/m3)                           0
   Material Name                                         aluminum
   Thermal BC Type                                       0
   Temperature (k)                                       293
   Heat Flux (w/m2)                                      0
   Convective Heat Transfer Coefficient (w/m2-k)         0
```

```
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

    new_cold_valve

        Condition                                           Value
        ---------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     1
        Temperature (k)                                     300
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
```

```
        Z-Component of Wall Translation (m/s)              0
        External Emissivity                                1
        External Radiation Temperature (k)                 300
                                                           (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                             0
        X-Position of Rotation-Axis Origin (m)             0
        Y-Position of Rotation-Axis Origin (m)             0
        Z-Position of Rotation-Axis Origin (m)             0
        X-Component of Rotation-Axis Direction             0
        Y-Component of Rotation-Axis Direction             0
        Z-Component of Rotation-Axis Direction             1
        X-component of shear stress (pascal)               0
        Y-component of shear stress (pascal)               0
        Z-component of shear stress (pascal)               0
        Surface tension gradient (n/m-k)                   0
        Specularity Coefficient                            0

     cold_walls

        Condition                                          Value
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                 0
        Heat Generation Rate (w/m3)                        0
        Material Name                                      copper
        Thermal BC Type                                    0
        Temperature (k)                                    283
        Heat Flux (w/m2)                                   0
        Convective Heat Transfer Coefficient (w/m2-k)      0
        Free Stream Temperature (k)                        300
        Enable shell conduction?                           no
        Wall Motion                                        0
        Shear Boundary Condition                           0
        Define wall motion relative to adjacent cell zone? yes
        Apply a rotational velocity to this wall?          no
        Velocity Magnitude (m/s)                           0
        X-Component of Wall Translation                    1
        Y-Component of Wall Translation                    0
        Z-Component of Wall Translation                    0
        Define wall velocity components?                   no
        X-Component of Wall Translation (m/s)              0
        Y-Component of Wall Translation (m/s)              0
        Z-Component of Wall Translation (m/s)              0
        External Emissivity                                1
        External Radiation Temperature (k)                 300
                                                           (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                             0
        X-Position of Rotation-Axis Origin (m)             0
        Y-Position of Rotation-Axis Origin (m)             0
        Z-Position of Rotation-Axis Origin (m)             0
        X-Component of Rotation-Axis Direction             0
        Y-Component of Rotation-Axis Direction             0
        Z-Component of Rotation-Axis Direction             1
```

```
        X-component of shear stress (pascal)              0
        Y-component of shear stress (pascal)              0
        Z-component of shear stress (pascal)              0
        Surface tension gradient (n/m-k)                  0
        Specularity Coefficient                           0

     cross_over_walls

        Condition                                         Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                0
        Heat Generation Rate (w/m3)                       0
        Material Name                                     copper
        Thermal BC Type                                   1
        Temperature (k)                                   300
        Heat Flux (w/m2)                                  0
        Convective Heat Transfer Coefficient (w/m2-k)     0
        Free Stream Temperature (k)                       300
        Enable shell conduction?                          no
        Wall Motion                                       0
        Shear Boundary Condition                          0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?         no
        Velocity Magnitude (m/s)                          0
        X-Component of Wall Translation                   1
        Y-Component of Wall Translation                   0
        Z-Component of Wall Translation                   0
        Define wall velocity components?                  no
        X-Component of Wall Translation (m/s)             0
        Y-Component of Wall Translation (m/s)             0
        Z-Component of Wall Translation (m/s)             0
        External Emissivity                               1
        External Radiation Temperature (k)                300
                                                          (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                            0
        X-Position of Rotation-Axis Origin (m)            0
        Y-Position of Rotation-Axis Origin (m)            0
        Z-Position of Rotation-Axis Origin (m)            0
        X-Component of Rotation-Axis Direction            0
        Y-Component of Rotation-Axis Direction            0
        Z-Component of Rotation-Axis Direction            1
        X-component of shear stress (pascal)              0
        Y-component of shear stress (pascal)              0
        Z-component of shear stress (pascal)              0
        Surface tension gradient (n/m-k)                  0
        Specularity Coefficient                           0

     hot_top_walls

        Condition                                         Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                0
        Heat Generation Rate (w/m3)                       0
```

```
        Material Name                                          copper
        Thermal BC Type                                        1
        Temperature (k)                                        0
        Heat Flux (w/m2)                                       0
        Convective Heat Transfer Coefficient (w/m2-k)          0
        Free Stream Temperature (k)                            300
        Enable shell conduction?                               no
        Wall Motion                                            0
        Shear Boundary Condition                               0
        Define wall motion relative to adjacent cell zone?     yes
        Apply a rotational velocity to this wall?              no
        Velocity Magnitude (m/s)                               0
        X-Component of Wall Translation                        1
        Y-Component of Wall Translation                        0
        Z-Component of Wall Translation                        0
        Define wall velocity components?                       no
        X-Component of Wall Translation (m/s)                  0
        Y-Component of Wall Translation (m/s)                  0
        Z-Component of Wall Translation (m/s)                  0
        External Emissivity                                    1
        External Radiation Temperature (k)                     300
                                                               (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                 0
        X-Position of Rotation-Axis Origin (m)                 0
        Y-Position of Rotation-Axis Origin (m)                 0
        Z-Position of Rotation-Axis Origin (m)                 0
        X-Component of Rotation-Axis Direction                 0
        Y-Component of Rotation-Axis Direction                 0
        Z-Component of Rotation-Axis Direction                 1
        X-component of shear stress (pascal)                   0
        Y-component of shear stress (pascal)                   0
        Z-component of shear stress (pascal)                   0
        Surface tension gradient (n/m-k)                       0
        Specularity Coefficient                                0

     hot_valve_walls

        Condition                                              Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                     0
        Heat Generation Rate (w/m3)                            0
        Material Name                                          copper
        Thermal BC Type                                        0
        Temperature (k)                                        386.5
        Heat Flux (w/m2)                                       0
        Convective Heat Transfer Coefficient (w/m2-k)          0
        Free Stream Temperature (k)                            300
        Enable shell conduction?                               no
        Wall Motion                                            0
        Shear Boundary Condition                               0
        Define wall motion relative to adjacent cell zone?     yes
        Apply a rotational velocity to this wall?              no
        Velocity Magnitude (m/s)                               0
        X-Component of Wall Translation                        1
```

```
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     pebble_walls

        Condition                                           Value
        ------------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     0
        Temperature (k)                                     (profile
udf peb_wall_temp_BC)
        Heat Flux (w/m2)                                    8889.0596
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
```

```
      X-Position of Rotation-Axis Origin (m)              0
      Y-Position of Rotation-Axis Origin (m)              0
      Z-Position of Rotation-Axis Origin (m)              0
      X-Component of Rotation-Axis Direction              0
      Y-Component of Rotation-Axis Direction              0
      Z-Component of Rotation-Axis Direction              1
      X-component of shear stress (pascal)                0
      Y-component of shear stress (pascal)                0
      Z-component of shear stress (pascal)                0
      Surface tension gradient (n/m-k)                    0
      Specularity Coefficient                             0

   default-interior

      Condition   Value
      -----------------

   default-interior:001

      Condition   Value
      -----------------

   default-interior:024

      Condition   Value
      -----------------

   default-interior:026

      Condition   Value
      -----------------

   default-interior:027

      Condition   Value
      -----------------

   default-interior:028

      Condition   Value
      -----------------

   default-interior:029

      Condition   Value
      -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes
```

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.2
Max. Iterations Per Time Step	200

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.80000001
Body Forces	0.89999998
Momentum	0.40000001
he	1
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit

Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)

```
      -----------------------------------------------------------------
--------------
      Mixture Species                           names
((he n2) () ())
      Density                         kg/m3     ideal-gas
#f
      Cp (Specific Heat)              j/kg-k    mixing-law
#f
      Thermal Conductivity            w/m-k     ideal-gas-mixing-law
#f
      Viscosity                       kg/m-s    ideal-gas-mixing-law
#f
      Mass Diffusivity                m2/s      kinetic-theory
#f
      Thermal Diffusion Coefficient   kg/m-s    kinetic-theory
#f
      Thermal Expansion Coefficient   1/k       constant                 0
      Speed of Sound                  m/s       none
#f

   Material: (nitrogen . mixture-template) (fluid)

      Property                    Units      Method            Value(s)
      -----------------------------------------------------------------
      Cp (Specific Heat)          j/kg-k     kinetic-theory    #f
      Thermal Conductivity        w/m-k      kinetic-theory    #f
      Viscosity                   kg/m-s     kinetic-theory    #f
      Molecular Weight            kg/kgmol   constant          28.013399
      L-J Characteristic Length   angstrom   constant          3.7980001
      L-J Energy Parameter        k          constant          71.400002
      Degrees of Freedom                     constant          5
      Speed of Sound              m/s        none              #f

   Material: nitrogen (fluid)

      Property                        Units      Method      Value(s)
      -------------------------------------------------------------
      Density                         kg/m3      constant    1.138
      Cp (Specific Heat)              j/kg-k     constant    1040.67
      Thermal Conductivity            w/m-k      constant    0.0242
      Viscosity                       kg/m-s     constant    1.663e-05
      Molecular Weight                kg/kgmol   constant    28.0134
      L-J Characteristic Length       angstrom   constant    3.621
      L-J Energy Parameter            k          constant    97.53
      Thermal Expansion Coefficient   1/k        constant    0
      Degrees of Freedom                         constant    0
      Speed of Sound                  m/s        none        #f

   Material: oxygen (fluid)

      Property                        Units      Method      Value(s)
      -------------------------------------------------------------
      Density                         kg/m3      constant    1.2999
      Cp (Specific Heat)              j/kg-k     constant    919.31
      Thermal Conductivity            w/m-k      constant    0.0246
      Viscosity                       kg/m-s     constant    1.919e-05
      Molecular Weight                kg/kgmol   constant    31.9988
```

L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Full Heating Phase Transient FLUENT Case

```
FLUENT
Version: 3d, dp, pbns, lam, unsteady (3d, double precision, pressure-
based, laminar, unsteady)
Release: 6.3.26
Title:

Models
------
```

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Disabled
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type
cold_valve	2	fluid
cold_leg	3	fluid
crossover	4	fluid
hot_top	5	fluid
pebbles	6	fluid
hot_valve	7	fluid
cold_valve_walls	8	wall
outlet	9	wall
cold_leg_bot.	10	interior
cold_leg_walls	11	wall
cold_leg_top	12	interior
crossover_walls	13	wall
hot_top_exit	14	interior
pebble_exit	15	interior
hot_top_wall	16	wall
pebble__walls	17	wall
hot_valve_wall	18	wall
pebble_enter	19	interior
inlet	20	wall
default-interior	22	interior
default-interior:001	1	interior
default-interior:021	21	interior
default-interior:023	23	interior
default-interior:024	24	interior
default-interior:025	25	interior

Boundary Conditions

cold_valve

Condition
Value

```
---------------------------------------------------------------------------
---------
         Material Name
helium
         Specify source terms?                                       no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
         Specify fixed values?                                       no
         Local Coordinate System for Fixed Velocities                no
         Fixed Values                                                ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (temperature (inactive . #f) (constant . 0)
(profile  )))
         Motion Type                                                 0
         X-Velocity Of Zone (m/s)                                    0
         Y-Velocity Of Zone (m/s)                                    0
         Z-Velocity Of Zone (m/s)                                    0
         Rotation speed (rad/s)                                      0
         X-Origin of Rotation-Axis (m)                               0
         Y-Origin of Rotation-Axis (m)                               0
         Z-Origin of Rotation-Axis (m)                               0
         X-Component of Rotation-Axis                                0
         Y-Component of Rotation-Axis                                0
         Z-Component of Rotation-Axis                                1
         Deactivated Thread                                          no
         Porous zone?                                                no
         Conical porous zone?                                        no
         X-Component of Direction-1 Vector                           1
         Y-Component of Direction-1 Vector                           0
         Z-Component of Direction-1 Vector                           0
         X-Component of Direction-2 Vector                           0
         Y-Component of Direction-2 Vector                           1
         Z-Component of Direction-2 Vector                           0
         X-Component of Cone Axis Vector                             1
         Y-Component of Cone Axis Vector                             0
         Z-Component of Cone Axis Vector                             0
         X-Coordinate of Point on Cone Axis (m)                      1
         Y-Coordinate of Point on Cone Axis (m)                      0
         Z-Coordinate of Point on Cone Axis (m)                      0
         Half Angle of Cone Relative to its Axis (deg)               0
         Relative Velocity Resistance Formulation?                   yes
         Direction-1 Viscous Resistance (1/m2)                       0
         Direction-2 Viscous Resistance (1/m2)                       0
         Direction-3 Viscous Resistance (1/m2)                       0
         Choose alternative formulation for inertial resistance?    no
         Direction-1 Inertial Resistance (1/m)                       0
         Direction-2 Inertial Resistance (1/m)                       0
         Direction-3 Inertial Resistance (1/m)                       0
         C0 Coefficient for Power-Law                                0
         C1 Coefficient for Power-Law                                0
         Porosity                                                    1
         Solid Material Name
aluminum

      cold_leg
```

```
        Condition
Value
        -----------------------------------------------------------------
---------------------------------------------------------------------------
---------------------------------------------------------------------------
---------------------------------------------------------------------------
---------
        Material Name
helium
        Specify source terms?                                   no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
        Specify fixed values?                                   no
        Local Coordinate System for Fixed Velocities            no
        Fixed Values                                            ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (temperature (inactive . #f) (constant . 0)
(profile  )))
        Motion Type                                             0
        X-Velocity Of Zone (m/s)                                0
        Y-Velocity Of Zone (m/s)                                0
        Z-Velocity Of Zone (m/s)                                0
        Rotation speed (rad/s)                                  0
        X-Origin of Rotation-Axis (m)                           0
        Y-Origin of Rotation-Axis (m)                           0
        Z-Origin of Rotation-Axis (m)                           0
        X-Component of Rotation-Axis                            0
        Y-Component of Rotation-Axis                            0
        Z-Component of Rotation-Axis                            1
        Deactivated Thread                                      no
        Porous zone?                                            no
        Conical porous zone?                                    no
        X-Component of Direction-1 Vector                       1
        Y-Component of Direction-1 Vector                       0
        Z-Component of Direction-1 Vector                       0
        X-Component of Direction-2 Vector                       0
        Y-Component of Direction-2 Vector                       1
        Z-Component of Direction-2 Vector                       0
        X-Component of Cone Axis Vector                         1
        Y-Component of Cone Axis Vector                         0
        Z-Component of Cone Axis Vector                         0
        X-Coordinate of Point on Cone Axis (m)                  1
        Y-Coordinate of Point on Cone Axis (m)                  0
        Z-Coordinate of Point on Cone Axis (m)                  0
        Half Angle of Cone Relative to its Axis (deg)           0
        Relative Velocity Resistance Formulation?               yes
        Direction-1 Viscous Resistance (1/m2)                   0
        Direction-2 Viscous Resistance (1/m2)                   0
        Direction-3 Viscous Resistance (1/m2)                   0
        Choose alternative formulation for inertial resistance? no
        Direction-1 Inertial Resistance (1/m)                   0
        Direction-2 Inertial Resistance (1/m)                   0
        Direction-3 Inertial Resistance (1/m)                   0
        C0 Coefficient for Power-Law                            0
        C1 Coefficient for Power-Law                            0
        Porosity                                                1
```

Solid Material Name
aluminum

crossover

Condition
Value

Material Name
helium
Specify source terms? no
Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
Specify fixed values? no
Local Coordinate System for Fixed Velocities no
Fixed Values ((x-velocity (inactive . #f) (constant . 0) (profile)) (y-velocity (inactive . #f) (constant . 0) (profile)) (z-velocity (inactive . #f) (constant . 0) (profile)) (temperature (inactive . #f) (constant . 0) (profile)))

Motion Type	0
X-Velocity Of Zone (m/s)	0
Y-Velocity Of Zone (m/s)	0
Z-Velocity Of Zone (m/s)	0
Rotation speed (rad/s)	0
X-Origin of Rotation-Axis (m)	0
Y-Origin of Rotation-Axis (m)	0
Z-Origin of Rotation-Axis (m)	0
X-Component of Rotation-Axis	0
Y-Component of Rotation-Axis	0
Z-Component of Rotation-Axis	1
Deactivated Thread	no
Porous zone?	no
Conical porous zone?	no
X-Component of Direction-1 Vector	1
Y-Component of Direction-1 Vector	0
Z-Component of Direction-1 Vector	0
X-Component of Direction-2 Vector	0
Y-Component of Direction-2 Vector	1
Z-Component of Direction-2 Vector	0
X-Component of Cone Axis Vector	1
Y-Component of Cone Axis Vector	0
Z-Component of Cone Axis Vector	0
X-Coordinate of Point on Cone Axis (m)	1
Y-Coordinate of Point on Cone Axis (m)	0
Z-Coordinate of Point on Cone Axis (m)	0
Half Angle of Cone Relative to its Axis (deg)	0
Relative Velocity Resistance Formulation?	yes
Direction-1 Viscous Resistance (1/m2)	0
Direction-2 Viscous Resistance (1/m2)	0
Direction-3 Viscous Resistance (1/m2)	0
Choose alternative formulation for inertial resistance?	no
Direction-1 Inertial Resistance (1/m)	0

```
         Direction-2 Inertial Resistance (1/m)                         0
         Direction-3 Inertial Resistance (1/m)                         0
         C0 Coefficient for Power-Law                                  0
         C1 Coefficient for Power-Law                                  0
         Porosity                                                      1
         Solid Material Name
aluminum

      hot_top

         Condition
Value
         --------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
---------
         Material Name
helium
         Specify source terms?                                         no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
         Specify fixed values?                                         no
         Local Coordinate System for Fixed Velocities                  no
         Fixed Values                                                  ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (temperature (inactive . #f) (constant . 0)
(profile  )))
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
         Z-Component of Rotation-Axis                                  1
         Deactivated Thread                                            no
         Porous zone?                                                  no
         Conical porous zone?                                          no
         X-Component of Direction-1 Vector                             1
         Y-Component of Direction-1 Vector                             0
         Z-Component of Direction-1 Vector                             0
         X-Component of Direction-2 Vector                             0
         Y-Component of Direction-2 Vector                             1
         Z-Component of Direction-2 Vector                             0
         X-Component of Cone Axis Vector                               1
         Y-Component of Cone Axis Vector                               0
         Z-Component of Cone Axis Vector                               0
         X-Coordinate of Point on Cone Axis (m)                        1
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
         Relative Velocity Resistance Formulation?                     yes
```

```
        Direction-1 Viscous Resistance (1/m2)                    0
        Direction-2 Viscous Resistance (1/m2)                    0
        Direction-3 Viscous Resistance (1/m2)                    0
        Choose alternative formulation for inertial resistance?  no
        Direction-1 Inertial Resistance (1/m)                    0
        Direction-2 Inertial Resistance (1/m)                    0
        Direction-3 Inertial Resistance (1/m)                    0
        C0 Coefficient for Power-Law                             0
        C1 Coefficient for Power-Law                             0
        Porosity                                                 1
        Solid Material Name
aluminum

     pebbles

        Condition
Value
        ---------------------------------------------------------------
------------------------------------------------------------------------
------------------------------------------------------------------------
------------------------------------------------------------------------
---------
        Material Name
helium
        Specify source terms?                                     no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
        Specify fixed values?                                     no
        Local Coordinate System for Fixed Velocities              no
        Fixed Values                                              ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (temperature (inactive . #f) (constant . 0)
(profile  )))
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
        Y-Velocity Of Zone (m/s)                                  0
        Z-Velocity Of Zone (m/s)                                  0
        Rotation speed (rad/s)                                    0
        X-Origin of Rotation-Axis (m)                             0
        Y-Origin of Rotation-Axis (m)                             0
        Z-Origin of Rotation-Axis (m)                             0
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
        Deactivated Thread                                        no
        Porous zone?                                              yes
        Conical porous zone?                                      no
        X-Component of Direction-1 Vector                         1
        Y-Component of Direction-1 Vector                         0
        Z-Component of Direction-1 Vector                         0
        X-Component of Direction-2 Vector                         0
        Y-Component of Direction-2 Vector                         1
        Z-Component of Direction-2 Vector                         0
        X-Component of Cone Axis Vector                           1
        Y-Component of Cone Axis Vector                           0
        Z-Component of Cone Axis Vector                           0
```

