Analyzing the Effect of Pressure Drop on Flow Rate of Hot Water in the Intercoolers Assembly of the Lean Operation Rotary Adsorption Cooling System

by

Jung Yun Susan Yoon

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2019

Signature of Author: Signature redacted
Department of Mechanical Engineering
May 10, 2019

Certified by: Signature redacted
Douglas Hart
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: Signature redacted
Maria Yang
Professor of Mechanical Engineering
Undergraduate Officer

Analyzing the Effect of Pressure Drop on Flow Rate of Hot Water in the Intercoolers Assembly of the Lean Operation Rotary Adsorption Cooling System

by

Jung Yun Susan Yoon

Submitted to the Department of Mechanical Engineering
on May 10, 2019 in Partial Fulfillment of the
Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

ABSTRACT

The lean operation rotary adsorption cooling system, a novel idea using a readily available low-grade heat and using desiccant wheel to provide a cooling power, was tested this semester. Specifically, this experimental study focuses on the pressure drop of hot water in the two intercoolers that are part of the desiccant wheel module and the flow rate. The measured pressure drop was 1.3 psi, which was close to the calculated value of 1.59 psi and 1.60 psi. There is a great potential for future work on this project as the initial testing results of the overall system were favorable. There were also various limitations of the testing environment that can be optimized in the future.

Thesis Supervisor: Prof. Doug Hart
Title: Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

First, I would like to thank my TA Peter Godart and advisor Prof. Doug Hart for their help and guidance on this research project and writing of this thesis. I would also like to thank the MIT Office of Sustainability for providing funding to work on this innovative project.

Besides my advisors, I would like to thank the 2.013 team for their novel design ideas and my fellow 2.014 team members of the LORACS Team. I would also like to thank my mentors and colleagues in the Department of Mechanical Engineering at MIT for teaching me and challenging me intellectually for the past 4 years at MIT.

Finally, I would like to thank my family, friends, and especially my twin sister (also a Course 2 Class of 2019) for their unconditional love and support. Special thanks to my Dad, for inspiring me to study Mechanical Engineering and to pursue academia as my future career path.

Table of Contents

1. Introduction

2. Experimental Design and Method

3. Results

1. Introduction

1.1 Motivation

The goal of this project is to validate the Lean Operation Adsorption Cooling System (LORACS) that the 2.013 Team designed this past fall through the first implementation, which is expected to have various applications in the field of sustainability. The MIT Office of Sustainability (MITOS) plans on using the MIT campus as a test bed and incubator for this novel design of a carbon-neutral cooling system. Since this project was sponsored by the MITOS, our solution is designed for average summer conditions of Boston; however, our system can also be extended to fulfill the needs in other parts of the world with similar temperature and humidity conditions. For example, China and India will continue to have growing demand of higher standard of living and thus will have a great potential for markets in air conditioning for space cooling.

Based on the recent Fourth National Climate Assessment in 2018, the average temperature in the Northeast U.S. is predicted to rise at least 2°C within next fifty years [2]. Globally, as the climate keeps warming up, the need for space cooling will also increase; for examples, for regions that previously did not need space cooling will very soon need it. By 2050, the demand for cooling energy is expected to double.

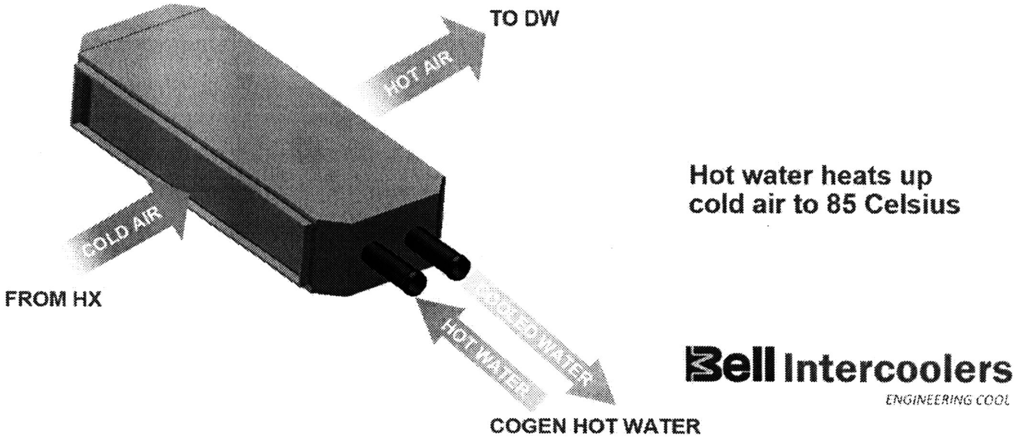


Figure 1: General diagram from Bell of air and water streams entering and exiting through a single intercooler unit

Specifically, the intercoolers—components of the Desiccant Wheel Module—have a crucial role as air heaters by warming up the cold return air to 85°C and drying the desiccant back out for a continued operation for cycling the low-grade heat. Macroscopically, the two intercoolers transfer heat from the hot water loop to the regeneration airstream. I will be regulating the water pressure drop and thus the flow from hot water supply through the two intercoolers and analyzing the relationship between water pressure drop and flow rate through Darcy's Law.