```
        X-Coordinate of Point on Cone Axis (m)                        1
        Y-Coordinate of Point on Cone Axis (m)                        0
        Z-Coordinate of Point on Cone Axis (m)                        0
        Half Angle of Cone Relative to its Axis (deg)                 0
        Relative Velocity Resistance Formulation?                     yes
        Direction-1 Viscous Resistance (1/m2)
5860000
        Direction-2 Viscous Resistance (1/m2)
5860000
        Direction-3 Viscous Resistance (1/m2)
5860000
        Choose alternative formulation for inertial resistance?       no
        Direction-1 Inertial Resistance (1/m)                         2734
        Direction-2 Inertial Resistance (1/m)                         2734
        Direction-3 Inertial Resistance (1/m)                         2734
        C0 Coefficient for Power-Law                                  0
        C1 Coefficient for Power-Law                                  0
        Porosity
0.40000001
        Solid Material Name
glass

      hot_valve

        Condition
Value
        ---------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
---------
        Material Name
helium
        Specify source terms?                                         no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (energy))
        Specify fixed values?                                         no
        Local Coordinate System for Fixed Velocities                  no
        Fixed Values                                                  ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (temperature (inactive . #f) (constant . 0)
(profile  )))
        Motion Type                                                   0
        X-Velocity Of Zone (m/s)                                      0
        Y-Velocity Of Zone (m/s)                                      0
        Z-Velocity Of Zone (m/s)                                      0
        Rotation speed (rad/s)                                        0
        X-Origin of Rotation-Axis (m)                                 0
        Y-Origin of Rotation-Axis (m)                                 0
        Z-Origin of Rotation-Axis (m)                                 0
        X-Component of Rotation-Axis                                  0
        Y-Component of Rotation-Axis                                  0
        Z-Component of Rotation-Axis                                  1
        Deactivated Thread                                            no
        Porous zone?                                                  no
        Conical porous zone?                                          no
```

```
        X-Component of Direction-1 Vector                              1
        Y-Component of Direction-1 Vector                              0
        Z-Component of Direction-1 Vector                              0
        X-Component of Direction-2 Vector                              0
        Y-Component of Direction-2 Vector                              1
        Z-Component of Direction-2 Vector                              0
        X-Component of Cone Axis Vector                                1
        Y-Component of Cone Axis Vector                                0
        Z-Component of Cone Axis Vector                                0
        X-Coordinate of Point on Cone Axis (m)                         1
        Y-Coordinate of Point on Cone Axis (m)                         0
        Z-Coordinate of Point on Cone Axis (m)                         0
        Half Angle of Cone Relative to its Axis (deg)                  0
        Relative Velocity Resistance Formulation?                      yes
        Direction-1 Viscous Resistance (1/m2)                          0
        Direction-2 Viscous Resistance (1/m2)                          0
        Direction-3 Viscous Resistance (1/m2)                          0
        Choose alternative formulation for inertial resistance?        no
        Direction-1 Inertial Resistance (1/m)                          0
        Direction-2 Inertial Resistance (1/m)                          0
        Direction-3 Inertial Resistance (1/m)                          0
        C0 Coefficient for Power-Law                                   0
        C1 Coefficient for Power-Law                                   0
        Porosity                                                       1
        Solid Material Name
aluminum

     cold_valve_walls

        Condition                                                  Value
        -------------------------------------------------------------------
        Wall Thickness (m)                                         0
        Heat Generation Rate (w/m3)                                0
        Material Name                                              copper
        Thermal BC Type                                            0
        Temperature (k)                                            291.79999
        Heat Flux (w/m2)                                           0
        Convective Heat Transfer Coefficient (w/m2-k)              0
        Free Stream Temperature (k)                                300
        Enable shell conduction?                                   no
        Wall Motion                                                0
        Shear Boundary Condition                                   0
        Define wall motion relative to adjacent cell zone?         yes
        Apply a rotational velocity to this wall?                  no
        Velocity Magnitude (m/s)                                   0
        X-Component of Wall Translation                            1
        Y-Component of Wall Translation                            0
        Z-Component of Wall Translation                            0
        Define wall velocity components?                           no
        X-Component of Wall Translation (m/s)                      0
        Y-Component of Wall Translation (m/s)                      0
        Z-Component of Wall Translation (m/s)                      0
        External Emissivity                                        1
        External Radiation Temperature (k)                         300
        Rotation Speed (rad/s)                                     0
        X-Position of Rotation-Axis Origin (m)                     0
        Y-Position of Rotation-Axis Origin (m)                     0
```

Condition	Value
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

outlet

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

cold_leg_bot.

Condition	Value

cold_leg_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	0
Temperature (k)	283
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

cold_leg_top

Condition	Value

crossover_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0

Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

hot_top_exit

Condition	Value

pebble_exit

Condition	Value

hot_top_wall

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0

```
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

    pebble__walls

        Condition                                           Value
        ------------------------------------------------------------
---------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     0
        Temperature (k)                                     (profile
udf peb_wall_temp_BC)
        Heat Flux (w/m2)                                    15500
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
```

Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

hot_valve_wall

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	0
Temperature (k)	386.5
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

pebble_enter

Condition	Value

inlet

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1

Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

default-interior

```
Condition   Value
-----------------
```

default-interior:001

```
Condition   Value
-----------------
```

default-interior:021

```
Condition   Value
-----------------
```

default-interior:023

```
Condition   Value
-----------------
```

default-interior:024

```
Condition   Value
-----------------
```

default-interior:025

Condition	Value

Solver Controls

Equations

Equation	Solved
Flow	yes
Energy	yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.0099999998
Max. Iterations Per Time Step	200

Relaxation

Variable	Relaxation Factor
Pressure	0.40000001
Density	0.60000002
Body Forces	1
Momentum	0.60000002
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	PISO
Skewness-Neighbour Coupling	yes
Skewness Correction	1
Neighbour Correction	1

Discretization Scheme

Variable	Scheme
Pressure	PRESTO!
Density	First Order Upwind
Momentum	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)·	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Zero Operating Density FLUENT Case

FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type

```
barrel                    2     fluid
cold_leg                  3     fluid
cold_valve                4     fluid
cross-over_leg            5     fluid
hot_top                   6     fluid
hot_valve                 7     fluid
pebbles                   8     fluid
wall                      9     wall
outlet                    10    interior
cold_exit                 11    interior
cold_enter                12    interior
hot_exit                  13    interior
pebble_exit               14    interior
pebble_enter              15    interior
inlet                     16    interior
barrel_walls              17    wall
new_cold_valve            18    wall
cold_walls                19    wall
cross_over_walls          20    wall
hot_top_walls             21    wall
hot_valve_walls           22    wall
pebble_walls              23    wall
default-interior          25    interior
default-interior:001      1     interior
default-interior:024      24    interior
default-interior:026      26    interior
default-interior:027      27    interior
default-interior:028      28    interior
default-interior:029      29    interior
```

Boundary Conditions

barrel

```
         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                  no
         Source Terms                                           ()
         Specify fixed values?                                  no
         Local Coordinate System for Fixed Velocities           no
         Fixed Values                                           ()
         Motion Type                                            0
         X-Velocity Of Zone (m/s)                               0
         Y-Velocity Of Zone (m/s)                               0
         Z-Velocity Of Zone (m/s)                               0
         Rotation speed (rad/s)                                 0
         X-Origin of Rotation-Axis (m)                          0
         Y-Origin of Rotation-Axis (m)                          0
         Z-Origin of Rotation-Axis (m)                          0
         X-Component of Rotation-Axis                           0
         Y-Component of Rotation-Axis                           0
         Z-Component of Rotation-Axis                           1
         Deactivated Thread                                     no
```

```
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      cold_leg

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ()
        Motion Type                                                 0
        X-Velocity Of Zone (m/s)                                    0
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
```

```
         Y-Component of Direction-1 Vector                      0
         Z-Component of Direction-1 Vector                      0
         X-Component of Direction-2 Vector                      0
         Y-Component of Direction-2 Vector                      1
         Z-Component of Direction-2 Vector                      0
         X-Component of Cone Axis Vector                        1
         Y-Component of Cone Axis Vector                        0
         Z-Component of Cone Axis Vector                        0
         X-Coordinate of Point on Cone Axis (m)                 1
         Y-Coordinate of Point on Cone Axis (m)                 0
         Z-Coordinate of Point on Cone Axis (m)                 0
         Half Angle of Cone Relative to its Axis (deg)          0
         Relative Velocity Resistance Formulation?              yes
         Direction-1 Viscous Resistance (1/m2)                  0
         Direction-2 Viscous Resistance (1/m2)                  0
         Direction-3 Viscous Resistance (1/m2)                  0
         Choose alternative formulation for inertial resistance?  no
         Direction-1 Inertial Resistance (1/m)                  0
         Direction-2 Inertial Resistance (1/m)                  0
         Direction-3 Inertial Resistance (1/m)                  0
         C0 Coefficient for Power-Law                           0
         C1 Coefficient for Power-Law                           0
         Porosity                                               1
         Solid Material Name
aluminum

      cold_valve

         Condition
Value
         -------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                  no
         Source Terms                                           ()
         Specify fixed values?                                  no
         Local Coordinate System for Fixed Velocities           no
         Fixed Values                                           ()
         Motion Type                                            0
         X-Velocity Of Zone (m/s)                               0
         Y-Velocity Of Zone (m/s)                               0
         Z-Velocity Of Zone (m/s)                               0
         Rotation speed (rad/s)                                 0
         X-Origin of Rotation-Axis (m)                          0
         Y-Origin of Rotation-Axis (m)                          0
         Z-Origin of Rotation-Axis (m)                          0
         X-Component of Rotation-Axis                           0
         Y-Component of Rotation-Axis                           0
         Z-Component of Rotation-Axis                           1
         Deactivated Thread                                     no
         Porous zone?                                           no
         Conical porous zone?                                   no
         X-Component of Direction-1 Vector                      1
         Y-Component of Direction-1 Vector                      0
         Z-Component of Direction-1 Vector                      0
         X-Component of Direction-2 Vector                      0
```

```
        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
        X-Coordinate of Point on Cone Axis (m)                     1
        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  yes
        Direction-1 Viscous Resistance (1/m2)                      0
        Direction-2 Viscous Resistance (1/m2)                      0
        Direction-3 Viscous Resistance (1/m2)                      0
        Choose alternative formulation for inertial resistance?    no
        Direction-1 Inertial Resistance (1/m)                      0
        Direction-2 Inertial Resistance (1/m)                      0
        Direction-3 Inertial Resistance (1/m)                      0
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity                                                   1
        Solid Material Name
aluminum

     cross-over_leg

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                      no
        Source Terms                                               ()
        Specify fixed values?                                      no
        Local Coordinate System for Fixed Velocities               no
        Fixed Values                                               ()
        Motion Type                                                0
        X-Velocity Of Zone (m/s)                                   0
        Y-Velocity Of Zone (m/s)                                   0
        Z-Velocity Of Zone (m/s)                                   0
        Rotation speed (rad/s)                                     0
        X-Origin of Rotation-Axis (m)                              0
        Y-Origin of Rotation-Axis (m)                              0
        Z-Origin of Rotation-Axis (m)                              0
        X-Component of Rotation-Axis                               0
        Y-Component of Rotation-Axis                               0
        Z-Component of Rotation-Axis                               1
        Deactivated Thread                                         no
        Porous zone?                                               no
        Conical porous zone?                                       no
        X-Component of Direction-1 Vector                          1
        Y-Component of Direction-1 Vector                          0
        Z-Component of Direction-1 Vector                          0
        X-Component of Direction-2 Vector                          0
        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
```

```
          Y-Component of Cone Axis Vector                                  0
          Z-Component of Cone Axis Vector                                  0
          X-Coordinate of Point on Cone Axis (m)                           1
          Y-Coordinate of Point on Cone Axis (m)                           0
          Z-Coordinate of Point on Cone Axis (m)                           0
          Half Angle of Cone Relative to its Axis (deg)                    0
          Relative Velocity Resistance Formulation?                        yes
          Direction-1 Viscous Resistance (1/m2)                            0
          Direction-2 Viscous Resistance (1/m2)                            0
          Direction-3 Viscous Resistance (1/m2)                            0
          Choose alternative formulation for inertial resistance?          no
          Direction-1 Inertial Resistance (1/m)                            0
          Direction-2 Inertial Resistance (1/m)                            0
          Direction-3 Inertial Resistance (1/m)                            0
          C0 Coefficient for Power-Law                                     0
          C1 Coefficient for Power-Law                                     0
          Porosity                                                         1
          Solid Material Name
aluminum

      hot_top

          Condition
Value
          -----------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                            no
          Source Terms                                                     ()
          Specify fixed values?                                            no
          Local Coordinate System for Fixed Velocities                     no
          Fixed Values                                                     ()
          Motion Type                                                      0
          X-Velocity Of Zone (m/s)                                         0
          Y-Velocity Of Zone (m/s)                                         0
          Z-Velocity Of Zone (m/s)                                         0
          Rotation speed (rad/s)                                           0
          X-Origin of Rotation-Axis (m)                                    0
          Y-Origin of Rotation-Axis (m)                                    0
          Z-Origin of Rotation-Axis (m)                                    0
          X-Component of Rotation-Axis                                     0
          Y-Component of Rotation-Axis                                     0
          Z-Component of Rotation-Axis                                     1
          Deactivated Thread                                               no
          Porous zone?                                                     no
          Conical porous zone?                                             no
          X-Component of Direction-1 Vector                                1
          Y-Component of Direction-1 Vector                                0
          Z-Component of Direction-1 Vector                                0
          X-Component of Direction-2 Vector                                0
          Y-Component of Direction-2 Vector                                1
          Z-Component of Direction-2 Vector                                0
          X-Component of Cone Axis Vector                                  1
          Y-Component of Cone Axis Vector                                  0
          Z-Component of Cone Axis Vector                                  0
          X-Coordinate of Point on Cone Axis (m)                           1
```

```
          Y-Coordinate of Point on Cone Axis (m)                        0
          Z-Coordinate of Point on Cone Axis (m)                        0
          Half Angle of Cone Relative to its Axis (deg)                 0
          Relative Velocity Resistance Formulation?                     yes
          Direction-1 Viscous Resistance (1/m2)                         0
          Direction-2 Viscous Resistance (1/m2)                         0
          Direction-3 Viscous Resistance (1/m2)                         0
          Choose alternative formulation for inertial resistance?       no
          Direction-1 Inertial Resistance (1/m)                         0
          Direction-2 Inertial Resistance (1/m)                         0
          Direction-3 Inertial Resistance (1/m)                         0
          C0 Coefficient for Power-Law                                  0
          C1 Coefficient for Power-Law                                  0
          Porosity                                                      1
          Solid Material Name
aluminum

       hot_valve

          Condition
Value
          -------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                         no
          Source Terms                                                  ()
          Specify fixed values?                                         no
          Local Coordinate System for Fixed Velocities                  no
          Fixed Values                                                  ()
          Motion Type                                                   0
          X-Velocity Of Zone (m/s)                                      0
          Y-Velocity Of Zone (m/s)                                      0
          Z-Velocity Of Zone (m/s)                                      0
          Rotation speed (rad/s)                                        0
          X-Origin of Rotation-Axis (m)                                 0
          Y-Origin of Rotation-Axis (m)                                 0
          Z-Origin of Rotation-Axis (m)                                 0
          X-Component of Rotation-Axis                                  0
          Y-Component of Rotation-Axis                                  0
          Z-Component of Rotation-Axis                                  1
          Deactivated Thread                                            no
          Porous zone?                                                  no
          Conical porous zone?                                          no
          X-Component of Direction-1 Vector                             1
          Y-Component of Direction-1 Vector                             0
          Z-Component of Direction-1 Vector                             0
          X-Component of Direction-2 Vector                             0
          Y-Component of Direction-2 Vector                             1
          Z-Component of Direction-2 Vector                             0
          X-Component of Cone Axis Vector                               1
          Y-Component of Cone Axis Vector                               0
          Z-Component of Cone Axis Vector                               0
          X-Coordinate of Point on Cone Axis (m)                        1
          Y-Coordinate of Point on Cone Axis (m)                        0
          Z-Coordinate of Point on Cone Axis (m)                        0
          Half Angle of Cone Relative to its Axis (deg)                 0
```

```
         Relative Velocity Resistance Formulation?                  yes
         Direction-1 Viscous Resistance (1/m2)                      0
         Direction-2 Viscous Resistance (1/m2)                      0
         Direction-3 Viscous Resistance (1/m2)                      0
         Choose alternative formulation for inertial resistance?    no
         Direction-1 Inertial Resistance (1/m)                      0
         Direction-2 Inertial Resistance (1/m)                      0
         Direction-3 Inertial Resistance (1/m)                      0
         C0 Coefficient for Power-Law                               0
         C1 Coefficient for Power-Law                               0
         Porosity                                                   1
         Solid Material Name
aluminum

      pebbles

         Condition
Value
         -------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
---------------------------------------------------------------
         Material Name
mixture-template
         Specify source terms?                                      no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
         Specify fixed values?                                      no
         Local Coordinate System for Fixed Velocities               no
         Fixed Values                                               ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
         Motion Type                                                0
         X-Velocity Of Zone (m/s)                                   0
         Y-Velocity Of Zone (m/s)                                   0
         Z-Velocity Of Zone (m/s)                                   0
         Rotation speed (rad/s)                                     0
         X-Origin of Rotation-Axis (m)                              0
         Y-Origin of Rotation-Axis (m)                              0
         Z-Origin of Rotation-Axis (m)                              0
         X-Component of Rotation-Axis                               0
         Y-Component of Rotation-Axis                               0
         Z-Component of Rotation-Axis                               1
         Deactivated Thread                                         no
         Porous zone?                                               yes
         Conical porous zone?                                       no
         X-Component of Direction-1 Vector                          1
         Y-Component of Direction-1 Vector                          0
         Z-Component of Direction-1 Vector                          0
         X-Component of Direction-2 Vector                          0
         Y-Component of Direction-2 Vector                          1
         Z-Component of Direction-2 Vector                          0
         X-Component of Cone Axis Vector                            1
         Y-Component of Cone Axis Vector                            0
```

```
        Z-Component of Cone Axis Vector                                0
        X-Coordinate of Point on Cone Axis (m)                         1
        Y-Coordinate of Point on Cone Axis (m)                         0
        Z-Coordinate of Point on Cone Axis (m)                         0
        Half Angle of Cone Relative to its Axis (deg)                  0
        Relative Velocity Resistance Formulation?                      no
        Direction-1 Viscous Resistance (1/m2)
5860000
        Direction-2 Viscous Resistance (1/m2)
5860000
        Direction-3 Viscous Resistance (1/m2)
5860000
        Choose alternative formulation for inertial resistance?        no
        Direction-1 Inertial Resistance (1/m)                          2734
        Direction-2 Inertial Resistance (1/m)                          2734
        Direction-3 Inertial Resistance (1/m)                          2734
        C0 Coefficient for Power-Law                                   0
        C1 Coefficient for Power-Law                                   0
        Porosity
0.40000001
        Solid Material Name
glass

      wall

        Condition                                                 Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                        0
        Heat Generation Rate (w/m3)                               0
        Material Name                                             copper
        Thermal BC Type                                           1
        Temperature (k)                                           300
        Heat Flux (w/m2)                                          0
        Convective Heat Transfer Coefficient (w/m2-k)             0
        Free Stream Temperature (k)                               300
        Enable shell conduction?                                  no
        Wall Motion                                               0
        Shear Boundary Condition                                  0
        Define wall motion relative to adjacent cell zone?        yes
        Apply a rotational velocity to this wall?                 no
        Velocity Magnitude (m/s)                                  0
        X-Component of Wall Translation                           1
        Y-Component of Wall Translation                           0
        Z-Component of Wall Translation                           0
        Define wall velocity components?                          no
        X-Component of Wall Translation (m/s)                     0
        Y-Component of Wall Translation (m/s)                     0
        Z-Component of Wall Translation (m/s)                     0
        External Emissivity                                       1
        External Radiation Temperature (k)                        300
                                                                  (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                    0
        X-Position of Rotation-Axis Origin (m)                    0
        Y-Position of Rotation-Axis Origin (m)                    0
```

Condition	Value
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

outlet

Condition	Value

cold_exit

Condition	Value

cold_enter

Condition	Value

hot_exit

Condition	Value

pebble_exit

Condition	Value

pebble_enter

Condition	Value

inlet

Condition	Value

barrel_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	aluminum
Thermal BC Type	0
Temperature (k)	293
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0

```
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                               0
        X-Position of Rotation-Axis Origin (m)               0
        Y-Position of Rotation-Axis Origin (m)               0
        Z-Position of Rotation-Axis Origin (m)               0
        X-Component of Rotation-Axis Direction               0
        Y-Component of Rotation-Axis Direction               0
        Z-Component of Rotation-Axis Direction               1
        X-component of shear stress (pascal)                 0
        Y-component of shear stress (pascal)                 0
        Z-component of shear stress (pascal)                 0
        Surface tension gradient (n/m-k)                     0
        Specularity Coefficient                              0

     new_cold_valve

        Condition                                            Value
        ------------------------------------------------------------
--------------------
        Wall Thickness (m)                                   0
        Heat Generation Rate (w/m3)                          0
        Material Name                                        copper
        Thermal BC Type                                      1
        Temperature (k)                                      300
        Heat Flux (w/m2)                                     0
        Convective Heat Transfer Coefficient (w/m2-k)        0
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
```

```
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                               0
        X-Position of Rotation-Axis Origin (m)               0
        Y-Position of Rotation-Axis Origin (m)               0
        Z-Position of Rotation-Axis Origin (m)               0
        X-Component of Rotation-Axis Direction               0
        Y-Component of Rotation-Axis Direction               0
        Z-Component of Rotation-Axis Direction               1
        X-component of shear stress (pascal)                 0
        Y-component of shear stress (pascal)                 0
        Z-component of shear stress (pascal)                 0
        Surface tension gradient (n/m-k)                     0
        Specularity Coefficient                              0

    cold_walls

        Condition                                            Value
        ----------------------------------------------------------------
--------------------
        Wall Thickness (m)                                   0
        Heat Generation Rate (w/m3)                          0
        Material Name                                        copper
        Thermal BC Type                                      0
        Temperature (k)                                      283
        Heat Flux (w/m2)                                     0
        Convective Heat Transfer Coefficient (w/m2-k)        0
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                               0
        X-Position of Rotation-Axis Origin (m)               0
        Y-Position of Rotation-Axis Origin (m)               0
        Z-Position of Rotation-Axis Origin (m)               0
        X-Component of Rotation-Axis Direction               0
        Y-Component of Rotation-Axis Direction               0
        Z-Component of Rotation-Axis Direction               1
```

```
         X-component of shear stress (pascal)                 0
         Y-component of shear stress (pascal)                 0
         Z-component of shear stress (pascal)                 0
         Surface tension gradient (n/m-k)                     0
         Specularity Coefficient                              0

      cross_over_walls

         Condition                                            Value
         -------------------------------------------------------------
---------------------
         Wall Thickness (m)                                   0
         Heat Generation Rate (w/m3)                          0
         Material Name                                        copper
         Thermal BC Type                                      1
         Temperature (k)                                      300
         Heat Flux (w/m2)                                     0
         Convective Heat Transfer Coefficient (w/m2-k)        0
         Free Stream Temperature (k)                          300
         Enable shell conduction?                             no
         Wall Motion                                          0
         Shear Boundary Condition                             0
         Define wall motion relative to adjacent cell zone?   yes
         Apply a rotational velocity to this wall?            no
         Velocity Magnitude (m/s)                             0
         X-Component of Wall Translation                      1
         Y-Component of Wall Translation                      0
         Z-Component of Wall Translation                      0
         Define wall velocity components?                     no
         X-Component of Wall Translation (m/s)                0
         Y-Component of Wall Translation (m/s)                0
         Z-Component of Wall Translation (m/s)                0
         External Emissivity                                  1
         External Radiation Temperature (k)                   300
                                                              (0)

(((constant . 0) (profile  )))
         Rotation Speed (rad/s)                               0
         X-Position of Rotation-Axis Origin (m)               0
         Y-Position of Rotation-Axis Origin (m)               0
         Z-Position of Rotation-Axis Origin (m)               0
         X-Component of Rotation-Axis Direction               0
         Y-Component of Rotation-Axis Direction               0
         Z-Component of Rotation-Axis Direction               1
         X-component of shear stress (pascal)                 0
         Y-component of shear stress (pascal)                 0
         Z-component of shear stress (pascal)                 0
         Surface tension gradient (n/m-k)                     0
         Specularity Coefficient                              0

      hot_top_walls

         Condition                                            Value
         -------------------------------------------------------------
---------------------
         Wall Thickness (m)                                   0
         Heat Generation Rate (w/m3)                          0
```

```
         Material Name                                          copper
         Thermal BC Type                                        1
         Temperature (k)                                        473
         Heat Flux (w/m2)                                       0
         Convective Heat Transfer Coefficient (w/m2-k)          0
         Free Stream Temperature (k)                            300
         Enable shell conduction?                               no
         Wall Motion                                            0
         Shear Boundary Condition                               0
         Define wall motion relative to adjacent cell zone?     yes
         Apply a rotational velocity to this wall?              no
         Velocity Magnitude (m/s)                               0
         X-Component of Wall Translation                        1
         Y-Component of Wall Translation                        0
         Z-Component of Wall Translation                        0
         Define wall velocity components?                       no
         X-Component of Wall Translation (m/s)                  0
         Y-Component of Wall Translation (m/s)                  0
         Z-Component of Wall Translation (m/s)                  0
         External Emissivity                                    1
         External Radiation Temperature (k)                     300
                                                                (0)

(((constant . 0) (profile  )))
         Rotation Speed (rad/s)                                 0
         X-Position of Rotation-Axis Origin (m)                 0
         Y-Position of Rotation-Axis Origin (m)                 0
         Z-Position of Rotation-Axis Origin (m)                 0
         X-Component of Rotation-Axis Direction                 0
         Y-Component of Rotation-Axis Direction                 0
         Z-Component of Rotation-Axis Direction                 1
         X-component of shear stress (pascal)                   0
         Y-component of shear stress (pascal)                   0
         Z-component of shear stress (pascal)                   0
         Surface tension gradient (n/m-k)                       0
         Specularity Coefficient                                0

      hot_valve_walls

         Condition                                              Value
         ---------------------------------------------------------------
---------------------
         Wall Thickness (m)                                     0
         Heat Generation Rate (w/m3)                            0
         Material Name                                          copper
         Thermal BC Type                                        1
         Temperature (k)                                        300
         Heat Flux (w/m2)                                       0
         Convective Heat Transfer Coefficient (w/m2-k)          0
         Free Stream Temperature (k)                            300
         Enable shell conduction?                               no
         Wall Motion                                            0
         Shear Boundary Condition                               0
         Define wall motion relative to adjacent cell zone?     yes
         Apply a rotational velocity to this wall?              no
         Velocity Magnitude (m/s)                               0
         X-Component of Wall Translation                        1
```

```
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

     pebble_walls

        Condition                                               Value
        --------------------------------------------------------------
--------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         0
        Temperature (k)                                         (profile
udf peb_wall_temp_BC)
        Heat Flux (w/m2)                                        8889.0596
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
```

```
      X-Position of Rotation-Axis Origin (m)                0
      Y-Position of Rotation-Axis Origin (m)                0
      Z-Position of Rotation-Axis Origin (m)                0
      X-Component of Rotation-Axis Direction                0
      Y-Component of Rotation-Axis Direction                0
      Z-Component of Rotation-Axis Direction                1
      X-component of shear stress (pascal)                  0
      Y-component of shear stress (pascal)                  0
      Z-component of shear stress (pascal)                  0
      Surface tension gradient (n/m-k)                      0
      Specularity Coefficient                               0

   default-interior

      Condition   Value
      -----------------

   default-interior:001

      Condition   Value
      -----------------

   default-interior:024

      Condition   Value
      -----------------

   default-interior:026

      Condition   Value
      -----------------

   default-interior:027

      Condition   Value
      -----------------

   default-interior:028

      Condition   Value
      -----------------

   default-interior:029

      Condition   Value
      -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes
```

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.1
Max. Iterations Per Time Step	200

Relaxation

Variable	Relaxation Factor
Pressure	0.30000001
Density	1
Body Forces	1
Momentum	0.69999999
he	1
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit

Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property Units Method
Value(s)

```
     ------------------------------------------------------------------
--------------
     Mixture Species                                names
((he n2) () ())
     Density                             kg/m3     ideal-gas
#f
     Cp (Specific Heat)                  j/kg-k    mixing-law
#f
     Thermal Conductivity                w/m-k     ideal-gas-mixing-law
#f
     Viscosity                           kg/m-s    ideal-gas-mixing-law
#f
     Mass Diffusivity                    m2/s      kinetic-theory
#f
     Thermal Diffusion Coefficient       kg/m-s    kinetic-theory
#f
     Thermal Expansion Coefficient       1/k       constant               0
     Speed of Sound                      m/s       none
#f
```

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988

L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

85% Helium Initial FLUENT Case

FLUENT
Version: 3d, dp, pbns, spe, lam, unsteady (3d, double precision, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type
barrel	2	fluid
cold_leg	3	fluid
cold_valve	4	fluid
cross-over_leg	5	fluid
hot_top	6	fluid
hot_valve	7	fluid
pebbles	8	fluid
wall	9	wall
outlet	10	interior
cold_exit	11	interior
cold_enter	12	interior
hot_exit	13	interior
pebble_exit	14	interior
pebble_enter	15	interior
inlet	16	interior
barrel_walls	17	wall
new_cold_valve	18	wall
cold_walls	19	wall
cross_over_walls	20	wall
hot_top_walls	21	wall
hot_valve_walls	22	wall
pebble_walls	23	wall
default-interior	25	interior
default-interior:001	1	interior
default-interior:024	24	interior
default-interior:026	26	interior
default-interior:027	27	interior
default-interior:028	28	interior
default-interior:029	29	interior

Boundary Conditions

barrel

Condition

Value

```
        ------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                      no
        Source Terms                                               ()
        Specify fixed values?                                      no
        Local Coordinate System for Fixed Velocities               no
        Fixed Values                                               ()
        Motion Type                                                0
        X-Velocity Of Zone (m/s)                                   0
        Y-Velocity Of Zone (m/s)                                   0
        Z-Velocity Of Zone (m/s)                                   0
        Rotation speed (rad/s)                                     0
        X-Origin of Rotation-Axis (m)                              0
        Y-Origin of Rotation-Axis (m)                              0
        Z-Origin of Rotation-Axis (m)                              0
        X-Component of Rotation-Axis                               0
        Y-Component of Rotation-Axis                               0
        Z-Component of Rotation-Axis                               1
        Deactivated Thread                                         no
        Porous zone?                                               no
        Conical porous zone?                                       no
        X-Component of Direction-1 Vector                          1
        Y-Component of Direction-1 Vector                          0
        Z-Component of Direction-1 Vector                          0
        X-Component of Direction-2 Vector                          0
        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
        X-Coordinate of Point on Cone Axis (m)                     1
        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  yes
        Direction-1 Viscous Resistance (1/m2)                      0
        Direction-2 Viscous Resistance (1/m2)                      0
        Direction-3 Viscous Resistance (1/m2)                      0
        Choose alternative formulation for inertial resistance?    no
        Direction-1 Inertial Resistance (1/m)                      0
        Direction-2 Inertial Resistance (1/m)                      0
        Direction-3 Inertial Resistance (1/m)                      0
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity                                                   1
        Solid Material Name
aluminum

     cold_leg

        Condition
Value
        ------------------------------------------------------------
------------
```

```
          Material Name
mixture-template
          Specify source terms?                                  no
          Source Terms                                           ()
          Specify fixed values?                                  no
          Local Coordinate System for Fixed Velocities           no
          Fixed Values                                           ()
          Motion Type                                            0
          X-Velocity Of Zone (m/s)                               0
          Y-Velocity Of Zone (m/s)                               0
          Z-Velocity Of Zone (m/s)                               0
          Rotation speed (rad/s)                                 0
          X-Origin of Rotation-Axis (m)                          0
          Y-Origin of Rotation-Axis (m)                          0
          Z-Origin of Rotation-Axis (m)                          0
          X-Component of Rotation-Axis                           0
          Y-Component of Rotation-Axis                           0
          Z-Component of Rotation-Axis                           1
          Deactivated Thread                                     no
          Porous zone?                                           no
          Conical porous zone?                                   no
          X-Component of Direction-1 Vector                      1
          Y-Component of Direction-1 Vector                      0
          Z-Component of Direction-1 Vector                      0
          X-Component of Direction-2 Vector                      0
          Y-Component of Direction-2 Vector                      1
          Z-Component of Direction-2 Vector                      0
          X-Component of Cone Axis Vector                        1
          Y-Component of Cone Axis Vector                        0
          Z-Component of Cone Axis Vector                        0
          X-Coordinate of Point on Cone Axis (m)                 1
          Y-Coordinate of Point on Cone Axis (m)                 0
          Z-Coordinate of Point on Cone Axis (m)                 0
          Half Angle of Cone Relative to its Axis (deg)          0
          Relative Velocity Resistance Formulation?              yes
          Direction-1 Viscous Resistance (1/m2)                  0
          Direction-2 Viscous Resistance (1/m2)                  0
          Direction-3 Viscous Resistance (1/m2)                  0
          Choose alternative formulation for inertial resistance?  no
          Direction-1 Inertial Resistance (1/m)                  0
          Direction-2 Inertial Resistance (1/m)                  0
          Direction-3 Inertial Resistance (1/m)                  0
          C0 Coefficient for Power-Law                           0
          C1 Coefficient for Power-Law                           0
          Porosity                                               1
          Solid Material Name
aluminum

      cold_valve

          Condition
Value
          --------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                  no
```

```
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
        Fixed Values                                                ()
        Motion Type                                                 0
        X-Velocity Of Zone (m/s)                                    0
        Y-Velocity Of Zone (m/s)                                    0
        Z-Velocity Of Zone (m/s)                                    0
        Rotation speed (rad/s)                                      0
        X-Origin of Rotation-Axis (m)                               0
        Y-Origin of Rotation-Axis (m)                               0
        Z-Origin of Rotation-Axis (m)                               0
        X-Component of Rotation-Axis                                0
        Y-Component of Rotation-Axis                                0
        Z-Component of Rotation-Axis                                1
        Deactivated Thread                                          no
        Porous zone?                                                no
        Conical porous zone?                                        no
        X-Component of Direction-1 Vector                           1
        Y-Component of Direction-1 Vector                           0
        Z-Component of Direction-1 Vector                           0
        X-Component of Direction-2 Vector                           0
        Y-Component of Direction-2 Vector                           1
        Z-Component of Direction-2 Vector                           0
        X-Component of Cone Axis Vector                             1
        Y-Component of Cone Axis Vector                             0
        Z-Component of Cone Axis Vector                             0
        X-Coordinate of Point on Cone Axis (m)                      1
        Y-Coordinate of Point on Cone Axis (m)                      0
        Z-Coordinate of Point on Cone Axis (m)                      0
        Half Angle of Cone Relative to its Axis (deg)               0
        Relative Velocity Resistance Formulation?                   yes
        Direction-1 Viscous Resistance (1/m2)                       0
        Direction-2 Viscous Resistance (1/m2)                       0
        Direction-3 Viscous Resistance (1/m2)                       0
        Choose alternative formulation for inertial resistance?     no
        Direction-1 Inertial Resistance (1/m)                       0
        Direction-2 Inertial Resistance (1/m)                       0
        Direction-3 Inertial Resistance (1/m)                       0
        C0 Coefficient for Power-Law                                0
        C1 Coefficient for Power-Law                                0
        Porosity                                                    1
        Solid Material Name
aluminum

      cross-over_leg

        Condition
Value
        ---------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                       no
        Source Terms                                                ()
        Specify fixed values?                                       no
        Local Coordinate System for Fixed Velocities                no
```

```
        Fixed Values                                              ()
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
        Y-Velocity Of Zone (m/s)                                  0
        Z-Velocity Of Zone (m/s)                                  0
        Rotation speed (rad/s)                                    0
        X-Origin of Rotation-Axis (m)                             0
        Y-Origin of Rotation-Axis (m)                             0
        Z-Origin of Rotation-Axis (m)                             0
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
        Deactivated Thread                                        no
        Porous zone?                                              no
        Conical porous zone?                                      no
        X-Component of Direction-1 Vector                         1
        Y-Component of Direction-1 Vector                         0
        Z-Component of Direction-1 Vector                         0
        X-Component of Direction-2 Vector                         0
        Y-Component of Direction-2 Vector                         1
        Z-Component of Direction-2 Vector                         0
        X-Component of Cone Axis Vector                           1
        Y-Component of Cone Axis Vector                           0
        Z-Component of Cone Axis Vector                           0
        X-Coordinate of Point on Cone Axis (m)                    1
        Y-Coordinate of Point on Cone Axis (m)                    0
        Z-Coordinate of Point on Cone Axis (m)                    0
        Half Angle of Cone Relative to its Axis (deg)             0
        Relative Velocity Resistance Formulation?                 yes
        Direction-1 Viscous Resistance (1/m2)                     0
        Direction-2 Viscous Resistance (1/m2)                     0
        Direction-3 Viscous Resistance (1/m2)                     0
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                     0
        Direction-2 Inertial Resistance (1/m)                     0
        Direction-3 Inertial Resistance (1/m)                     0
        C0 Coefficient for Power-Law                              0
        C1 Coefficient for Power-Law                              0
        Porosity                                                  1
        Solid Material Name
aluminum

      hot_top

        Condition
Value
        ---------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                     no
        Source Terms                                              ()
        Specify fixed values?                                     no
        Local Coordinate System for Fixed Velocities              no
        Fixed Values                                              ()
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
```

```
        Y-Velocity Of Zone (m/s)                                   0
        Z-Velocity Of Zone (m/s)                                   0
        Rotation speed (rad/s)                                     0
        X-Origin of Rotation-Axis (m)                              0
        Y-Origin of Rotation-Axis (m)                              0
        Z-Origin of Rotation-Axis (m)                              0
        X-Component of Rotation-Axis                               0
        Y-Component of Rotation-Axis                               0
        Z-Component of Rotation-Axis                               1
        Deactivated Thread                                         no
        Porous zone?                                               no
        Conical porous zone?                                       no
        X-Component of Direction-1 Vector                          1
        Y-Component of Direction-1 Vector                          0
        Z-Component of Direction-1 Vector                          0
        X-Component of Direction-2 Vector                          0
        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
        X-Coordinate of Point on Cone Axis (m)                     1
        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  yes
        Direction-1 Viscous Resistance (1/m2)                      0
        Direction-2 Viscous Resistance (1/m2)                      0
        Direction-3 Viscous Resistance (1/m2)                      0
        Choose alternative formulation for inertial resistance?    no
        Direction-1 Inertial Resistance (1/m)                      0
        Direction-2 Inertial Resistance (1/m)                      0
        Direction-3 Inertial Resistance (1/m)                      0
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity                                                   1
        Solid Material Name
aluminum

     hot_valve

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                      no
        Source Terms                                               ()
        Specify fixed values?                                      no
        Local Coordinate System for Fixed Velocities               no
        Fixed Values                                               ()
        Motion Type                                                0
        X-Velocity Of Zone (m/s)                                   0
        Y-Velocity Of Zone (m/s)                                   0
        Z-Velocity Of Zone (m/s)                                   0
        Rotation speed (rad/s)                                     0
```