1.2 Lean Operation Rotary Adsorption Cooling System (LORACS)

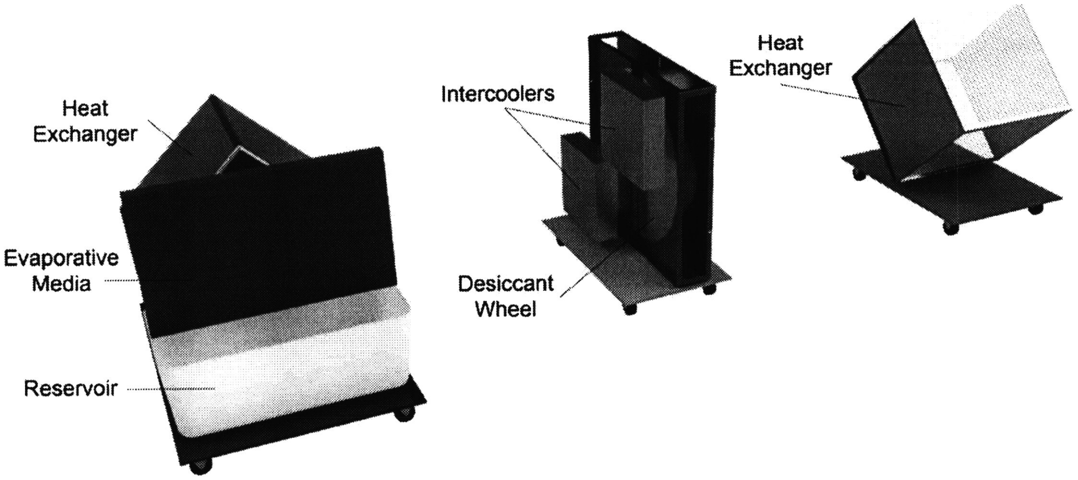


Figure 2: CAD model of the overall LORACS divided into three main modules

The LORACS is a carbon-neutral cooling system that aims to provide comfortable temperature range for living spaces without exacerbating global warming. It is designed to have enough power to cool a 550 ft^2 space and enhance the efficiency by using a low-grade heat for cooling. Using a low-grade heat is advantageous because it is readily available here at MIT through existing cogeneration plant.

In contrast to our proposed design (LORACS), most cooling systems widely used today in residential and commercial spaces mainly use a vapor compression cycle that relies on refrigerants, which contribute to global warming. The refrigerants also make it difficult to maintain the cooling units due to possibility of leakages.

There are three main modules that comprise the LORACS: Cascade Module, Desiccant Wheel Module, and Evaporative Cooler Module. We tested our system in the basement of MIT building W59 in a 550 ft^2 space, which is equivalent of a modest one family dwelling [3]. The LORACS have four inputs: outside air, air from the room to be cooled, hot water waste from the CUP, and electricity. The system feeds the colder water back into the CUP's hot water loop, hot air to the outside, and cooled air into the cooled space. MIT's cogeneration plant supplies 600 gallons per minute of hot water [3].

Currently, there are similar solutions of air-to-air heat exchangers used in the HVAC (heating, ventilation, and air-conditioning) systems and intercoolers in the automotive industry. There are also existing solutions for liquid-to-air heat exchangers in the automotive industry. The LORACS is innovative in the overall design in that it incorporate Desiccant Wheel to dry out the air.

1.3 Purpose of the Intercoolers in the Desiccant Wheel Module

Figure 3: Image of the two intercoolers mounted on the DW Module before plumbing was added.

As briefly mentioned in Section 1.1, the intercoolers is crucial in the regeneration process. They transfer the heat from the hot water loop to the regeneration airstream to allow for a continued operation using a low-grade heat. In other words, the intercoolers utilize a pressure drop of the hot water to generate a temperature rise in the air. The hot water heats up the cold air to 85°C. The performance of the intercoolers can be analyzed as a thermal performance by taking the ratio of the actual change in temperature to the ideal change in temperature. The thermal performance depends on the exposed area between the fluids, which lead our team to get help from Bell to customize our intercoolers for a target efficiency.