```
         X-Origin of Rotation-Axis (m)                                  0
         Y-Origin of Rotation-Axis (m)                                  0
         Z-Origin of Rotation-Axis (m)                                  0
         X-Component of Rotation-Axis                                   0
         Y-Component of Rotation-Axis                                   0
         Z-Component of Rotation-Axis                                   1
         Deactivated Thread                                             no
         Porous zone?                                                   no
         Conical porous zone?                                           no
         X-Component of Direction-1 Vector                              1
         Y-Component of Direction-1 Vector                              0
         Z-Component of Direction-1 Vector                              0
         X-Component of Direction-2 Vector                              0
         Y-Component of Direction-2 Vector                              1
         Z-Component of Direction-2 Vector                              0
         X-Component of Cone Axis Vector                                1
         Y-Component of Cone Axis Vector                                0
         Z-Component of Cone Axis Vector                                0
         X-Coordinate of Point on Cone Axis (m)                         1
         Y-Coordinate of Point on Cone Axis (m)                         0
         Z-Coordinate of Point on Cone Axis (m)                         0
         Half Angle of Cone Relative to its Axis (deg)                  0
         Relative Velocity Resistance Formulation?                      yes
         Direction-1 Viscous Resistance (1/m2)                          0
         Direction-2 Viscous Resistance (1/m2)                          0
         Direction-3 Viscous Resistance (1/m2)                          0
         Choose alternative formulation for inertial resistance?        no
         Direction-1 Inertial Resistance (1/m)                          0
         Direction-2 Inertial Resistance (1/m)                          0
         Direction-3 Inertial Resistance (1/m)                          0
         C0 Coefficient for Power-Law                                   0
         C1 Coefficient for Power-Law                                   0
         Porosity                                                       1
         Solid Material Name
aluminum

      pebbles

         Condition
Value
         ---------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
----------------------------------------------------------------

         Material Name
mixture-template
         Specify source terms?                                          no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
         Specify fixed values?                                          no
         Local Coordinate System for Fixed Velocities                   no
         Fixed Values                                                   ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
```

```
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 yes
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    no
        Direction-1 Viscous Resistance (1/m2)
5860000
        Direction-2 Viscous Resistance (1/m2)
5860000
        Direction-3 Viscous Resistance (1/m2)
5860000
        Choose alternative formulation for inertial resistance?      no
        Direction-1 Inertial Resistance (1/m)                        2734
        Direction-2 Inertial Resistance (1/m)                        2734
        Direction-3 Inertial Resistance (1/m)                        2734
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity
0.40000001
        Solid Material Name
glass

     wall

        Condition                                               Value
        -----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         1
        Temperature (k)                                         300
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
```

```
          Free Stream Temperature (k)                             300
          Enable shell conduction?                                no
          Wall Motion                                             0
          Shear Boundary Condition                                0
          Define wall motion relative to adjacent cell zone?      yes
          Apply a rotational velocity to this wall?               no
          Velocity Magnitude (m/s)                                0
          X-Component of Wall Translation                         1
          Y-Component of Wall Translation                         0
          Z-Component of Wall Translation                         0
          Define wall velocity components?                        no
          X-Component of Wall Translation (m/s)                   0
          Y-Component of Wall Translation (m/s)                   0
          Z-Component of Wall Translation (m/s)                   0
          External Emissivity                                     1
          External Radiation Temperature (k)                      300
                                                                  (0)

(((constant . 0) (profile  )))
          Rotation Speed (rad/s)                                  0
          X-Position of Rotation-Axis Origin (m)                  0
          Y-Position of Rotation-Axis Origin (m)                  0
          Z-Position of Rotation-Axis Origin (m)                  0
          X-Component of Rotation-Axis Direction                  0
          Y-Component of Rotation-Axis Direction                  0
          Z-Component of Rotation-Axis Direction                  1
          X-component of shear stress (pascal)                    0
          Y-component of shear stress (pascal)                    0
          Z-component of shear stress (pascal)                    0
          Surface tension gradient (n/m-k)                        0
          Specularity Coefficient                                 0

       outlet

          Condition   Value
          -----------------

       cold_exit

          Condition   Value
          -----------------

       cold_enter

          Condition   Value
          -----------------

       hot_exit

          Condition   Value
          -----------------

       pebble_exit

          Condition   Value
          -----------------
```

```
pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                              Value
   -----------------------------------------------------------------
---------------------
   Wall Thickness (m)                                     0
   Heat Generation Rate (w/m3)                            0
   Material Name                                          aluminum
   Thermal BC Type                                        0
   Temperature (k)                                        293
   Heat Flux (w/m2)                                       0
   Convective Heat Transfer Coefficient (w/m2-k)          0
   Free Stream Temperature (k)                            300
   Enable shell conduction?                               no
   Wall Motion                                            0
   Shear Boundary Condition                               0
   Define wall motion relative to adjacent cell zone?     yes
   Apply a rotational velocity to this wall?              no
   Velocity Magnitude (m/s)                               0
   X-Component of Wall Translation                        1
   Y-Component of Wall Translation                        0
   Z-Component of Wall Translation                        0
   Define wall velocity components?                       no
   X-Component of Wall Translation (m/s)                  0
   Y-Component of Wall Translation (m/s)                  0
   Z-Component of Wall Translation (m/s)                  0
   External Emissivity                                    1
   External Radiation Temperature (k)                     300
                                                          (0)

(((constant . 0) (profile  )))
   Rotation Speed (rad/s)                                 0
   X-Position of Rotation-Axis Origin (m)                 0
   Y-Position of Rotation-Axis Origin (m)                 0
   Z-Position of Rotation-Axis Origin (m)                 0
   X-Component of Rotation-Axis Direction                 0
   Y-Component of Rotation-Axis Direction                 0
   Z-Component of Rotation-Axis Direction                 1
   X-component of shear stress (pascal)                   0
   Y-component of shear stress (pascal)                   0
   Z-component of shear stress (pascal)                   0
   Surface tension gradient (n/m-k)                       0
   Specularity Coefficient                                0

new_cold_valve

   Condition                                              Value
```

```
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

     cold_walls

        Condition                                             Value
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       0
        Temperature (k)                                       283
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
```

```
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                               0
        X-Position of Rotation-Axis Origin (m)               0
        Y-Position of Rotation-Axis Origin (m)               0
        Z-Position of Rotation-Axis Origin (m)               0
        X-Component of Rotation-Axis Direction               0
        Y-Component of Rotation-Axis Direction               0
        Z-Component of Rotation-Axis Direction               1
        X-component of shear stress (pascal)                 0
        Y-component of shear stress (pascal)                 0
        Z-component of shear stress (pascal)                 0
        Surface tension gradient (n/m-k)                     0
        Specularity Coefficient                              0

     cross_over_walls

        Condition                                            Value
        -------------------------------------------------------------
---------------------
        Wall Thickness (m)                                   0
        Heat Generation Rate (w/m3)                          0
        Material Name                                        copper
        Thermal BC Type                                      1
        Temperature (k)                                      300
        Heat Flux (w/m2)                                     0
        Convective Heat Transfer Coefficient (w/m2-k)        0
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)
```

```
(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

     hot_top_walls

        Condition                                             Value
        -----------------------------------------------------------------
---------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       0
        Temperature (k)                                       473
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
```

```
        Specularity Coefficient                          0

     hot_valve_walls

        Condition                                        Value
        -----------------------------------------------------------------
--------------------
        Wall Thickness (m)                               0
        Heat Generation Rate (w/m3)                      0
        Material Name                                    copper
        Thermal BC Type                                  1
        Temperature (k)                                  300
        Heat Flux (w/m2)                                 0
        Convective Heat Transfer Coefficient (w/m2-k)    0
        Free Stream Temperature (k)                      300
        Enable shell conduction?                         no
        Wall Motion                                      0
        Shear Boundary Condition                         0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?        no
        Velocity Magnitude (m/s)                         0
        X-Component of Wall Translation                  1
        Y-Component of Wall Translation                  0
        Z-Component of Wall Translation                  0
        Define wall velocity components?                 no
        X-Component of Wall Translation (m/s)            0
        Y-Component of Wall Translation (m/s)            0
        Z-Component of Wall Translation (m/s)            0
        External Emissivity                              1
        External Radiation Temperature (k)               300
                                                         (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                           0
        X-Position of Rotation-Axis Origin (m)           0
        Y-Position of Rotation-Axis Origin (m)           0
        Z-Position of Rotation-Axis Origin (m)           0
        X-Component of Rotation-Axis Direction           0
        Y-Component of Rotation-Axis Direction           0
        Z-Component of Rotation-Axis Direction           1
        X-component of shear stress (pascal)             0
        Y-component of shear stress (pascal)             0
        Z-component of shear stress (pascal)             0
        Surface tension gradient (n/m-k)                 0
        Specularity Coefficient                          0

     pebble_walls

        Condition                                        Value
        -----------------------------------------------------------------
--------------------
        Wall Thickness (m)                               0
        Heat Generation Rate (w/m3)                      0
        Material Name                                    copper
        Thermal BC Type                                  0
        Temperature (k)                                  473
        Heat Flux (w/m2)                                 0
```

Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

default-interior

Condition	Value

default-interior:001

Condition	Value

default-interior:024

Condition	Value

default-interior:026

Condition	Value

default-interior:027

Condition	Value

default-interior:028

Condition	Value

default-interior:029

Condition	Value

Solver Controls

Equations

Equation	Solved
Flow	yes
he	yes
Energy	yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Unsteady Calculation Parameters

Time Step (s)	0.2
Max. Iterations Per Time Step	200

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.69999999
Body Forces	1
Momentum	0.40000001
he	1
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	ideal-gas-mixing-law	#f
Viscosity	kg/m-s	ideal-gas-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0
Speed of Sound	m/s	none	#f

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Update A FLUENT Case

FLUENT
Version: 3d, pbns, spe, lam, unsteady (3d, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type
barrel	2	fluid
cold_leg	3	fluid
cold_valve	4	fluid
cross-over_leg	5	fluid
hot_top	6	fluid
hot_valve	7	fluid
pebbles	8	fluid
wall	9	wall
outlet	10	interior
cold_exit	11	interior
cold_enter	12	interior
hot_exit	13	interior
pebble_exit	14	interior
pebble_enter	15	interior
inlet	16	interior
barrel_walls	17	wall

```
    new_cold_valve         18   wall
    cold_walls             19   wall
    cross_over_walls       20   wall
    hot_top_walls          21   wall
    hot_valve_walls        22   wall
    pebble_walls           23   wall
    default-interior       25   interior
    default-interior:001   1    interior
    default-interior:024   24   interior
    default-interior:026   26   interior
    default-interior:027   27   interior
    default-interior:028   28   interior
    default-interior:029   29   interior

 Boundary Conditions

    barrel

       Condition
Value
       ---------------------------------------------------------------
------------
       Material Name
mixture-template
       Specify source terms?                                       no
       Source Terms                                                ()
       Specify fixed values?                                       no
       Local Coordinate System for Fixed Velocities                no
       Fixed Values                                                ()
       Motion Type                                                 0
       X-Velocity Of Zone (m/s)                                    0
       Y-Velocity Of Zone (m/s)                                    0
       Z-Velocity Of Zone (m/s)                                    0
       Rotation speed (rad/s)                                      0
       X-Origin of Rotation-Axis (m)                               0
       Y-Origin of Rotation-Axis (m)                               0
       Z-Origin of Rotation-Axis (m)                               0
       X-Component of Rotation-Axis                                0
       Y-Component of Rotation-Axis                                0
       Z-Component of Rotation-Axis                                1
       Deactivated Thread                                          no
       Porous zone?                                                no
       Conical porous zone?                                        no
       X-Component of Direction-1 Vector                           1
       Y-Component of Direction-1 Vector                           0
       Z-Component of Direction-1 Vector                           0
       X-Component of Direction-2 Vector                           0
       Y-Component of Direction-2 Vector                           1
       Z-Component of Direction-2 Vector                           0
       X-Component of Cone Axis Vector                             1
       Y-Component of Cone Axis Vector                             0
       Z-Component of Cone Axis Vector                             0
       X-Coordinate of Point on Cone Axis (m)                      1
       Y-Coordinate of Point on Cone Axis (m)                      0
       Z-Coordinate of Point on Cone Axis (m)                      0
       Half Angle of Cone Relative to its Axis (deg)               0
       Relative Velocity Resistance Formulation?                   yes
```

```
          Direction-1 Viscous Resistance (1/m2)                      0
          Direction-2 Viscous Resistance (1/m2)                      0
          Direction-3 Viscous Resistance (1/m2)                      0
          Choose alternative formulation for inertial resistance?    no
          Direction-1 Inertial Resistance (1/m)                      0
          Direction-2 Inertial Resistance (1/m)                      0
          Direction-3 Inertial Resistance (1/m)                      0
          C0 Coefficient for Power-Law                               0
          C1 Coefficient for Power-Law                               0
          Porosity                                                   1
          Solid Material Name
aluminum

       cold_leg

          Condition
Value
          ------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                      no
          Source Terms                                               ()
          Specify fixed values?                                      no
          Local Coordinate System for Fixed Velocities               no
          Fixed Values                                               ()
          Motion Type                                                0
          X-Velocity Of Zone (m/s)                                   0
          Y-Velocity Of Zone (m/s)                                   0
          Z-Velocity Of Zone (m/s)                                   0
          Rotation speed (rad/s)                                     0
          X-Origin of Rotation-Axis (m)                              0
          Y-Origin of Rotation-Axis (m)                              0
          Z-Origin of Rotation-Axis (m)                              0
          X-Component of Rotation-Axis                               0
          Y-Component of Rotation-Axis                               0
          Z-Component of Rotation-Axis                               1
          Deactivated Thread                                         no
          Porous zone?                                               no
          Conical porous zone?                                       no
          X-Component of Direction-1 Vector                          1
          Y-Component of Direction-1 Vector                          0
          Z-Component of Direction-1 Vector                          0
          X-Component of Direction-2 Vector                          0
          Y-Component of Direction-2 Vector                          1
          Z-Component of Direction-2 Vector                          0
          X-Component of Cone Axis Vector                            1
          Y-Component of Cone Axis Vector                            0
          Z-Component of Cone Axis Vector                            0
          X-Coordinate of Point on Cone Axis (m)                     1
          Y-Coordinate of Point on Cone Axis (m)                     0
          Z-Coordinate of Point on Cone Axis (m)                     0
          Half Angle of Cone Relative to its Axis (deg)              0
          Relative Velocity Resistance Formulation?                  yes
          Direction-1 Viscous Resistance (1/m2)                      0
          Direction-2 Viscous Resistance (1/m2)                      0
          Direction-3 Viscous Resistance (1/m2)                      0
```

```
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                     0
        Direction-2 Inertial Resistance (1/m)                     0
        Direction-3 Inertial Resistance (1/m)                     0
        C0 Coefficient for Power-Law                              0
        C1 Coefficient for Power-Law                              0
        Porosity                                                  1
        Solid Material Name
aluminum

      cold_valve

        Condition
Value
        -------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                     no
        Source Terms                                              ()
        Specify fixed values?                                     no
        Local Coordinate System for Fixed Velocities              no
        Fixed Values                                              ()
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
        Y-Velocity Of Zone (m/s)                                  0
        Z-Velocity Of Zone (m/s)                                  0
        Rotation speed (rad/s)                                    0
        X-Origin of Rotation-Axis (m)                             0
        Y-Origin of Rotation-Axis (m)                             0
        Z-Origin of Rotation-Axis (m)                             0
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
        Deactivated Thread                                        no
        Porous zone?                                              no
        Conical porous zone?                                      no
        X-Component of Direction-1 Vector                         1
        Y-Component of Direction-1 Vector                         0
        Z-Component of Direction-1 Vector                         0
        X-Component of Direction-2 Vector                         0
        Y-Component of Direction-2 Vector                         1
        Z-Component of Direction-2 Vector                         0
        X-Component of Cone Axis Vector                           1
        Y-Component of Cone Axis Vector                           0
        Z-Component of Cone Axis Vector                           0
        X-Coordinate of Point on Cone Axis (m)                    1
        Y-Coordinate of Point on Cone Axis (m)                    0
        Z-Coordinate of Point on Cone Axis (m)                    0
        Half Angle of Cone Relative to its Axis (deg)             0
        Relative Velocity Resistance Formulation?                 yes
        Direction-1 Viscous Resistance (1/m2)                     0
        Direction-2 Viscous Resistance (1/m2)                     0
        Direction-3 Viscous Resistance (1/m2)                     0
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                     0
        Direction-2 Inertial Resistance (1/m)                     0
```

```
         Direction-3 Inertial Resistance (1/m)                    0
         C0 Coefficient for Power-Law                             0
         C1 Coefficient for Power-Law                             0
         Porosity                                                 1
         Solid Material Name
aluminum

      cross-over_leg

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                    no
         Source Terms                                             ()
         Specify fixed values?                                    no
         Local Coordinate System for Fixed Velocities             no
         Fixed Values                                             ()
         Motion Type                                              0
         X-Velocity Of Zone (m/s)                                 0
         Y-Velocity Of Zone (m/s)                                 0
         Z-Velocity Of Zone (m/s)                                 0
         Rotation speed (rad/s)                                   0
         X-Origin of Rotation-Axis (m)                            0
         Y-Origin of Rotation-Axis (m)                            0
         Z-Origin of Rotation-Axis (m)                            0
         X-Component of Rotation-Axis                             0
         Y-Component of Rotation-Axis                             0
         Z-Component of Rotation-Axis                             1
         Deactivated Thread                                       no
         Porous zone?                                             no
         Conical porous zone?                                     no
         X-Component of Direction-1 Vector                        1
         Y-Component of Direction-1 Vector                        0
         Z-Component of Direction-1 Vector                        0
         X-Component of Direction-2 Vector                        0
         Y-Component of Direction-2 Vector                        1
         Z-Component of Direction-2 Vector                        0
         X-Component of Cone Axis Vector                          1
         Y-Component of Cone Axis Vector                          0
         Z-Component of Cone Axis Vector                          0
         X-Coordinate of Point on Cone Axis (m)                   1
         Y-Coordinate of Point on Cone Axis (m)                   0
         Z-Coordinate of Point on Cone Axis (m)                   0
         Half Angle of Cone Relative to its Axis (deg)            0
         Relative Velocity Resistance Formulation?                yes
         Direction-1 Viscous Resistance (1/m2)                    0
         Direction-2 Viscous Resistance (1/m2)                    0
         Direction-3 Viscous Resistance (1/m2)                    0
         Choose alternative formulation for inertial resistance?  no
         Direction-1 Inertial Resistance (1/m)                    0
         Direction-2 Inertial Resistance (1/m)                    0
         Direction-3 Inertial Resistance (1/m)                    0
         C0 Coefficient for Power-Law                             0
         C1 Coefficient for Power-Law                             0
```

```
         Porosity                                                  1
         Solid Material Name
aluminum

      hot_top

         Condition
Value
         --------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum
```

```
      hot_valve

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                         no
         Source Terms                                                  ()
         Specify fixed values?                                         no
         Local Coordinate System for Fixed Velocities                  no
         Fixed Values                                                  ()
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
         Z-Component of Rotation-Axis                                  1
         Deactivated Thread                                            no
         Porous zone?                                                  no
         Conical porous zone?                                          no
         X-Component of Direction-1 Vector                             1
         Y-Component of Direction-1 Vector                             0
         Z-Component of Direction-1 Vector                             0
         X-Component of Direction-2 Vector                             0
         Y-Component of Direction-2 Vector                             1
         Z-Component of Direction-2 Vector                             0
         X-Component of Cone Axis Vector                               1
         Y-Component of Cone Axis Vector                               0
         Z-Component of Cone Axis Vector                               0
         X-Coordinate of Point on Cone Axis (m)                        1
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
         Relative Velocity Resistance Formulation?                     yes
         Direction-1 Viscous Resistance (1/m2)                         0
         Direction-2 Viscous Resistance (1/m2)                         0
         Direction-3 Viscous Resistance (1/m2)                         0
         Choose alternative formulation for inertial resistance?       no
         Direction-1 Inertial Resistance (1/m)                         0
         Direction-2 Inertial Resistance (1/m)                         0
         Direction-3 Inertial Resistance (1/m)                         0
         C0 Coefficient for Power-Law                                  0
         C1 Coefficient for Power-Law                                  0
         Porosity                                                      1
         Solid Material Name
aluminum

      pebbles
```

```
        Condition
Value
        ---------------------------------------------------------------
-------------------------------------------------------------------------
-------------------------------------------------------------------------
-------------------------------------------------------------------------
-----------------------------------------------------------------
        Material Name
mixture-template
        Specify source terms?                                    no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
        Specify fixed values?                                    no
        Local Coordinate System for Fixed Velocities             no
        Fixed Values                                             ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
        Motion Type                                              0
        X-Velocity Of Zone (m/s)                                 0
        Y-Velocity Of Zone (m/s)                                 0
        Z-Velocity Of Zone (m/s)                                 0
        Rotation speed (rad/s)                                   0
        X-Origin of Rotation-Axis (m)                            0
        Y-Origin of Rotation-Axis (m)                            0
        Z-Origin of Rotation-Axis (m)                            0
        X-Component of Rotation-Axis                             0
        Y-Component of Rotation-Axis                             0
        Z-Component of Rotation-Axis                             1
        Deactivated Thread                                       no
        Porous zone?                                             yes
        Conical porous zone?                                     no
        X-Component of Direction-1 Vector                        1
        Y-Component of Direction-1 Vector                        0
        Z-Component of Direction-1 Vector                        0
        X-Component of Direction-2 Vector                        0
        Y-Component of Direction-2 Vector                        1
        Z-Component of Direction-2 Vector                        0
        X-Component of Cone Axis Vector                          1
        Y-Component of Cone Axis Vector                          0
        Z-Component of Cone Axis Vector                          0
        X-Coordinate of Point on Cone Axis (m)                   1
        Y-Coordinate of Point on Cone Axis (m)                   0
        Z-Coordinate of Point on Cone Axis (m)                   0
        Half Angle of Cone Relative to its Axis (deg)            0
        Relative Velocity Resistance Formulation?                no
        Direction-1 Viscous Resistance (1/m2)                    0
        Direction-2 Viscous Resistance (1/m2)                    0
        Direction-3 Viscous Resistance (1/m2)                    0
        Choose alternative formulation for inertial resistance?  no
        Direction-1 Inertial Resistance (1/m)                    0
        Direction-2 Inertial Resistance (1/m)                    0
        Direction-3 Inertial Resistance (1/m)                    0
        C0 Coefficient for Power-Law                             341
        C1 Coefficient for Power-Law
1.6107
```

```
        Porosity
0.39500001
        Solid Material Name
glass

      wall

        Condition                                             Value
        ------------------------------------------------------------
---------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

      outlet

        Condition   Value
        -----------------

      cold_exit

        Condition   Value
```

```
   -----------------

cold_enter

   Condition   Value
   -----------------

hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                                  Value
   ---------------------------------------------------------------
---------------------
   Wall Thickness (m)                                         0
   Heat Generation Rate (w/m3)                                0
   Material Name                                              aluminum
   Thermal BC Type                                            0
   Temperature (k)                                            293
   Heat Flux (w/m2)                                           0
   Convective Heat Transfer Coefficient (w/m2-k)              0
   Free Stream Temperature (k)                                300
   Enable shell conduction?                                   no
   Wall Motion                                                0
   Shear Boundary Condition                                   0
   Define wall motion relative to adjacent cell zone?         yes
   Apply a rotational velocity to this wall?                  no
   Velocity Magnitude (m/s)                                   0
   X-Component of Wall Translation                            1
   Y-Component of Wall Translation                            0
   Z-Component of Wall Translation                            0
   Define wall velocity components?                           no
   X-Component of Wall Translation (m/s)                      0
   Y-Component of Wall Translation (m/s)                      0
   Z-Component of Wall Translation (m/s)                      0
   External Emissivity                                        1
   External Radiation Temperature (k)                         300
                                                              (0)
```

```
(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     new_cold_valve

        Condition                                           Value
        ------------------------------------------------------------------
---------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     1
        Temperature (k)                                     300
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
```

```
         Specularity Coefficient                           0

      cold_walls

         Condition                                         Value
         -----------------------------------------------------------
--------------------
         Wall Thickness (m)                                0
         Heat Generation Rate (w/m3)                       0
         Material Name                                     copper
         Thermal BC Type                                   0
         Temperature (k)                                   283
         Heat Flux (w/m2)                                  0
         Convective Heat Transfer Coefficient (w/m2-k)     0
         Free Stream Temperature (k)                       300
         Enable shell conduction?                          no
         Wall Motion                                       0
         Shear Boundary Condition                          0
         Define wall motion relative to adjacent cell zone?   yes
         Apply a rotational velocity to this wall?         no
         Velocity Magnitude (m/s)                          0
         X-Component of Wall Translation                   1
         Y-Component of Wall Translation                   0
         Z-Component of Wall Translation                   0
         Define wall velocity components?                  no
         X-Component of Wall Translation (m/s)             0
         Y-Component of Wall Translation (m/s)             0
         Z-Component of Wall Translation (m/s)             0
         External Emissivity                               1
         External Radiation Temperature (k)                300
                                                           (0)

(((constant . 0) (profile  )))
         Rotation Speed (rad/s)                            0
         X-Position of Rotation-Axis Origin (m)            0
         Y-Position of Rotation-Axis Origin (m)            0
         Z-Position of Rotation-Axis Origin (m)            0
         X-Component of Rotation-Axis Direction            0
         Y-Component of Rotation-Axis Direction            0
         Z-Component of Rotation-Axis Direction            1
         X-component of shear stress (pascal)              0
         Y-component of shear stress (pascal)              0
         Z-component of shear stress (pascal)              0
         Surface tension gradient (n/m-k)                  0
         Specularity Coefficient                           0

      cross_over_walls

         Condition                                         Value
         -----------------------------------------------------------
--------------------
         Wall Thickness (m)                                0
         Heat Generation Rate (w/m3)                       0
         Material Name                                     copper
         Thermal BC Type                                   1
         Temperature (k)                                   300
         Heat Flux (w/m2)                                  0
```

```
        Convective Heat Transfer Coefficient (w/m2-k)        0
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
        Y-Component of Wall Translation (m/s)                0
        Z-Component of Wall Translation (m/s)                0
        External Emissivity                                  1
        External Radiation Temperature (k)                   300
                                                             (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                               0
        X-Position of Rotation-Axis Origin (m)               0
        Y-Position of Rotation-Axis Origin (m)               0
        Z-Position of Rotation-Axis Origin (m)               0
        X-Component of Rotation-Axis Direction               0
        Y-Component of Rotation-Axis Direction               0
        Z-Component of Rotation-Axis Direction               1
        X-component of shear stress (pascal)                 0
        Y-component of shear stress (pascal)                 0
        Z-component of shear stress (pascal)                 0
        Surface tension gradient (n/m-k)                     0
        Specularity Coefficient                              0

     hot_top_walls

        Condition                                            Value
        --------------------------------------------------------------
---------------------
        Wall Thickness (m)                                   0
        Heat Generation Rate (w/m3)                          0
        Material Name                                        copper
        Thermal BC Type                                      0
        Temperature (k)                                      473
        Heat Flux (w/m2)                                     0
        Convective Heat Transfer Coefficient (w/m2-k)        0
        Free Stream Temperature (k)                          300
        Enable shell conduction?                             no
        Wall Motion                                          0
        Shear Boundary Condition                             0
        Define wall motion relative to adjacent cell zone?   yes
        Apply a rotational velocity to this wall?            no
        Velocity Magnitude (m/s)                             0
        X-Component of Wall Translation                      1
        Y-Component of Wall Translation                      0
        Z-Component of Wall Translation                      0
        Define wall velocity components?                     no
        X-Component of Wall Translation (m/s)                0
```

```
        Y-Component of Wall Translation (m/s)              0
        Z-Component of Wall Translation (m/s)              0
        External Emissivity                                1
        External Radiation Temperature (k)                 300
                                                           (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                             0
        X-Position of Rotation-Axis Origin (m)             0
        Y-Position of Rotation-Axis Origin (m)             0
        Z-Position of Rotation-Axis Origin (m)             0
        X-Component of Rotation-Axis Direction             0
        Y-Component of Rotation-Axis Direction             0
        Z-Component of Rotation-Axis Direction             1
        X-component of shear stress (pascal)               0
        Y-component of shear stress (pascal)               0
        Z-component of shear stress (pascal)               0
        Surface tension gradient (n/m-k)                   0
        Specularity Coefficient                            0

     hot_valve_walls

        Condition                                          Value
        ------------------------------------------------------------
--------------------
        Wall Thickness (m)                                 0
        Heat Generation Rate (w/m3)                        0
        Material Name                                      copper
        Thermal BC Type                                    1
        Temperature (k)                                    300
        Heat Flux (w/m2)                                   0
        Convective Heat Transfer Coefficient (w/m2-k)      0
        Free Stream Temperature (k)                        300
        Enable shell conduction?                           no
        Wall Motion                                        0
        Shear Boundary Condition                           0
        Define wall motion relative to adjacent cell zone? yes
        Apply a rotational velocity to this wall?          no
        Velocity Magnitude (m/s)                           0
        X-Component of Wall Translation                    1
        Y-Component of Wall Translation                    0
        Z-Component of Wall Translation                    0
        Define wall velocity components?                   no
        X-Component of Wall Translation (m/s)              0
        Y-Component of Wall Translation (m/s)              0
        Z-Component of Wall Translation (m/s)              0
        External Emissivity                                1
        External Radiation Temperature (k)                 300
                                                           (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                             0
        X-Position of Rotation-Axis Origin (m)             0
        Y-Position of Rotation-Axis Origin (m)             0
        Z-Position of Rotation-Axis Origin (m)             0
        X-Component of Rotation-Axis Direction             0
        Y-Component of Rotation-Axis Direction             0
```

```
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     pebble_walls

        Condition                                           Value
        --------------------------------------------------------------
---------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     0
        Temperature (k)                                     473
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     default-interior

        Condition   Value
        -----------------

     default-interior:001
```

```
      Condition   Value
      -----------------

   default-interior:024

      Condition   Value
      -----------------

   default-interior:026

      Condition   Value
      -----------------

   default-interior:027

      Condition   Value
      -----------------

   default-interior:028

      Condition   Value
      -----------------

   default-interior:029

      Condition   Value
      -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes

   Numerics

      Numeric                                Enabled
      ---------------------------------------
      Absolute Velocity Formulation    yes

   Unsteady Calculation Parameters


      -----------------------------------
      Time Step (s)                    0.2
      Max. Iterations Per Time Step    100

   Relaxation

      Variable      Relaxation Factor
      -------------------------------
```

Pressure	0.60000002
Density	0.80000001
Body Forces	0.69999999
Momentum	0.40000001
he	0.80000001
Energy	0.89999998

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	SIMPLE

Discretization Scheme

Variable	Scheme
Pressure	Body Force Weighted
Density	First Order Upwind
Momentum	First Order Upwind
he	First Order Upwind
Energy	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.576
L-J Energy Parameter	k	constant	10.2
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.1625
Cp (Specific Heat)	j/kg-k	constant	5193
Thermal Conductivity	w/m-k	constant	0.152
Viscosity	kg/m-s	constant	1.99e-05
Molecular Weight	kg/kgmol	constant	4.0026
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	mass-weighted-mixing-law	#f
Viscosity	kg/m-s	mass-weighted-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0

Speed of Sound	m/s	none	

#f

Material: (nitrogen . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.681
L-J Energy Parameter	k	constant	91.5
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4

Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Injection (1cc/min) FLUENT Case

FLUENT
Version: 3d, dp, pbns, spe, lam, unsteady (3d, double precision, pressure-based, species, laminar, unsteady)
Release: 6.3.26
Title:

Models

Model	Settings
Space	3D
Time	Unsteady, 1st-Order Implicit
Viscous	Laminar
Heat Transfer	Enabled
Solidification and Melting	Disabled
Radiation	None
Species Transport	Non-Reacting (2 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

name	id	type
barrel	2	fluid
cold_leg	3	fluid
cold_valve	4	fluid
cross-over_leg	5	fluid
hot_top	6	fluid
hot_valve	7	fluid
pebbles	8	fluid
injection_point	9	mass-flow-inlet
outlet	10	interior
cold_exit	11	interior
cold_enter	12	interior
hot_exit	13	interior
pebble_exit	14	interior
pebble_enter	15	interior
inlet	16	interior
barrel_walls	17	wall
new_cold_valve	18	wall
cold_walls	19	wall
cross_over_walls	20	wall
hot_top_walls	21	wall
hot_valve_walls	22	wall
pebble_walls	23	wall
default-interior	25	interior
default-interior:001	1	interior
default-interior:024	24	interior
default-interior:026	26	interior
default-interior:027	27	interior
default-interior:028	28	interior
default-interior:029	29	interior

Boundary Conditions

barrel

Condition	Value
Material Name	mixture-template
Specify source terms?	no
Source Terms	()
Specify fixed values?	no
Local Coordinate System for Fixed Velocities	no
Fixed Values	()
Motion Type	0
X-Velocity Of Zone (m/s)	0
Y-Velocity Of Zone (m/s)	0
Z-Velocity Of Zone (m/s)	0
Rotation speed (rad/s)	0
X-Origin of Rotation-Axis (m)	0
Y-Origin of Rotation-Axis (m)	0
Z-Origin of Rotation-Axis (m)	0

```
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
        Deactivated Thread                                        no
        Porous zone?                                              no
        Conical porous zone?                                      no
        X-Component of Direction-1 Vector                         1
        Y-Component of Direction-1 Vector                         0
        Z-Component of Direction-1 Vector                         0
        X-Component of Direction-2 Vector                         0
        Y-Component of Direction-2 Vector                         1
        Z-Component of Direction-2 Vector                         0
        X-Component of Cone Axis Vector                           1
        Y-Component of Cone Axis Vector                           0
        Z-Component of Cone Axis Vector                           0
        X-Coordinate of Point on Cone Axis (m)                    1
        Y-Coordinate of Point on Cone Axis (m)                    0
        Z-Coordinate of Point on Cone Axis (m)                    0
        Half Angle of Cone Relative to its Axis (deg)             0
        Relative Velocity Resistance Formulation?                 yes
        Direction-1 Viscous Resistance (1/m2)                     0
        Direction-2 Viscous Resistance (1/m2)                     0
        Direction-3 Viscous Resistance (1/m2)                     0
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                     0
        Direction-2 Inertial Resistance (1/m)                     0
        Direction-3 Inertial Resistance (1/m)                     0
        C0 Coefficient for Power-Law                              0
        C1 Coefficient for Power-Law                              0
        Porosity                                                  1
        Solid Material Name
aluminum

      cold_leg

        Condition
Value
        --------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                     no
        Source Terms                                              ()
        Specify fixed values?                                     no
        Local Coordinate System for Fixed Velocities              no
        Fixed Values                                              ()
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
        Y-Velocity Of Zone (m/s)                                  0
        Z-Velocity Of Zone (m/s)                                  0
        Rotation speed (rad/s)                                    0
        X-Origin of Rotation-Axis (m)                             0
        Y-Origin of Rotation-Axis (m)                             0
        Z-Origin of Rotation-Axis (m)                             0
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
```

```
         Deactivated Thread                                            no
         Porous zone?                                                  no
         Conical porous zone?                                          no
         X-Component of Direction-1 Vector                             1
         Y-Component of Direction-1 Vector                             0
         Z-Component of Direction-1 Vector                             0
         X-Component of Direction-2 Vector                             0
         Y-Component of Direction-2 Vector                             1
         Z-Component of Direction-2 Vector                             0
         X-Component of Cone Axis Vector                               1
         Y-Component of Cone Axis Vector                               0
         Z-Component of Cone Axis Vector                               0
         X-Coordinate of Point on Cone Axis (m)                        1
         Y-Coordinate of Point on Cone Axis (m)                        0
         Z-Coordinate of Point on Cone Axis (m)                        0
         Half Angle of Cone Relative to its Axis (deg)                 0
         Relative Velocity Resistance Formulation?                     yes
         Direction-1 Viscous Resistance (1/m2)                         0
         Direction-2 Viscous Resistance (1/m2)                         0
         Direction-3 Viscous Resistance (1/m2)                         0
         Choose alternative formulation for inertial resistance?       no
         Direction-1 Inertial Resistance (1/m)                         0
         Direction-2 Inertial Resistance (1/m)                         0
         Direction-3 Inertial Resistance (1/m)                         0
         C0 Coefficient for Power-Law                                  0
         C1 Coefficient for Power-Law                                  0
         Porosity                                                      1
         Solid Material Name
aluminum

      cold_valve

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                         no
         Source Terms                                                  ()
         Specify fixed values?                                         no
         Local Coordinate System for Fixed Velocities                  no
         Fixed Values                                                  ()
         Motion Type                                                   0
         X-Velocity Of Zone (m/s)                                      0
         Y-Velocity Of Zone (m/s)                                      0
         Z-Velocity Of Zone (m/s)                                      0
         Rotation speed (rad/s)                                        0
         X-Origin of Rotation-Axis (m)                                 0
         Y-Origin of Rotation-Axis (m)                                 0
         Z-Origin of Rotation-Axis (m)                                 0
         X-Component of Rotation-Axis                                  0
         Y-Component of Rotation-Axis                                  0
         Z-Component of Rotation-Axis                                  1
         Deactivated Thread                                            no
         Porous zone?                                                  no
         Conical porous zone?                                          no
```

```
          X-Component of Direction-1 Vector                          1
          Y-Component of Direction-1 Vector                          0
          Z-Component of Direction-1 Vector                          0
          X-Component of Direction-2 Vector                          0
          Y-Component of Direction-2 Vector                          1
          Z-Component of Direction-2 Vector                          0
          X-Component of Cone Axis Vector                            1
          Y-Component of Cone Axis Vector                            0
          Z-Component of Cone Axis Vector                            0
          X-Coordinate of Point on Cone Axis (m)                     1
          Y-Coordinate of Point on Cone Axis (m)                     0
          Z-Coordinate of Point on Cone Axis (m)                     0
          Half Angle of Cone Relative to its Axis (deg)              0
          Relative Velocity Resistance Formulation?                  yes
          Direction-1 Viscous Resistance (1/m2)                      0
          Direction-2 Viscous Resistance (1/m2)                      0
          Direction-3 Viscous Resistance (1/m2)                      0
          Choose alternative formulation for inertial resistance?    no
          Direction-1 Inertial Resistance (1/m)                      0
          Direction-2 Inertial Resistance (1/m)                      0
          Direction-3 Inertial Resistance (1/m)                      0
          C0 Coefficient for Power-Law                               0
          C1 Coefficient for Power-Law                               0
          Porosity                                                   1
          Solid Material Name
aluminum

       cross-over_leg

          Condition
Value
          -------------------------------------------------------------
------------
          Material Name
mixture-template
          Specify source terms?                                      no
          Source Terms                                               ()
          Specify fixed values?                                      no
          Local Coordinate System for Fixed Velocities               no
          Fixed Values                                               ()
          Motion Type                                                0
          X-Velocity Of Zone (m/s)                                   0
          Y-Velocity Of Zone (m/s)                                   0
          Z-Velocity Of Zone (m/s)                                   0
          Rotation speed (rad/s)                                     0
          X-Origin of Rotation-Axis (m)                              0
          Y-Origin of Rotation-Axis (m)                              0
          Z-Origin of Rotation-Axis (m)                              0
          X-Component of Rotation-Axis                               0
          Y-Component of Rotation-Axis                               0
          Z-Component of Rotation-Axis                               1
          Deactivated Thread                                         no
          Porous zone?                                               no
          Conical porous zone?                                       no
          X-Component of Direction-1 Vector                          1
          Y-Component of Direction-1 Vector                          0
          Z-Component of Direction-1 Vector                          0
```