1.4 Overview of the Module Design from 2.013 Team

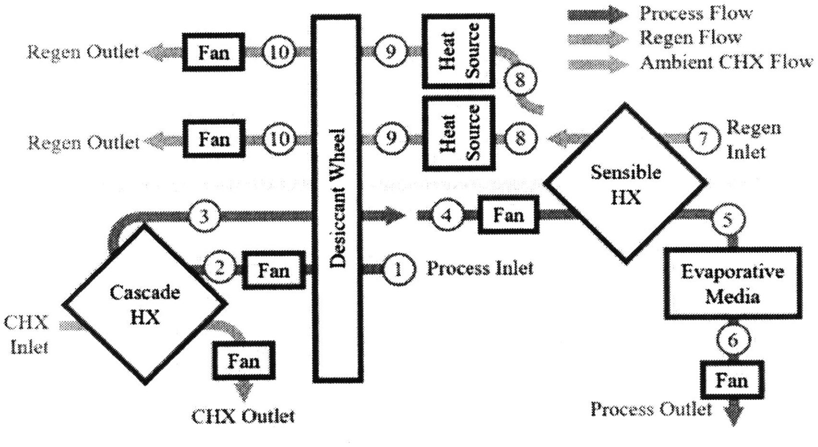


Figure 4: Schematic of the LORACS for On-Campus Integration

Fig. 4 above is a schematic of the LORACS in the testing location. The intercoolers are part of the regeneration flow process, which is labelled in green in the upper half of the schematic. Specifically, step 8 to step 9 shows the two intercoolers joined in parallel.

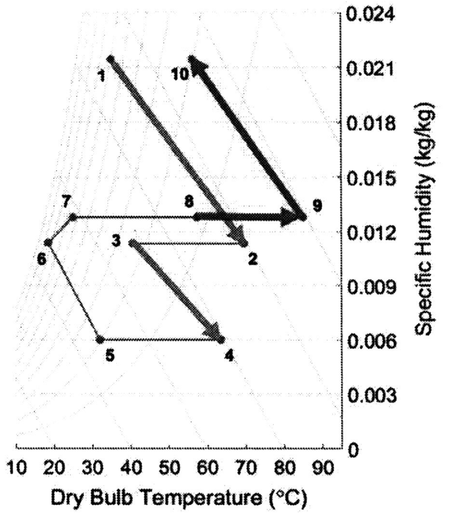


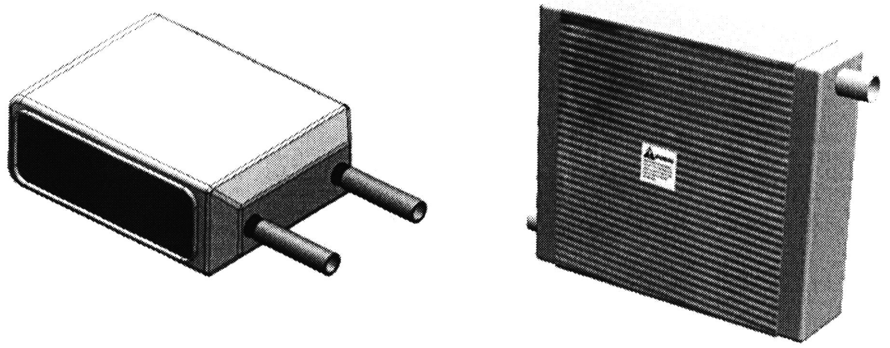
Figure 5: Psychrometric chart of the overall system where red arrows show the intercoolers regeneration process.

Fig. 5 above shows the psychrometric chart of the overall system from step 1 to 10. The intercooler process is highlighted in red from step 8 to 9. This diagram has the same step numbers labelled as the schematic figure above.

1.5 Design Changes in 2.014

The intercoolers was initially part of the Cascade Heat Exchanger Module in 2.013; however, due to logistics, a different heat exchanger was ordered which led to slight dimension changes in the Cascade Module. As a result, the two intercoolers were moved to the Desiccant Wheel Module.

The orientation of the intercoolers was initially stacked vertically above and below the sensible heat exchanger in 2.013 design, but we changed it to be in the corners aligned diagonally to increase performance efficiency. The initial orientation limited the inlet areas; for a given volume flow, small inlet is disadvantageous because small inlet means faster flow speed and higher pressure drop. It was forcing too much flow through a small inlet space, and the pressure drop was too high. As a result, we customized our intercoolers to fit out target performance goals by getting a help from Bell. We gave Bell the required delta temperature of the airstream, initial temperature of hot water, and flow rates for both ends, which Bell used to come up with the needed volume and surface area. To lower the initially high pressure drop, we kept the volume of the intercooler to be the same but made it short and wide from long and narrow to lower the pressure drop.



2.013 Configuration

2.014 Configuration

Figure 6: Change in the intercooler from 2.013 to 2.014.

1.6 Pressure Drop Calculations

- **Darcy-Weisbach Equation** (pressure loss in pipe flow calculation)

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2}$$

Where Δp is pressure loss, f is the Darcy friction factor, L is length of pipe or pipe part, D is inner diameter of the pipe, ρ is density of fluid, and v is flow velocity.