```
         X-Component of Direction-2 Vector                            0
         Y-Component of Direction-2 Vector                            1
         Z-Component of Direction-2 Vector                            0
         X-Component of Cone Axis Vector                              1
         Y-Component of Cone Axis Vector                              0
         Z-Component of Cone Axis Vector                              0
         X-Coordinate of Point on Cone Axis (m)                       1
         Y-Coordinate of Point on Cone Axis (m)                       0
         Z-Coordinate of Point on Cone Axis (m)                       0
         Half Angle of Cone Relative to its Axis (deg)                0
         Relative Velocity Resistance Formulation?                    yes
         Direction-1 Viscous Resistance (1/m2)                        0
         Direction-2 Viscous Resistance (1/m2)                        0
         Direction-3 Viscous Resistance (1/m2)                        0
         Choose alternative formulation for inertial resistance?     no
         Direction-1 Inertial Resistance (1/m)                        0
         Direction-2 Inertial Resistance (1/m)                        0
         Direction-3 Inertial Resistance (1/m)                        0
         C0 Coefficient for Power-Law                                 0
         C1 Coefficient for Power-Law                                 0
         Porosity                                                     1
         Solid Material Name
aluminum

      hot_top

         Condition
Value
         ---------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                        no
         Source Terms                                                 ()
         Specify fixed values?                                        no
         Local Coordinate System for Fixed Velocities                 no
         Fixed Values                                                 ()
         Motion Type                                                  0
         X-Velocity Of Zone (m/s)                                     0
         Y-Velocity Of Zone (m/s)                                     0
         Z-Velocity Of Zone (m/s)                                     0
         Rotation speed (rad/s)                                       0
         X-Origin of Rotation-Axis (m)                                0
         Y-Origin of Rotation-Axis (m)                                0
         Z-Origin of Rotation-Axis (m)                                0
         X-Component of Rotation-Axis                                 0
         Y-Component of Rotation-Axis                                 0
         Z-Component of Rotation-Axis                                 1
         Deactivated Thread                                           no
         Porous zone?                                                 no
         Conical porous zone?                                         no
         X-Component of Direction-1 Vector                            1
         Y-Component of Direction-1 Vector                            0
         Z-Component of Direction-1 Vector                            0
         X-Component of Direction-2 Vector                            0
         Y-Component of Direction-2 Vector                            1
         Z-Component of Direction-2 Vector                            0
```

```
        X-Component of Cone Axis Vector                          1
        Y-Component of Cone Axis Vector                          0
        Z-Component of Cone Axis Vector                          0
        X-Coordinate of Point on Cone Axis (m)                   1
        Y-Coordinate of Point on Cone Axis (m)                   0
        Z-Coordinate of Point on Cone Axis (m)                   0
        Half Angle of Cone Relative to its Axis (deg)            0
        Relative Velocity Resistance Formulation?                yes
        Direction-1 Viscous Resistance (1/m2)                    0
        Direction-2 Viscous Resistance (1/m2)                    0
        Direction-3 Viscous Resistance (1/m2)                    0
        Choose alternative formulation for inertial resistance?  no
        Direction-1 Inertial Resistance (1/m)                    0
        Direction-2 Inertial Resistance (1/m)                    0
        Direction-3 Inertial Resistance (1/m)                    0
        C0 Coefficient for Power-Law                             0
        C1 Coefficient for Power-Law                             0
        Porosity                                                 1
        Solid Material Name
aluminum

      hot_valve

        Condition
Value
        --------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                    no
        Source Terms                                             ()
        Specify fixed values?                                    no
        Local Coordinate System for Fixed Velocities             no
        Fixed Values                                             ()
        Motion Type                                              0
        X-Velocity Of Zone (m/s)                                 0
        Y-Velocity Of Zone (m/s)                                 0
        Z-Velocity Of Zone (m/s)                                 0
        Rotation speed (rad/s)                                   0
        X-Origin of Rotation-Axis (m)                            0
        Y-Origin of Rotation-Axis (m)                            0
        Z-Origin of Rotation-Axis (m)                            0
        X-Component of Rotation-Axis                             0
        Y-Component of Rotation-Axis                             0
        Z-Component of Rotation-Axis                             1
        Deactivated Thread                                       no
        Porous zone?                                             no
        Conical porous zone?                                     no
        X-Component of Direction-1 Vector                        1
        Y-Component of Direction-1 Vector                        0
        Z-Component of Direction-1 Vector                        0
        X-Component of Direction-2 Vector                        0
        Y-Component of Direction-2 Vector                        1
        Z-Component of Direction-2 Vector                        0
        X-Component of Cone Axis Vector                          1
        Y-Component of Cone Axis Vector                          0
        Z-Component of Cone Axis Vector                          0
```

```
         X-Coordinate of Point on Cone Axis (m)                      1
         Y-Coordinate of Point on Cone Axis (m)                      0
         Z-Coordinate of Point on Cone Axis (m)                      0
         Half Angle of Cone Relative to its Axis (deg)               0
         Relative Velocity Resistance Formulation?                   yes
         Direction-1 Viscous Resistance (1/m2)                       0
         Direction-2 Viscous Resistance (1/m2)                       0
         Direction-3 Viscous Resistance (1/m2)                       0
         Choose alternative formulation for inertial resistance?    no
         Direction-1 Inertial Resistance (1/m)                       0
         Direction-2 Inertial Resistance (1/m)                       0
         Direction-3 Inertial Resistance (1/m)                       0
         C0 Coefficient for Power-Law                                0
         C1 Coefficient for Power-Law                                0
         Porosity                                                    1
         Solid Material Name
aluminum

      pebbles

         Condition
Value
         --------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
----------------------------------------------------------------------
---------------------------------------------------------------
         Material Name
mixture-template
         Specify source terms?                                       no
         Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
         Specify fixed values?                                       no
         Local Coordinate System for Fixed Velocities                no
         Fixed Values                                                ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
         Motion Type                                                 0
         X-Velocity Of Zone (m/s)                                    0
         Y-Velocity Of Zone (m/s)                                    0
         Z-Velocity Of Zone (m/s)                                    0
         Rotation speed (rad/s)                                      0
         X-Origin of Rotation-Axis (m)                               0
         Y-Origin of Rotation-Axis (m)                               0
         Z-Origin of Rotation-Axis (m)                               0
         X-Component of Rotation-Axis                                0
         Y-Component of Rotation-Axis                                0
         Z-Component of Rotation-Axis                                1
         Deactivated Thread                                          no
         Porous zone?                                                yes
         Conical porous zone?                                        no
         X-Component of Direction-1 Vector                           1
         Y-Component of Direction-1 Vector                           0
         Z-Component of Direction-1 Vector                           0
         X-Component of Direction-2 Vector                           0
```

```
        Y-Component of Direction-2 Vector                          1
        Z-Component of Direction-2 Vector                          0
        X-Component of Cone Axis Vector                            1
        Y-Component of Cone Axis Vector                            0
        Z-Component of Cone Axis Vector                            0
        X-Coordinate of Point on Cone Axis (m)                     1
        Y-Coordinate of Point on Cone Axis (m)                     0
        Z-Coordinate of Point on Cone Axis (m)                     0
        Half Angle of Cone Relative to its Axis (deg)              0
        Relative Velocity Resistance Formulation?                  yes
        Direction-1 Viscous Resistance (1/m2)
5860000
        Direction-2 Viscous Resistance (1/m2)
5860000
        Direction-3 Viscous Resistance (1/m2)
5860000
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                      2734
        Direction-2 Inertial Resistance (1/m)                      2734
        Direction-3 Inertial Resistance (1/m)                      2734
        C0 Coefficient for Power-Law                               0
        C1 Coefficient for Power-Law                               0
        Porosity
0.40000001
        Solid Material Name
glass

      injection_point

        Condition                                     Value
        --------------------------------------------------------------
-------------
        Mass Flow Specification Method                0
        Mass Flow-Rate (kg/s)                         2.78e-09
        Mass Flux (kg/m2-s)                           1
        Average Mass Flux (kg/m2-s)                   1
        Upstream Torque Integral (n-m)                1
        Upstream Total Enthalpy Integral (w/m2)       1
        Total Temperature (k)                         293
        Supersonic/Initial Gauge Pressure (pascal)    0
        Direction Specification Method                0
        Reference Frame                               0
        Coordinate System                             0
        X-Component of Flow Direction                 0
        Y-Component of Flow Direction                 0
        Z-Component of Flow Direction                 -1
        X-Component of Axis Direction                 1
        Y-Component of Axis Direction                 0
        Z-Component of Axis Direction                 0
        X-Coordinate of Axis Origin (m)               0
        Y-Coordinate of Axis Origin (m)               0
        Z-Coordinate of Axis Origin (m)               0
                                                      (((constant . 1)
(profile  )))
        is zone used in mixing-plane model?           no

      outlet
```

```
   Condition   Value
   -----------------

cold_exit

   Condition   Value
   -----------------

cold_enter

   Condition   Value
   -----------------

hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                              Value
   ----------------------------------------------------------------
---------------------
      Wall Thickness (m)                                  0
      Heat Generation Rate (w/m3)                         0
      Material Name                                       aluminum
      Thermal BC Type                                     0
      Temperature (k)                                     293
      Heat Flux (w/m2)                                    0
      Convective Heat Transfer Coefficient (w/m2-k)       0
      Free Stream Temperature (k)                         300
      Enable shell conduction?                            no
      Wall Motion                                         0
      Shear Boundary Condition                            0
      Define wall motion relative to adjacent cell zone?  yes
      Apply a rotational velocity to this wall?           no
      Velocity Magnitude (m/s)                            0
      X-Component of Wall Translation                     1
      Y-Component of Wall Translation                     0
      Z-Component of Wall Translation                     0
      Define wall velocity components?                    no
```

```
        X-Component of Wall Translation (m/s)                    0
        Y-Component of Wall Translation (m/s)                    0
        Z-Component of Wall Translation (m/s)                    0
        External Emissivity                                      1
        External Radiation Temperature (k)                       300
                                                                 (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                   0
        X-Position of Rotation-Axis Origin (m)                   0
        Y-Position of Rotation-Axis Origin (m)                   0
        Z-Position of Rotation-Axis Origin (m)                   0
        X-Component of Rotation-Axis Direction                   0
        Y-Component of Rotation-Axis Direction                   0
        Z-Component of Rotation-Axis Direction                   1
        X-component of shear stress (pascal)                     0
        Y-component of shear stress (pascal)                     0
        Z-component of shear stress (pascal)                     0
        Surface tension gradient (n/m-k)                         0
        Specularity Coefficient                                  0

     new_cold_valve

        Condition                                                Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                       0
        Heat Generation Rate (w/m3)                              0
        Material Name                                            copper
        Thermal BC Type                                          1
        Temperature (k)                                          300
        Heat Flux (w/m2)                                         0
        Convective Heat Transfer Coefficient (w/m2-k)            0
        Free Stream Temperature (k)                              300
        Enable shell conduction?                                 no
        Wall Motion                                              0
        Shear Boundary Condition                                 0
        Define wall motion relative to adjacent cell zone?       yes
        Apply a rotational velocity to this wall?                no
        Velocity Magnitude (m/s)                                 0
        X-Component of Wall Translation                          1
        Y-Component of Wall Translation                          0
        Z-Component of Wall Translation                          0
        Define wall velocity components?                         no
        X-Component of Wall Translation (m/s)                    0
        Y-Component of Wall Translation (m/s)                    0
        Z-Component of Wall Translation (m/s)                    0
        External Emissivity                                      1
        External Radiation Temperature (k)                       300
                                                                 (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                   0
        X-Position of Rotation-Axis Origin (m)                   0
        Y-Position of Rotation-Axis Origin (m)                   0
        Z-Position of Rotation-Axis Origin (m)                   0
        X-Component of Rotation-Axis Direction                   0
```

```
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     cold_walls

        Condition                                           Value
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     0
        Temperature (k)                                     283
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     cross_over_walls

        Condition                                           Value
        -------------------------------------------------------------
--------------------
```

```
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
        Velocity Magnitude (m/s)                              0
        X-Component of Wall Translation                       1
        Y-Component of Wall Translation                       0
        Z-Component of Wall Translation                       0
        Define wall velocity components?                      no
        X-Component of Wall Translation (m/s)                 0
        Y-Component of Wall Translation (m/s)                 0
        Z-Component of Wall Translation (m/s)                 0
        External Emissivity                                   1
        External Radiation Temperature (k)                    300
                                                              (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                0
        X-Position of Rotation-Axis Origin (m)                0
        Y-Position of Rotation-Axis Origin (m)                0
        Z-Position of Rotation-Axis Origin (m)                0
        X-Component of Rotation-Axis Direction                0
        Y-Component of Rotation-Axis Direction                0
        Z-Component of Rotation-Axis Direction                1
        X-component of shear stress (pascal)                  0
        Y-component of shear stress (pascal)                  0
        Z-component of shear stress (pascal)                  0
        Surface tension gradient (n/m-k)                      0
        Specularity Coefficient                               0

     hot_top_walls

        Condition                                             Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                    0
        Heat Generation Rate (w/m3)                           0
        Material Name                                         copper
        Thermal BC Type                                       1
        Temperature (k)                                       300
        Heat Flux (w/m2)                                      0
        Convective Heat Transfer Coefficient (w/m2-k)         0
        Free Stream Temperature (k)                           300
        Enable shell conduction?                              no
        Wall Motion                                           0
        Shear Boundary Condition                              0
        Define wall motion relative to adjacent cell zone?    yes
        Apply a rotational velocity to this wall?             no
```

```
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                  0
        X-Position of Rotation-Axis Origin (m)                  0
        Y-Position of Rotation-Axis Origin (m)                  0
        Z-Position of Rotation-Axis Origin (m)                  0
        X-Component of Rotation-Axis Direction                  0
        Y-Component of Rotation-Axis Direction                  0
        Z-Component of Rotation-Axis Direction                  1
        X-component of shear stress (pascal)                    0
        Y-component of shear stress (pascal)                    0
        Z-component of shear stress (pascal)                    0
        Surface tension gradient (n/m-k)                        0
        Specularity Coefficient                                 0

      hot_valve_walls

        Condition                                               Value
        -------------------------------------------------------------
--------------------
        Wall Thickness (m)                                      0
        Heat Generation Rate (w/m3)                             0
        Material Name                                           copper
        Thermal BC Type                                         1
        Temperature (k)                                         300
        Heat Flux (w/m2)                                        0
        Convective Heat Transfer Coefficient (w/m2-k)           0
        Free Stream Temperature (k)                             300
        Enable shell conduction?                                no
        Wall Motion                                             0
        Shear Boundary Condition                                0
        Define wall motion relative to adjacent cell zone?      yes
        Apply a rotational velocity to this wall?               no
        Velocity Magnitude (m/s)                                0
        X-Component of Wall Translation                         1
        Y-Component of Wall Translation                         0
        Z-Component of Wall Translation                         0
        Define wall velocity components?                        no
        X-Component of Wall Translation (m/s)                   0
        Y-Component of Wall Translation (m/s)                   0
        Z-Component of Wall Translation (m/s)                   0
        External Emissivity                                     1
        External Radiation Temperature (k)                      300
                                                                (0)

(((constant . 0) (profile  )))
```

```
        Rotation Speed (rad/s)                                      0
        X-Position of Rotation-Axis Origin (m)                      0
        Y-Position of Rotation-Axis Origin (m)                      0
        Z-Position of Rotation-Axis Origin (m)                      0
        X-Component of Rotation-Axis Direction                      0
        Y-Component of Rotation-Axis Direction                      0
        Z-Component of Rotation-Axis Direction                      1
        X-component of shear stress (pascal)                        0
        Y-component of shear stress (pascal)                        0
        Z-component of shear stress (pascal)                        0
        Surface tension gradient (n/m-k)                            0
        Specularity Coefficient                                     0

     pebble_walls

        Condition                                                   Value
        ------------------------------------------------------------------
---------------------
        Wall Thickness (m)                                          0
        Heat Generation Rate (w/m3)                                 0
        Material Name                                               copper
        Thermal BC Type                                             0
        Temperature (k)                                             473
        Heat Flux (w/m2)                                            0
        Convective Heat Transfer Coefficient (w/m2-k)               0
        Free Stream Temperature (k)                                 300
        Enable shell conduction?                                    no
        Wall Motion                                                 0
        Shear Boundary Condition                                    0
        Define wall motion relative to adjacent cell zone?          yes
        Apply a rotational velocity to this wall?                   no
        Velocity Magnitude (m/s)                                    0
        X-Component of Wall Translation                             1
        Y-Component of Wall Translation                             0
        Z-Component of Wall Translation                             0
        Define wall velocity components?                            no
        X-Component of Wall Translation (m/s)                       0
        Y-Component of Wall Translation (m/s)                       0
        Z-Component of Wall Translation (m/s)                       0
        External Emissivity                                         1
        External Radiation Temperature (k)                          300
                                                                    (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                                      0
        X-Position of Rotation-Axis Origin (m)                      0
        Y-Position of Rotation-Axis Origin (m)                      0
        Z-Position of Rotation-Axis Origin (m)                      0
        X-Component of Rotation-Axis Direction                      0
        Y-Component of Rotation-Axis Direction                      0
        Z-Component of Rotation-Axis Direction                      1
        X-component of shear stress (pascal)                        0
        Y-component of shear stress (pascal)                        0
        Z-component of shear stress (pascal)                        0
        Surface tension gradient (n/m-k)                            0
        Specularity Coefficient                                     0
```

```
      default-interior

         Condition   Value
         -----------------

      default-interior:001

         Condition   Value
         -----------------

      default-interior:024

         Condition   Value
         -----------------

      default-interior:026

         Condition   Value
         -----------------

      default-interior:027

         Condition   Value
         -----------------

      default-interior:028

         Condition   Value
         -----------------

      default-interior:029

         Condition   Value
         -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes

   Numerics

      Numeric                         Enabled
      ---------------------------------------
      Absolute Velocity Formulation   yes

   Unsteady Calculation Parameters


      --------------------------------------------
      Time Step (s)                   0.0099999998
```

Max. Iterations Per Time Step 200

Relaxation

Variable	Relaxation Factor
Pressure	0.60000002
Density	0.5
Body Forces	1
Momentum	0.40000001
he	1
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	PISO
Skewness-Neighbour Coupling	yes
Skewness Correction	1
Neighbour Correction	1

Discretization Scheme

Variable	Scheme
Pressure	PRESTO!
Density	Second Order Upwind
Momentum	Second Order Upwind
he	Power Law
Energy	Second Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (nitrogen-new . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Thermal Expansion Coefficient	1/k	constant	0

```
      Degrees of Freedom                             constant          3
      Speed of Sound                   m/s           none              #f

   Material: nitrogen-new (fluid)

      Property                         Units         Method
Value(s)
      -----------------------------------------------------------------
----
      Density                          kg/m3         ideal-gas         #f
      Cp (Specific Heat)               j/kg-k        kinetic-theory    #f
      Thermal Conductivity             w/m-k         kinetic-theory    #f
      Viscosity                        kg/m-s        kinetic-theory    #f
      Molecular Weight                 kg/kgmol      constant
28.013399
      L-J Characteristic Length        angstrom      constant
3.7980001
      L-J Energy Parameter             k             constant
71.400002
      Thermal Expansion Coefficient    1/k           constant          0
      Degrees of Freedom                             constant          5
      Speed of Sound                   m/s           none              #f

   Material: mixture-template (mixture)

      Property                         Units       Method
Value(s)
      -----------------------------------------------------------------
------------------
      Mixture Species                              names
((he n2-new) () ())
      Density                          kg/m3       ideal-gas
#f
      Cp (Specific Heat)               j/kg-k      mixing-law
#f
      Thermal Conductivity             w/m-k       ideal-gas-mixing-law
#f
      Viscosity                        kg/m-s      ideal-gas-mixing-law
#f
      Mass Diffusivity                 m2/s        kinetic-theory
#f
      Thermal Diffusion Coefficient    kg/m-s      kinetic-theory
#f
      Thermal Expansion Coefficient    1/k         constant                   0
      Speed of Sound                   m/s         none
#f

   Material: nitrogen (fluid)

      Property                         Units         Method      Value(s)
      ---------------------------------------------------------------
      Density                          kg/m3         constant    1.138
      Cp (Specific Heat)               j/kg-k        constant    1040.67
      Thermal Conductivity             w/m-k         constant    0.0242
      Viscosity                        kg/m-s        constant    1.663e-05
      Molecular Weight                 kg/kgmol      constant    28.0134
      L-J Characteristic Length        angstrom      constant    3.621
```

L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.39999

Stop Injection FLUENT Case

```
FLUENT
Version: 3d, dp, pbns, spe, lam, unsteady (3d, double precision,
pressure-based,  species, laminar, unsteady)
Release: 6.3.26
Title:

Models
------

   Model                         Settings
   ---------------------------------------------------------
   Space                         3D
   Time                          Unsteady, 1st-Order Implicit
   Viscous                       Laminar
   Heat Transfer                 Enabled
   Solidification and Melting    Disabled
   Radiation                     None
   Species Transport             Non-Reacting (2 species)
   Coupled Dispersed Phase       Disabled
   Pollutants                    Disabled
   Pollutants                    Disabled
   Soot                          Disabled

Boundary Conditions
-------------------

   Zones

      name                    id   type
      -----------------------------------
      barrel                  2    fluid
      cold_leg                3    fluid
      cold_valve              4    fluid
      cross-over_leg          5    fluid
      hot_top                 6    fluid
      hot_valve               7    fluid
      pebbles                 8    fluid
      injection_point         9    wall
      outlet                  10   interior
      cold_exit               11   interior
      cold_enter              12   interior
      hot_exit                13   interior
      pebble_exit             14   interior
      pebble_enter            15   interior
      inlet                   16   interior
      barrel_walls            17   wall
      new_cold_valve          18   wall
      cold_walls              19   wall
      cross_over_walls        20   wall
      hot_top_walls           21   wall
      hot_valve_walls         22   wall
      pebble_walls            23   wall
```

```
    default-interior        25   interior
    default-interior:001    1    interior
    default-interior:024    24   interior
    default-interior:026    26   interior
    default-interior:027    27   interior
    default-interior:028    28   interior
    default-interior:029    29   interior

 Boundary Conditions

    barrel

       Condition
Value
       ----------------------------------------------------------------
------------
       Material Name
mixture-template
       Specify source terms?                                       no
       Source Terms                                                ()
       Specify fixed values?                                       no
       Local Coordinate System for Fixed Velocities                no
       Fixed Values                                                ()
       Motion Type                                                 0
       X-Velocity Of Zone (m/s)                                    0
       Y-Velocity Of Zone (m/s)                                    0
       Z-Velocity Of Zone (m/s)                                    0
       Rotation speed (rad/s)                                      0
       X-Origin of Rotation-Axis (m)                               0
       Y-Origin of Rotation-Axis (m)                               0
       Z-Origin of Rotation-Axis (m)                               0
       X-Component of Rotation-Axis                                0
       Y-Component of Rotation-Axis                                0
       Z-Component of Rotation-Axis                                1
       Deactivated Thread                                          no
       Porous zone?                                                no
       Conical porous zone?                                        no
       X-Component of Direction-1 Vector                           1
       Y-Component of Direction-1 Vector                           0
       Z-Component of Direction-1 Vector                           0
       X-Component of Direction-2 Vector                           0
       Y-Component of Direction-2 Vector                           1
       Z-Component of Direction-2 Vector                           0
       X-Component of Cone Axis Vector                             1
       Y-Component of Cone Axis Vector                             0
       Z-Component of Cone Axis Vector                             0
       X-Coordinate of Point on Cone Axis (m)                      1
       Y-Coordinate of Point on Cone Axis (m)                      0
       Z-Coordinate of Point on Cone Axis (m)                      0
       Half Angle of Cone Relative to its Axis (deg)               0
       Relative Velocity Resistance Formulation?                   yes
       Direction-1 Viscous Resistance (1/m2)                       0
       Direction-2 Viscous Resistance (1/m2)                       0
       Direction-3 Viscous Resistance (1/m2)                       0
       Choose alternative formulation for inertial resistance?     no
       Direction-1 Inertial Resistance (1/m)                       0
       Direction-2 Inertial Resistance (1/m)                       0
```

```
        Direction-3 Inertial Resistance (1/m)                        0
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity                                                     1
        Solid Material Name
aluminum

      cold_leg

        Condition
Value
        --------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                        no
        Source Terms                                                 ()
        Specify fixed values?                                        no
        Local Coordinate System for Fixed Velocities                 no
        Fixed Values                                                 ()
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 no
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    yes
        Direction-1 Viscous Resistance (1/m2)                        0
        Direction-2 Viscous Resistance (1/m2)                        0
        Direction-3 Viscous Resistance (1/m2)                        0
        Choose alternative formulation for inertial resistance?      no
        Direction-1 Inertial Resistance (1/m)                        0
        Direction-2 Inertial Resistance (1/m)                        0
        Direction-3 Inertial Resistance (1/m)                        0
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
```

```
         Porosity                                                  1
         Solid Material Name
aluminum

      cold_valve

         Condition
Value
         --------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum
```

cross-over_leg

Condition	Value
Material Name	mixture-template
Specify source terms?	no
Source Terms	()
Specify fixed values?	no
Local Coordinate System for Fixed Velocities	no
Fixed Values	()
Motion Type	0
X-Velocity Of Zone (m/s)	0
Y-Velocity Of Zone (m/s)	0
Z-Velocity Of Zone (m/s)	0
Rotation speed (rad/s)	0
X-Origin of Rotation-Axis (m)	0
Y-Origin of Rotation-Axis (m)	0
Z-Origin of Rotation-Axis (m)	0
X-Component of Rotation-Axis	0
Y-Component of Rotation-Axis	0
Z-Component of Rotation-Axis	1
Deactivated Thread	no
Porous zone?	no
Conical porous zone?	no
X-Component of Direction-1 Vector	1
Y-Component of Direction-1 Vector	0
Z-Component of Direction-1 Vector	0
X-Component of Direction-2 Vector	0
Y-Component of Direction-2 Vector	1
Z-Component of Direction-2 Vector	0
X-Component of Cone Axis Vector	1
Y-Component of Cone Axis Vector	0
Z-Component of Cone Axis Vector	0
X-Coordinate of Point on Cone Axis (m)	1
Y-Coordinate of Point on Cone Axis (m)	0
Z-Coordinate of Point on Cone Axis (m)	0
Half Angle of Cone Relative to its Axis (deg)	0
Relative Velocity Resistance Formulation?	yes
Direction-1 Viscous Resistance (1/m2)	0
Direction-2 Viscous Resistance (1/m2)	0
Direction-3 Viscous Resistance (1/m2)	0
Choose alternative formulation for inertial resistance?	no
Direction-1 Inertial Resistance (1/m)	0
Direction-2 Inertial Resistance (1/m)	0
Direction-3 Inertial Resistance (1/m)	0
C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminum

hot_top

```
        Condition
Value
        ----------------------------------------------------------------
------------
        Material Name
mixture-template
        Specify source terms?                                     no
        Source Terms                                              ()
        Specify fixed values?                                     no
        Local Coordinate System for Fixed Velocities              no
        Fixed Values                                              ()
        Motion Type                                               0
        X-Velocity Of Zone (m/s)                                  0
        Y-Velocity Of Zone (m/s)                                  0
        Z-Velocity Of Zone (m/s)                                  0
        Rotation speed (rad/s)                                    0
        X-Origin of Rotation-Axis (m)                             0
        Y-Origin of Rotation-Axis (m)                             0
        Z-Origin of Rotation-Axis (m)                             0
        X-Component of Rotation-Axis                              0
        Y-Component of Rotation-Axis                              0
        Z-Component of Rotation-Axis                              1
        Deactivated Thread                                        no
        Porous zone?                                              no
        Conical porous zone?                                      no
        X-Component of Direction-1 Vector                         1
        Y-Component of Direction-1 Vector                         0
        Z-Component of Direction-1 Vector                         0
        X-Component of Direction-2 Vector                         0
        Y-Component of Direction-2 Vector                         1
        Z-Component of Direction-2 Vector                         0
        X-Component of Cone Axis Vector                           1
        Y-Component of Cone Axis Vector                           0
        Z-Component of Cone Axis Vector                           0
        X-Coordinate of Point on Cone Axis (m)                    1
        Y-Coordinate of Point on Cone Axis (m)                    0
        Z-Coordinate of Point on Cone Axis (m)                    0
        Half Angle of Cone Relative to its Axis (deg)             0
        Relative Velocity Resistance Formulation?                 yes
        Direction-1 Viscous Resistance (1/m2)                     0
        Direction-2 Viscous Resistance (1/m2)                     0
        Direction-3 Viscous Resistance (1/m2)                     0
        Choose alternative formulation for inertial resistance?   no
        Direction-1 Inertial Resistance (1/m)                     0
        Direction-2 Inertial Resistance (1/m)                     0
        Direction-3 Inertial Resistance (1/m)                     0
        C0 Coefficient for Power-Law                              0
        C1 Coefficient for Power-Law                              0
        Porosity                                                  1
        Solid Material Name
aluminum

      hot_valve

        Condition
Value
```

```
         --------------------------------------------------------------
------------
         Material Name
mixture-template
         Specify source terms?                                     no
         Source Terms                                              ()
         Specify fixed values?                                     no
         Local Coordinate System for Fixed Velocities              no
         Fixed Values                                              ()
         Motion Type                                               0
         X-Velocity Of Zone (m/s)                                  0
         Y-Velocity Of Zone (m/s)                                  0
         Z-Velocity Of Zone (m/s)                                  0
         Rotation speed (rad/s)                                    0
         X-Origin of Rotation-Axis (m)                             0
         Y-Origin of Rotation-Axis (m)                             0
         Z-Origin of Rotation-Axis (m)                             0
         X-Component of Rotation-Axis                              0
         Y-Component of Rotation-Axis                              0
         Z-Component of Rotation-Axis                              1
         Deactivated Thread                                        no
         Porous zone?                                              no
         Conical porous zone?                                      no
         X-Component of Direction-1 Vector                         1
         Y-Component of Direction-1 Vector                         0
         Z-Component of Direction-1 Vector                         0
         X-Component of Direction-2 Vector                         0
         Y-Component of Direction-2 Vector                         1
         Z-Component of Direction-2 Vector                         0
         X-Component of Cone Axis Vector                           1
         Y-Component of Cone Axis Vector                           0
         Z-Component of Cone Axis Vector                           0
         X-Coordinate of Point on Cone Axis (m)                    1
         Y-Coordinate of Point on Cone Axis (m)                    0
         Z-Coordinate of Point on Cone Axis (m)                    0
         Half Angle of Cone Relative to its Axis (deg)             0
         Relative Velocity Resistance Formulation?                 yes
         Direction-1 Viscous Resistance (1/m2)                     0
         Direction-2 Viscous Resistance (1/m2)                     0
         Direction-3 Viscous Resistance (1/m2)                     0
         Choose alternative formulation for inertial resistance?   no
         Direction-1 Inertial Resistance (1/m)                     0
         Direction-2 Inertial Resistance (1/m)                     0
         Direction-3 Inertial Resistance (1/m)                     0
         C0 Coefficient for Power-Law                              0
         C1 Coefficient for Power-Law                              0
         Porosity                                                  1
         Solid Material Name
aluminum

      pebbles

         Condition
Value
         --------------------------------------------------------------
-----------------------------------------------------------------------
-----------------------------------------------------------------------
```

```
------------------------------------------------------------------------
----------------------------------------------------------------
        Material Name
mixture-template
        Specify source terms?                                        no
        Source Terms
((mass) (x-momentum) (y-momentum) (z-momentum) (species-0) (energy))
        Specify fixed values?                                        no
        Local Coordinate System for Fixed Velocities                 no
        Fixed Values                                                 ((x-
velocity (inactive . #f) (constant . 0) (profile  )) (y-velocity
(inactive . #f) (constant . 0) (profile  )) (z-velocity (inactive . #f)
(constant . 0) (profile  )) (species-0 (inactive . #f) (constant . 0)
(profile  )) (temperature (inactive . #f) (constant . 0) (profile  )))
        Motion Type                                                  0
        X-Velocity Of Zone (m/s)                                     0
        Y-Velocity Of Zone (m/s)                                     0
        Z-Velocity Of Zone (m/s)                                     0
        Rotation speed (rad/s)                                       0
        X-Origin of Rotation-Axis (m)                                0
        Y-Origin of Rotation-Axis (m)                                0
        Z-Origin of Rotation-Axis (m)                                0
        X-Component of Rotation-Axis                                 0
        Y-Component of Rotation-Axis                                 0
        Z-Component of Rotation-Axis                                 1
        Deactivated Thread                                           no
        Porous zone?                                                 yes
        Conical porous zone?                                         no
        X-Component of Direction-1 Vector                            1
        Y-Component of Direction-1 Vector                            0
        Z-Component of Direction-1 Vector                            0
        X-Component of Direction-2 Vector                            0
        Y-Component of Direction-2 Vector                            1
        Z-Component of Direction-2 Vector                            0
        X-Component of Cone Axis Vector                              1
        Y-Component of Cone Axis Vector                              0
        Z-Component of Cone Axis Vector                              0
        X-Coordinate of Point on Cone Axis (m)                       1
        Y-Coordinate of Point on Cone Axis (m)                       0
        Z-Coordinate of Point on Cone Axis (m)                       0
        Half Angle of Cone Relative to its Axis (deg)                0
        Relative Velocity Resistance Formulation?                    yes
        Direction-1 Viscous Resistance (1/m2)
5860000
        Direction-2 Viscous Resistance (1/m2)
5860000
        Direction-3 Viscous Resistance (1/m2)
5860000
        Choose alternative formulation for inertial resistance?      no
        Direction-1 Inertial Resistance (1/m)                        2734
        Direction-2 Inertial Resistance (1/m)                        2734
        Direction-3 Inertial Resistance (1/m)                        2734
        C0 Coefficient for Power-Law                                 0
        C1 Coefficient for Power-Law                                 0
        Porosity
0.40000001
```

Solid Material Name
glass

injection_point

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	0
Y-Component of Wall Translation	0
Z-Component of Wall Translation	-1
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 1) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	1
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	0
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

outlet

Condition	Value

cold_exit

Condition	Value

```
cold_enter

   Condition   Value
   -----------------

hot_exit

   Condition   Value
   -----------------

pebble_exit

   Condition   Value
   -----------------

pebble_enter

   Condition   Value
   -----------------

inlet

   Condition   Value
   -----------------

barrel_walls

   Condition                                                   Value
   ------------------------------------------------------------------
---------------------
   Wall Thickness (m)                                          0
   Heat Generation Rate (w/m3)                                 0
   Material Name                                               aluminum
   Thermal BC Type                                             0
   Temperature (k)                                             293
   Heat Flux (w/m2)                                            0
   Convective Heat Transfer Coefficient (w/m2-k)               0
   Free Stream Temperature (k)                                 300
   Enable shell conduction?                                    no
   Wall Motion                                                 0
   Shear Boundary Condition                                    0
   Define wall motion relative to adjacent cell zone?          yes
   Apply a rotational velocity to this wall?                   no
   Velocity Magnitude (m/s)                                    0
   X-Component of Wall Translation                             1
   Y-Component of Wall Translation                             0
   Z-Component of Wall Translation                             0
   Define wall velocity components?                            no
   X-Component of Wall Translation (m/s)                       0
   Y-Component of Wall Translation (m/s)                       0
   Z-Component of Wall Translation (m/s)                       0
   External Emissivity                                         1
   External Radiation Temperature (k)                          300
                                                               (0)

(((constant . 0) (profile  )))
   Rotation Speed (rad/s)                                      0
```

```
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     new_cold_valve

        Condition                                           Value
        ------------------------------------------------------------
---------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     1
        Temperature (k)                                     300
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     cold_walls
```

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	0
Temperature (k)	283
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no
Wall Motion	0
Shear Boundary Condition	0
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude (m/s)	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Z-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation (m/s)	0
Y-Component of Wall Translation (m/s)	0
Z-Component of Wall Translation (m/s)	0
External Emissivity	1
External Radiation Temperature (k)	300
	(0)

(((constant . 0) (profile)))

Rotation Speed (rad/s)	0
X-Position of Rotation-Axis Origin (m)	0
Y-Position of Rotation-Axis Origin (m)	0
Z-Position of Rotation-Axis Origin (m)	0
X-Component of Rotation-Axis Direction	0
Y-Component of Rotation-Axis Direction	0
Z-Component of Rotation-Axis Direction	1
X-component of shear stress (pascal)	0
Y-component of shear stress (pascal)	0
Z-component of shear stress (pascal)	0
Surface tension gradient (n/m-k)	0
Specularity Coefficient	0

cross_over_walls

Condition	Value
Wall Thickness (m)	0
Heat Generation Rate (w/m3)	0
Material Name	copper
Thermal BC Type	1
Temperature (k)	300
Heat Flux (w/m2)	0
Convective Heat Transfer Coefficient (w/m2-k)	0
Free Stream Temperature (k)	300
Enable shell conduction?	no

```
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
        External Radiation Temperature (k)                  300
                                                            (0)

(((constant . 0) (profile  )))
        Rotation Speed (rad/s)                              0
        X-Position of Rotation-Axis Origin (m)              0
        Y-Position of Rotation-Axis Origin (m)              0
        Z-Position of Rotation-Axis Origin (m)              0
        X-Component of Rotation-Axis Direction              0
        Y-Component of Rotation-Axis Direction              0
        Z-Component of Rotation-Axis Direction              1
        X-component of shear stress (pascal)                0
        Y-component of shear stress (pascal)                0
        Z-component of shear stress (pascal)                0
        Surface tension gradient (n/m-k)                    0
        Specularity Coefficient                             0

     hot_top_walls

        Condition                                           Value
        ---------------------------------------------------------------
---------------------
        Wall Thickness (m)                                  0
        Heat Generation Rate (w/m3)                         0
        Material Name                                       copper
        Thermal BC Type                                     1
        Temperature (k)                                     300
        Heat Flux (w/m2)                                    0
        Convective Heat Transfer Coefficient (w/m2-k)       0
        Free Stream Temperature (k)                         300
        Enable shell conduction?                            no
        Wall Motion                                         0
        Shear Boundary Condition                            0
        Define wall motion relative to adjacent cell zone?  yes
        Apply a rotational velocity to this wall?           no
        Velocity Magnitude (m/s)                            0
        X-Component of Wall Translation                     1
        Y-Component of Wall Translation                     0
        Z-Component of Wall Translation                     0
        Define wall velocity components?                    no
        X-Component of Wall Translation (m/s)               0
        Y-Component of Wall Translation (m/s)               0
        Z-Component of Wall Translation (m/s)               0
        External Emissivity                                 1
```