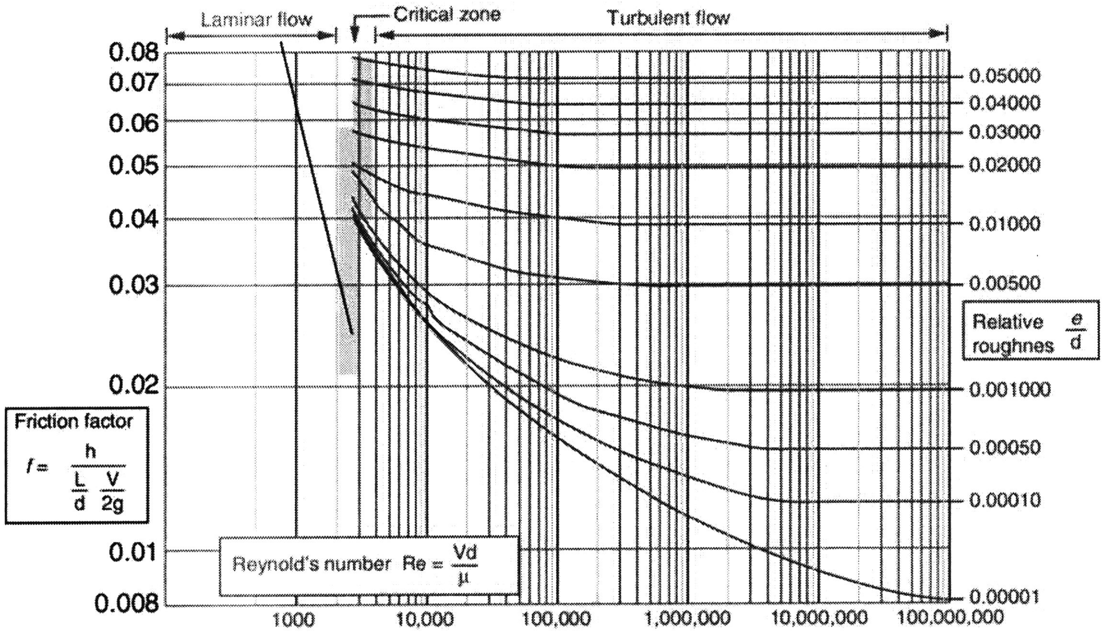


Figure 7: Moody Chart for deriving Reynolds numbers

- **Reynolds Number:**

$$Re = \frac{\rho v D}{\mu}$$

Where v is the velocity, D is hydraulic diameter, ρ is density of the fluid, and μ is dynamic viscosity. Re less than 2300 is considered laminar flow. The transition from laminar to turbulent flow ends approximately at 4000.

- **Volumetric flow rate:**

$$Q = Av = \pi R^2 v$$

$$Q = Av = wlv$$

- **Colebrook Equation** (used to solve the Darcy friction factor for turbulent flow)

$$\frac{1}{\sqrt{f}} = -2.0 \log(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}})$$

Where f is the Darcy friction factor, e is roughness of the pipe, D is inner diameter of the pipe, and *Re* is the Reynolds number.

1.6.1 Assumptions

Volumetric Flow Rate

- Q=2 gallons/min=.00012618 m^3/s

Smooth Pipe

- relative roughness ($\frac{e}{D}$) is 0
- roughness (e) is 0 mm

Rough Pipe

- roughness (e) is 0.0015 mm

1.6.2 Calculations for Steam Hose

$D = 1.25'' = 31.75\,mm$

$$v = \frac{Q}{A} = \frac{Q}{\pi({}^{D}/_{2})^2} = \frac{.00012618\, m^3/s}{\pi(.03175\, m/2)^2} = .1594\, m/s$$

$$Re = \frac{\rho v D}{\mu} = \frac{\left(1000\,\frac{kg}{m^3}\right)\left(\frac{.1594\, m}{s}\right)(.03175\, m)}{8.9\times10^{-4}\, Pa{*}s} = 5685.5 \text{ [turbulent]}$$

1.6.2.1 Calculations for Steam Hose as a Smooth Pipe

$f = .0360464$

$L = 108'' = 2.7432\, m$

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.0360464)(2.7432\, m)\left(1000\frac{kg}{m^3}\right)(.1594\, m)^2}{(.03175\, m)(2)} = \mathbf{39.57\ Pa}$$

1.6.2.2 Calculations for Steam Hose as a Rough Pipe

$f = .0361024$

$L = 108'' = 2.7432\, m$

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.0361024)(2.7432\, m)\left(1000\frac{kg}{m^3}\right)(.1594\, m)^2}{(.03175\, m)(2)} = \mathbf{39.63\ Pa}$$

1.6.3 Calculations for T-joints and Pipes

$D = 1'' = 25.4mm$

$$v = \frac{Q}{A} = \frac{Q}{\pi({}^{D}/_{2})^2} = \frac{.00012618\, m^3/s}{\pi(.0254\, m/2)^2} = .2490\, m/s$$

$$Re = \frac{\rho v D}{\mu} = \frac{\left(1000\,\frac{kg}{m^3}\right)\left(\frac{.2490\, m}{s}\right)(.0254\, m)}{8.9\times10^{-4}\, Pa{*}s} = 7106.3 \text{ [turbulent]}$$

1.6.3.1 Calculations for T-joints and Pipes as a Smooth Pipe

$f = .0338687$

$L = 36'' = 914.4\, mm$

- For pipes:

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.0338687)(.9144\ m)\left(1000\frac{kg}{m^3}\right)(.2490\ m)^2}{(.0254\ m)(2)} = \mathbf{37.8\ Pa}$$

- For the four T-joints:

$K = .69$

$pressure\ drop = (1 + 4K)(\Delta p) = (3.76)(37.8\ Pa) = \boldsymbol{142.13\ Pa}$

1.6.3.2 Calculations for T-joints and Pipes as a Rough Pipe

$f = .0339462$

$L = 36'' = 914.4\ mm$

- For pipes:

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.0339462)(.9144\ m)\left(1000\frac{kg}{m^3}\right)(.2490\ m)^2}{(.0254\ m)(2)} = \mathbf{37.9\ Pa}$$

- For the four T-joints:

$K = .69$

$pressure\ drop = (1 + 4K)(\Delta p) = (3.76)(37.9\ Pa) = \boldsymbol{142.43\ Pa}$

1.6.4 Calculations for Rectangular Channels inside the Intercoolers

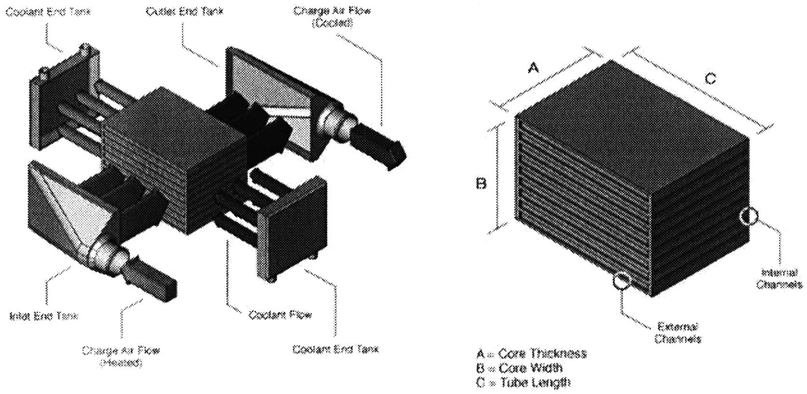


Figure 8: Detailed drawing of the intercooler from Bell with dimensions

$A = 4.44'' = 112.78\,mm$

$B = 15'' = 381\,mm$

$C = 15'' = 381\,mm$

By assuming the channel to have an equilateral triangle surface with length of 3 mm, the hydraulic diameter was calculated to be 1.732 mm.

$$D_h = \frac{x\sin\theta}{1+\sin(\theta/2)} = 1.732\,mm$$

Based on the approximation, there are 75 triangles channels per row. There are approximately 74 rows of channels on the AB plane of the intercoolers. Therefore, there is a total of approximately 5550 channels for the one entire intercooler unit. Due to alternating rows of occupied channels on the surface, the area used for calculating the flow velocity from the volumetric flow rate was assumed to be 40% of the surface area.

$$v = \frac{Q}{0.4A} = \frac{Q}{0.4 * A * B} = \frac{.00012618\,m^3/s}{0.4(.11278\,m)(.381\,m)} = .00734\,m/s$$

$$Re = \frac{\rho v D_h}{\mu} = \frac{\left(1000\,\frac{kg}{m^3}\right)\left(\frac{.00734\,m}{s}\right)(.001732\,m)}{8.9\times10^{-4}\,Pa*s} = 14.29\ \text{[laminar]}$$

1.6.4.1 Calculations for the Intercooler Channels as a Smooth Pipe

$f = .327748$

$L = C = 15'' = 381\,mm$

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.327748)(.381\,m)\left(1000\frac{kg}{m^3}\right)(.00734\,m)^2}{(.001732\,m)(2)} = \mathbf{1.942\ Pa}$$

1.6.4.2 Calculations for the Intercooler Channels as a Rough Pipe

$f = .328790$

$L = C = 15'' = 381\,mm$

$$\Delta p = f\frac{L}{D}\frac{\rho v^2}{2} = \frac{(.328790)(.381\,m)\left(1000\frac{kg}{m^3}\right)(.00734\,m)^2}{(.001732\,m)(2)} = \mathbf{1.948\ Pa}$$