```
        External Radiation Temperature (k)                           300
                                                                     (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                       0
        X-Position of Rotation-Axis Origin (m)                       0
        Y-Position of Rotation-Axis Origin (m)                       0
        Z-Position of Rotation-Axis Origin (m)                       0
        X-Component of Rotation-Axis Direction                       0
        Y-Component of Rotation-Axis Direction                       0
        Z-Component of Rotation-Axis Direction                       1
        X-component of shear stress (pascal)                         0
        Y-component of shear stress (pascal)                         0
        Z-component of shear stress (pascal)                         0
        Surface tension gradient (n/m-k)                             0
        Specularity Coefficient                                      0

     hot_valve_walls

        Condition                                                    Value
        ------------------------------------------------------------------
--------------------
        Wall Thickness (m)                                           0
        Heat Generation Rate (w/m3)                                  0
        Material Name                                                copper
        Thermal BC Type                                              1
        Temperature (k)                                              300
        Heat Flux (w/m2)                                             0
        Convective Heat Transfer Coefficient (w/m2-k)                0
        Free Stream Temperature (k)                                  300
        Enable shell conduction?                                     no
        Wall Motion                                                  0
        Shear Boundary Condition                                     0
        Define wall motion relative to adjacent cell zone?           yes
        Apply a rotational velocity to this wall?                    no
        Velocity Magnitude (m/s)                                     0
        X-Component of Wall Translation                              1
        Y-Component of Wall Translation                              0
        Z-Component of Wall Translation                              0
        Define wall velocity components?                             no
        X-Component of Wall Translation (m/s)                        0
        Y-Component of Wall Translation (m/s)                        0
        Z-Component of Wall Translation (m/s)                        0
        External Emissivity                                          1
        External Radiation Temperature (k)                           300
                                                                     (0)

(((constant . 0) (profile )))
        Rotation Speed (rad/s)                                       0
        X-Position of Rotation-Axis Origin (m)                       0
        Y-Position of Rotation-Axis Origin (m)                       0
        Z-Position of Rotation-Axis Origin (m)                       0
        X-Component of Rotation-Axis Direction                       0
        Y-Component of Rotation-Axis Direction                       0
        Z-Component of Rotation-Axis Direction                       1
        X-component of shear stress (pascal)                         0
        Y-component of shear stress (pascal)                         0
```

```
         Z-component of shear stress (pascal)                0
         Surface tension gradient (n/m-k)                    0
         Specularity Coefficient                             0

      pebble_walls

         Condition                                           Value
         -------------------------------------------------------------
---------------------
         Wall Thickness (m)                                  0
         Heat Generation Rate (w/m3)                         0
         Material Name                                       copper
         Thermal BC Type                                     0
         Temperature (k)                                     473
         Heat Flux (w/m2)                                    0
         Convective Heat Transfer Coefficient (w/m2-k)       0
         Free Stream Temperature (k)                         300
         Enable shell conduction?                            no
         Wall Motion                                         0
         Shear Boundary Condition                            0
         Define wall motion relative to adjacent cell zone?  yes
         Apply a rotational velocity to this wall?           no
         Velocity Magnitude (m/s)                            0
         X-Component of Wall Translation                     1
         Y-Component of Wall Translation                     0
         Z-Component of Wall Translation                     0
         Define wall velocity components?                    no
         X-Component of Wall Translation (m/s)               0
         Y-Component of Wall Translation (m/s)               0
         Z-Component of Wall Translation (m/s)               0
         External Emissivity                                 1
         External Radiation Temperature (k)                  300
                                                              (0)

(((constant . 0) (profile )))
         Rotation Speed (rad/s)                              0
         X-Position of Rotation-Axis Origin (m)              0
         Y-Position of Rotation-Axis Origin (m)              0
         Z-Position of Rotation-Axis Origin (m)              0
         X-Component of Rotation-Axis Direction              0
         Y-Component of Rotation-Axis Direction              0
         Z-Component of Rotation-Axis Direction              1
         X-component of shear stress (pascal)                0
         Y-component of shear stress (pascal)                0
         Z-component of shear stress (pascal)                0
         Surface tension gradient (n/m-k)                    0
         Specularity Coefficient                             0

      default-interior

         Condition   Value
         -----------------

      default-interior:001

         Condition   Value
         -----------------
```

```
      default-interior:024

         Condition   Value
         -----------------

      default-interior:026

         Condition   Value
         -----------------

      default-interior:027

         Condition   Value
         -----------------

      default-interior:028

         Condition   Value
         -----------------

      default-interior:029

         Condition   Value
         -----------------

Solver Controls
---------------

   Equations

      Equation   Solved
      -----------------
      Flow       yes
      he         yes
      Energy     yes

   Numerics

      Numeric                         Enabled
      ---------------------------------------
      Absolute Velocity Formulation   yes

   Unsteady Calculation Parameters


      ------------------------------------
      Time Step (s)                   0.12
      Max. Iterations Per Time Step   200

   Relaxation

      Variable      Relaxation Factor
      -------------------------------
      Pressure      0.60000002
      Density       0.5
      Body Forces   1
```

Momentum	0.40000001
he	1
Energy	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
he	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Pressure-Velocity Coupling

Parameter	Value
Type	PISO
Skewness-Neighbour Coupling	yes
Skewness Correction	1
Neighbour Correction	1

Discretization Scheme

Variable	Scheme
Pressure	PRESTO!
Density	Second Order Upwind
Momentum	Second Order Upwind
he	Power Law
Energy	Second Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: glass (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2440
Cp (Specific Heat)	j/kg-k	constant	840
Thermal Conductivity	w/m-k	constant	0.93699998

Material: copper (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	8978
Cp (Specific Heat)	j/kg-k	constant	381
Thermal Conductivity	w/m-k	constant	387.60001

Material: (nitrogen-new . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: (helium . mixture-template) (fluid)

Property	Units	Method	Value(s)
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: helium (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	4.0026002
L-J Characteristic Length	angstrom	constant	2.5510001
L-J Energy Parameter	k	constant	10.22
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	3
Speed of Sound	m/s	none	#f

Material: nitrogen-new (fluid)

Property	Units	Method	Value(s)

Property	Units	Method	Value(s)
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	kinetic-theory	#f
Thermal Conductivity	w/m-k	kinetic-theory	#f
Viscosity	kg/m-s	kinetic-theory	#f
Molecular Weight	kg/kgmol	constant	28.013399
L-J Characteristic Length	angstrom	constant	3.7980001
L-J Energy Parameter	k	constant	71.400002
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	5
Speed of Sound	m/s	none	#f

Material: mixture-template (mixture)

Property	Units	Method	Value(s)
Mixture Species		names	((he n2-new) () ())
Density	kg/m3	ideal-gas	#f
Cp (Specific Heat)	j/kg-k	mixing-law	#f
Thermal Conductivity	w/m-k	ideal-gas-mixing-law	#f
Viscosity	kg/m-s	ideal-gas-mixing-law	#f
Mass Diffusivity	m2/s	kinetic-theory	#f
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0
Speed of Sound	m/s	none	#f

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.138
Cp (Specific Heat)	j/kg-k	constant	1040.67
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.663e-05
Molecular Weight	kg/kgmol	constant	28.0134
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: oxygen (fluid)

Property	Units	Method	Value(s)

Density	kg/m3	constant	1.2999
Cp (Specific Heat)	j/kg-k	constant	919.31
Thermal Conductivity	w/m-k	constant	0.0246
Viscosity	kg/m-s	constant	1.919e-05
Molecular Weight	kg/kgmol	constant	31.9988
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	0.5542
Cp (Specific Heat)	j/kg-k	constant	2014
Thermal Conductivity	w/m-k	constant	0.0261
Viscosity	kg/m-s	constant	1.34e-05
Molecular Weight	kg/kgmol	constant	18.01534
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: air (fluid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	1.225
Cp (Specific Heat)	j/kg-k	constant	1006.43
Thermal Conductivity	w/m-k	constant	0.0242
Viscosity	kg/m-s	constant	1.7894e-05
Molecular Weight	kg/kgmol	constant	28.966
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Thermal Expansion Coefficient	1/k	constant	0
Degrees of Freedom		constant	0
Speed of Sound	m/s	none	#f

Material: aluminum (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.39999

A3. 1-D Diffusion Matlab Script

```
%% Determine analytical solution to diffusion equation for 62x
experiment
%% Determine onset time when buoyant force is greater than helium
cushion
%% Parameters
clear all
close all
% 62x apparatus dimensions
H = 60.5; % total hot leg height [in.]
h = 39; % pebble bed height [in.]
poro = 0.4; % porosity
% calculate diffusion path length
Ld = (poro/(1-poro))*h+H; % [in.]
Ld = Ld*0.0254; % [m]
H = H*0.0254; % convert height to [m]
% cross over leg
Lc = 0.2921; % cross over leg length [m]
% temperatures
Th = 200; % hot leg temp [degC]
Th = Th + 273; % [K]
Tc = 10; % cold leg temp [degC]
Tc = Tc + 273; % [K]
% compute total concentration
g = 9.81; % [m/s^2]
P =  101325; % operating pressure [Pa]
Rbar = 8.314; % gas constant [J/mol-K]
chot = P/Rbar/Th; % total concentration in hot leg [mol/m^3]
ccold = P/Rbar/Tc; % tot. concentration in cold leg [mol/m^3]
%% Diffusion Coefficient
MHe = 4.0026; % [kg/kmol]
MAir = 28.9536; % [kg/kmol]
vHe = 2.88; % helium diffusion volume
vAir = 20.1; % air diffusion volume
% hot leg diffusion coefficient
Dhot = 1e-4*1e-
3*Th^1.75*sqrt((MHe+MAir)/(MHe*MAir))/(vHe^(1/3)+vAir^(1/3))^2;
% cold leg diffusion coefficient
Dcold = 1e-4*1e-
3*Tc^1.75*sqrt((MHe+MAir)/(MHe*MAir))/(vHe^(1/3)+vAir^(1/3))^2;
%% Driving Density Difference At Steady-State Natural Circulation
% at this point in time, all air circulating through apparatus
Rair = Rbar/(MAir/1000); % air gas constant [J/kg/K]
% hot leg density
rhoHA = P/Rair/Th; % [kg/m^3]
% cold leg density
rhoCA = P/Rair/Tc; % [kg/m^3]
% driving density difference
diffSS = rhoCA-rhoHA; % [kg/m^3]
%% Height Intervals
ih = 10; % intervals in hot leg
ic = 10; % intervals in cold leg
dh = Ld/ih;
dc = H/ic;
xH = 0:dh:Ld; % hot leg position points
xC = 0:dc:H; % cold leg position points
xH = xH';
xC = xC';
```

```
%% Cross over leg temps.
ico = 10; % intervals in cross overleg
dco = Lc/ico;
xCO = 0:dco:Lc;
Tco = Th + xCO.*(Tc-Th)/Lc;
%% Boundary Condition
% Use solution for 1-D diffusion up both hot and cold legs, with
constant
% ambient air concentration at inlet
Tam = 293; % [K]
c0h = P/Rbar/Tam; % hot leg inlet condition [mol/m^3]
c0c = P/Rbar/Tam; % cold leg inlet condition [mol/m^3]
%% Solve Diffusion Eqn
% total concentrations in hot and cold legs
cHt = P/Rbar/Th; % hot leg [mol/m^3]
cCt = P/Rbar/Tc; % cold leg [mol/m^3]
MAir = MAir/1000; % [kg/mol]
MHe = MHe/1000; % [kg/mol]
% run time
run = 6; % hours
run = run*3600; % [s]
dt = 1; % time interval [s]
t = 0.0001:dt:run; % time vector
tmin = t./60; % time vector in minutes
% preset vectors
difLH = zeros(length(t),1);
difLC = zeros(length(t),length(xH));
cAH = zeros(length(t),length(xH));
XXAH = zeros(length(t),length(xH));
rhoHOT = zeros(length(t),length(xH));
cAC = zeros(length(t),length(xC));
XXAC = zeros(length(t),length(xC));
rhoCOLD = zeros(length(t),length(xC));
cAFH = zeros(length(t),length(xCO));
cAFC = zeros(length(t),length(xCO));
cACO = zeros(length(t),length(xCO));
cTCO = zeros(length(t),length(xCO));
XXCO = zeros(length(t),length(xCO));
rhoCO = zeros(length(t),length(xCO));
% Time Loop
for j = 1:length(t)
    difLH(j) = sqrt(4*Dhot*t(j)); % hot leg characteristic diffusion
length
    difLC(j) = sqrt(4*Dcold*t(j));% cold leg characteristic diffusion
length
    % hot leg loop
    for k = 1:length(xH)
        % air mole concentration at point k at time j
        cAH(j,k) = c0h.*erfc(xH(k)/difLH(j)); % [mol/m^3]
        if cAH(j,k)>cHt
            cAH(j,k)=cHt;
        end
        % mole fraction at point k at time j
        XXAH(j,k) = cAH(j,k)/cHt;
        % gas mixture density at at point k at time j
        rhoHOT(j,k) = P*(XXAH(j,k)*MAir+(1-XXAH(j,k))*MHe)/(Rbar*Th);
    end
```

```
    % Average hot leg density
    %AVGHOT(j) = mean(rhoHOT(j,k));
    % cold leg loop
    for l = 1:length(xC)
        % air mole concentration at point l at time j
        cAC(j,l) = c0c.*erfc(xC(l)/difLC(j)); % [mol/m^3]
        if cAC(j,l)>cCt;
            cAC(j,l)=cCt;
        end
        % mole fraction at point l at time j
        XXAC(j,l) = cAC(j,l)/cCt;
        % gas mixture density at point l at time j
        rhoCOLD(j,l) = P*(XXAC(j,l)*MAir+(1-XXAC(j,l))*MHe)/(Rbar*Tc);
    end
    % Average cold leg density
    %AVGCOLD(j) = mean(rhoCOLD(j,l));
    % DRIVING DENSITY DIFFERENCE
    %diffDR(j) = AVGCOLD(j)-AVGHOT(j);
    % cross-over leg loop
    for m = 1:length(xCO)
        % air mole concentration contribution from hot leg
        cAFH(j,m) = c0h.*erfc((xCO(m)+Ld)/difLH(j));
        % air mole concentration contribution from cold leg
        cAFC(j,m) = c0c.*erfc((Lc-xCO(m)+H)/difLC(j));
        % sum from hot and cold legs
        cACO(j,m) = cAFH(j,m)+cAFC(j,m);
        % total concentation at each point
        cTCO(j,m) = P/Rbar/Tco(m);
        % mole fraction at each point
        XXCO(j,m) = cACO(j,m)/cTCO(j,m);
        % density at each point
        rhoCO(j,m) = P*(XXCO(j,m)*MAir+(1-
XXCO(j,m))*MHe)/(Rbar*Tco(m));
    end

end
%% COMPUTE AVERAGE VALUES AT EACH TIME STEP
% Average hot leg density at each time step
AVGHOT = mean(rhoHOT,2);
% Average cold leg density at each time step
AVGCOLD = mean(rhoCOLD,2);
% Driving density difference at each time step
diffDR = AVGCOLD-AVGHOT;
% Average cross-over leg density at each time step
AVGCROSS = mean(rhoCO,2);
% Average mole fraction in cross-over leg at each time step
AVGXX = mean(XXCO,2);
AVGHEX = 1-AVGXX; % average helium mole fraction
% Compare helium cushion to buoyancy force
HeCushion = diffDR - AVGCROSS.*(Lc/H);
% difference in hot leg and cross over leg density
hotCOdiff = AVGCROSS-AVGHOT;
% perhaps this is the cushion
HECUS2 = hotCOdiff - AVGCROSS.*(Lc/H);
%% PLOTS
%plot(tmin,HeCushion,tmin,HECUS2)
%figure
```

```
%plot(tmin,AVGHEX)
%figure
%plot(tmin,diffDR,tmin,AVGCROSS)
%plot(tmin,diffDR(:))
%figure
%plot(tmin,XXAH(:,2),tmin,XXAH(:,3),tmin,XXAH(:,4),tmin,XXAH(:,10),tmin
,XXAH(:,11))
%figure
%plot(tmin,AVGHOT,tmin,AVGCOLD)
```

A4. Pebble Wall Temperature UDF

```
/*********************************************************************/
/*Pebble Wall Temperature Boundary Condition*************/
/*********************************************************************/

#include "udf.h"

DEFINE_PROFILE(peb_wall_temp_BC, thread, index)
{
   real x[ND_ND];
   real y;
   face_t f;

   begin_f_loop(f, thread)
     {
      F_CENTROID(x,f,thread);
      y = x[1];
      F_PROFILE(f, thread, index) = 689.31*(y*y*y)-1686.8*y*y+1291.8*y+169.1;
     }
   end_f_loop(f, thread)
}
```

A5. MIR Matlab Script

```
%% Determine the Helium MIR
clear all
%% Make guesses for what molar concentrations are:
M_He = 4; % molar mass of He
M_Air = 29; % molar mass of air
R = 8.314; % gas constant for He    [(m3*Pa)/(K*mol)]
P = 103000; % atmospheric pressure    [Pa]
Th = 1600+273; % hot leg temperature    [K]
Tc = 552; % cold leg temperature    [K]
% molar concentration in hot leg (value from FLUENT)
c_h = P/(R*Th); % [mol/m^3]
% molar concentration in cold leg (value from FLUENT)
c_c = P/(R*Tc); % [mol/m^3]

%% He mole fraction boundary conditions taken from FLUENT results
Xh_o = 0.46399277; %top
Xh_L = 0.014123678; %bottom

Xc_o = 0.55848438;%0.75; %top
Xc_L = 0.081556395; %bottom

%% Estimate Mass Diffusivity
DvolHe = 2.88;
DvolAir = 20.1;
```

```
Dh = 1e-
7*Th^1.75*(((M_He+M_Air)/(M_He*M_Air))^(1/2))/((DvolHe^(1/3)+DvolAir^(1/3))^2
); % [m^2/s]
Dc = 1e-
7*Tc^1.75*(((M_He+M_Air)/(M_He*M_Air))^(1/2))/((DvolHe^(1/3)+DvolAir^(1/3))^2
);

%% Find the MIR of He
Lc = 19.33; % cold leg height [m]
Lh = 19.33; % hot leg height [m]
Ah = 0.5542; % hot leg flow area [m^2]
Ac = 0.7559; % cold leg flow area [m^2]
Sstar = Ac/Ah;
% molar flux of He in hot leg
Nh = c_h*Dh*(Xh_o-Xh_L)/Lh;
% Iterate to solve for Nc
diff = 1;
counter = 0;
%Nc1_g = 100*Nh; % initial guess for Nc
Nc1 = 10*Nh;
%Nstar_g = 1 + Nh/(Sstar*Nc1); % initial guess for Nstar
Nstar = 1 + Nh/(Sstar*Nc1);
U = [Nc1; Nstar];
Rmat = [1;1];
while ( abs(Rmat(2))>1e-10 ||abs(Rmat(1))>1e-10 )   %abs(Rmat(2))>1e-10 ||
R1 = U(1) - c_c*Dc*log(abs((1-Nstar*Xc_L)/(1-Nstar*Xc_o)))/(Nstar*Lc);
R2 = U(2) - (1 + Nh/(Sstar*Nc1));

%NR
%Derivative matrix
d1dN = 1;
d1dNs = -(c_c*Dc/Lc)* ...
     (((log(abs((1-Nstar*Xc_L)/(1-Nstar*Xc_o))))*(-1/Nstar^2)) + ...
     ((1/Nstar)*(((1-Nstar*Xc_o)*-Xc_L) - ((1-Nstar*Xc_L)*-Xc_o))/((1-
Nstar*Xc_L)*(1-Nstar*Xc_o))));
d2dN = Nh/(Sstar*(Nc1^2));
d2dNs = 1;
dMatrix = [d1dN d1dNs; d2dN d2dNs];
Rmat = [R1; R2];

Delta = dMatrix\-Rmat;

U = U+(Delta);

Nc1=abs(U(1));
Nstar=abs(U(2));
counter = counter + 1;
end;
U
N_He = U(1) + Nh;
Nh=Nh*A;
Nc=U(1)*A*Sstar;
N_He_molpers = Nh + Nc; %mol/s
N_He_kgpers = N_He_molpers*M_He/1000; %kg/s
```

N_He_molpers

N_He_kgpers