1.6.5 Calculations for Total Pressure Drop

For a smooth pipe assumption:

$$\Delta p = \Delta p_{steam\ hose} + \Delta p_{pipes} + \Delta p_{T-joints} + \Delta p_{intercoolers} = \mathbf{10.99\ kPa}$$

For a rough pipe assumption:

$$\Delta p = \Delta p_{steam\ hose} + \Delta p_{pipes} + \Delta p_{T-joints} + \Delta p_{intercoolers} = \mathbf{11.03\ kPa}$$

2. Experimental Design and Method

The LORACS was tested in the basement of MIT building W59. For collecting data from the pressure and temperature sensors, Arduino and Raspberry Pi were used. The flow meter was installed to collect data for the flow rate, and thermocouple was used to measure the water temperature.

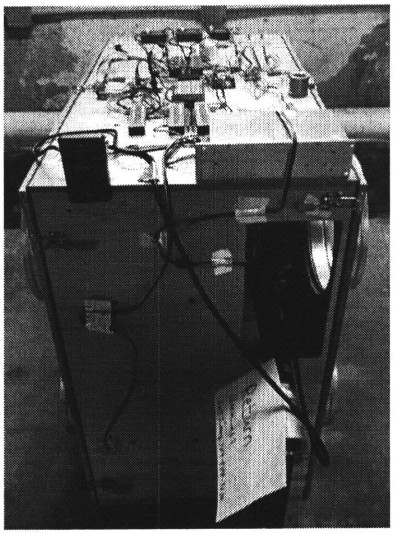


Figure 9: Electronics set-up on top of the DW Module

2.1 Overall Layout of the LORACS

The overall set-up of the LORACS is shown below in Fig. 10. The three modules, rooms, electricity, water, and air and water streams are all labelled in detail. The three modules were not physically aligned in a straight line in the actual testing location (W59) due to physical barriers and limitations due to plumbing and outlets and inlets.

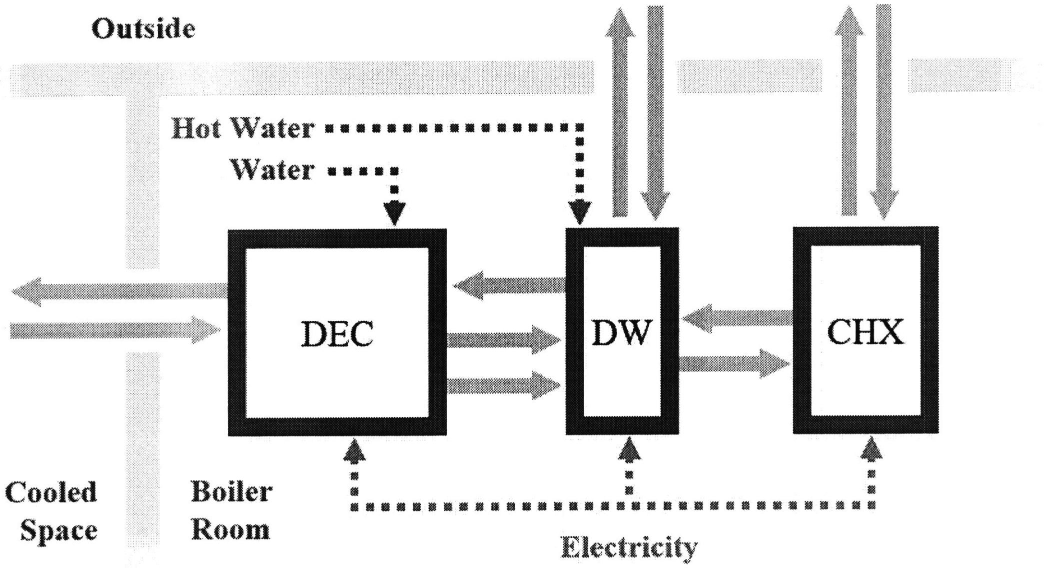


Figure 10: Block diagram of the overall system for installation in W59

2.2 Location of the Intercoolers in the Desiccant Wheel Module

As shown in Fig. 11 below, the two intercoolers were placed in the opposite corners to keep to separate regenerative air streams, which helps decrease the relative humidity without having to increase the regeneration energy.

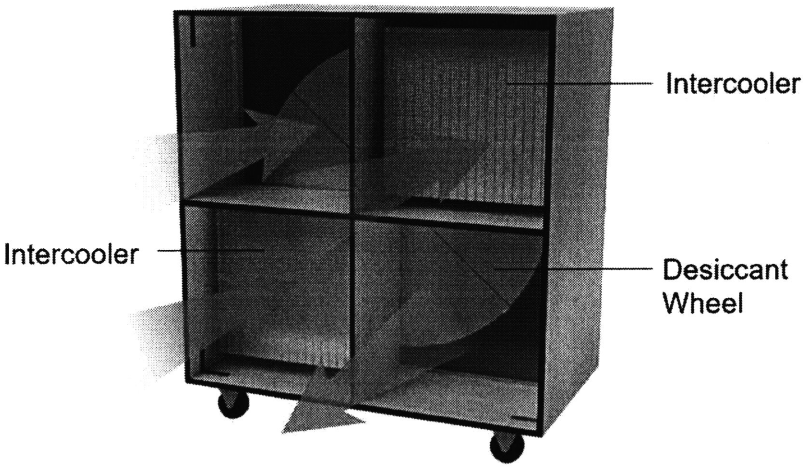
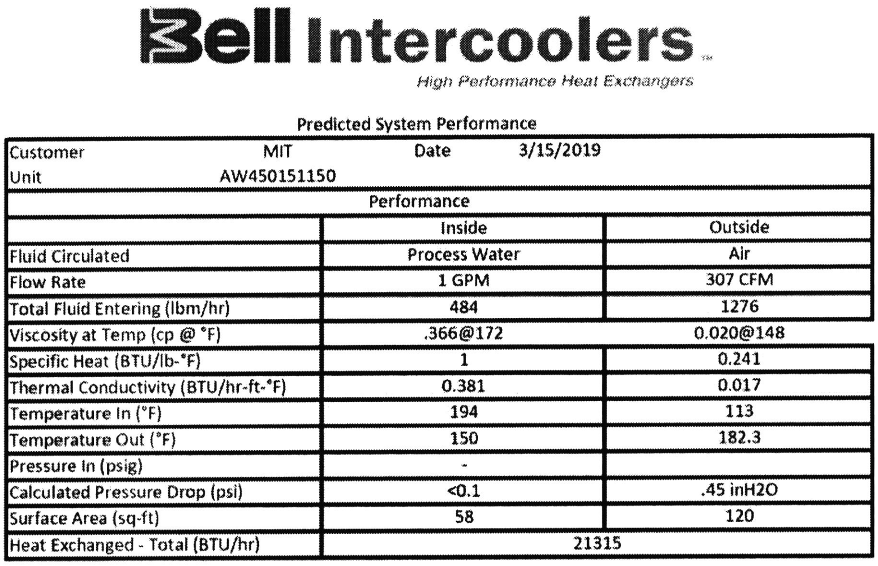


Figure 11: Model of DW Module showing location of the two intercoolers in respect to the wheel

2.3 Details Regarding Selecting the Intercoolers for Optimal Performance

Based on the target performance numbers that the 2.013 team came up with in the fall, Bell customized the two intercoolers to fit the need of the LORACS. Below, table 1 shows the performance specifications. Figure 12 is a rough drawing of each intercooler unit.

Table 1: Intercooler Specification Table sent from Bell for our customized intercooler



Bell Intercoolers

High Performance Heat Exchangers

Predicted System Performance

Customer MIT Date 3/15/2019

Unit AW450151150

Performance

	Inside	Outside
Fluid Circulated	Process Water	Air
Flow Rate	1 GPM	307 CFM
Total Fluid Entering (lbm/hr)	484	1276
Viscosity at Temp (cp @ °F)	.366@172	0.020@148
Specific Heat (BTU/lb-°F)	1	0.241
Thermal Conductivity (BTU/hr-ft-°F)	0.381	0.017
Temperature In (°F)	194	113
Temperature Out (°F)	150	182.3
Pressure In (psig)	-	
Calculated Pressure Drop (psi)	<0.1	.45 inH2O
Surface Area (sq-ft)	58	120
Heat Exchanged - Total (BTU/hr)	21315	

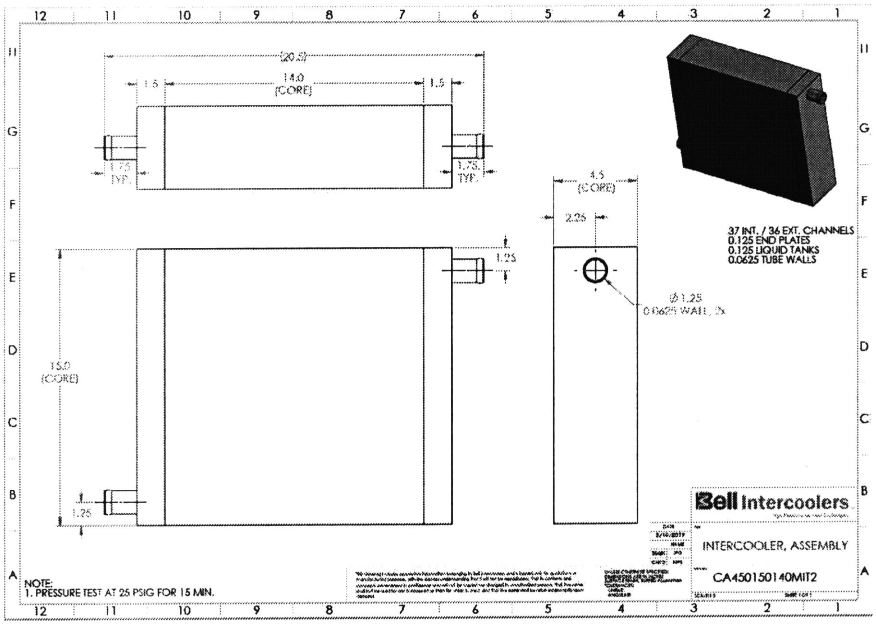


Figure 12: Sketch of a single intercooler unit from Bell

2.4 Hot Water Plumbing Schematic for the Testing Location

The intercoolers had to be connected in parallel; the hot water plumbing schematic of the two intercoolers is show below in Figure 13. Four T-joints, flow-meter, ball valve, pressure regulator valve, two intercoolers, ducts, supply, and return tanks are all labelled. The hot water supply had a condition of 50 psi, 200 °F, and flow of 200 gallons per minute.

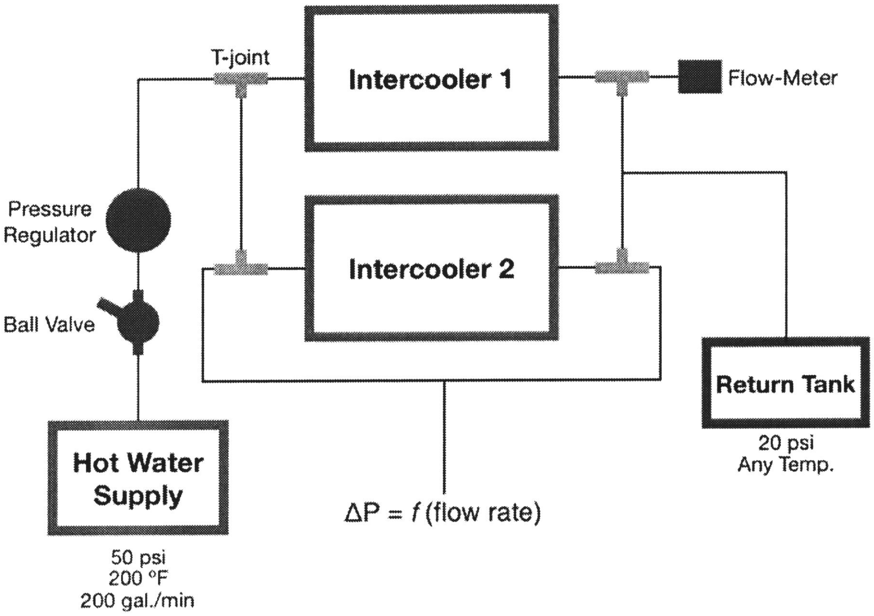


Figure 13: Hot water plumbing schematic for the Intercoolers

Image on the left-side in Figure ____ shows the actual setup of the Desiccant Wheel Module in the basement of W59 before plumbing. Image on the right-side shows the Desiccant Wheel Module after plumbing work has been completed.

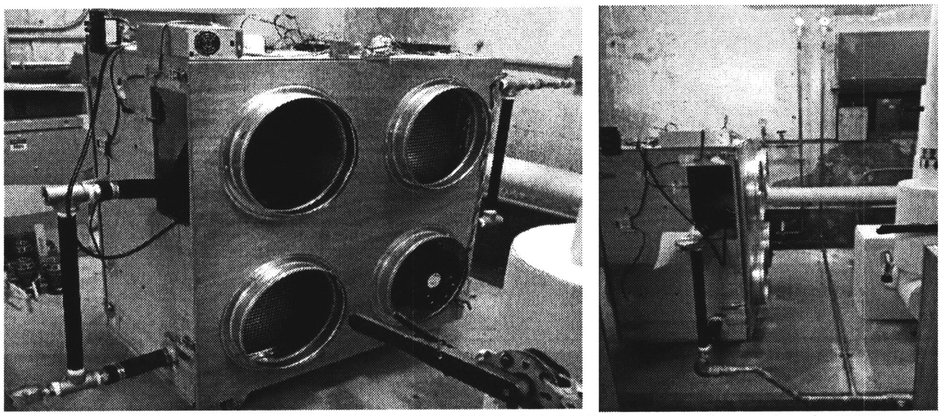


Figure 14: Intercoolers and Desiccant Wheel Module's final set-up for testing in W59

3. Results

Figure 15 shows the electronics set-up, hot water plumbing, and the ducting around the Desiccant Wheel Module, which encompasses the two intercoolers.

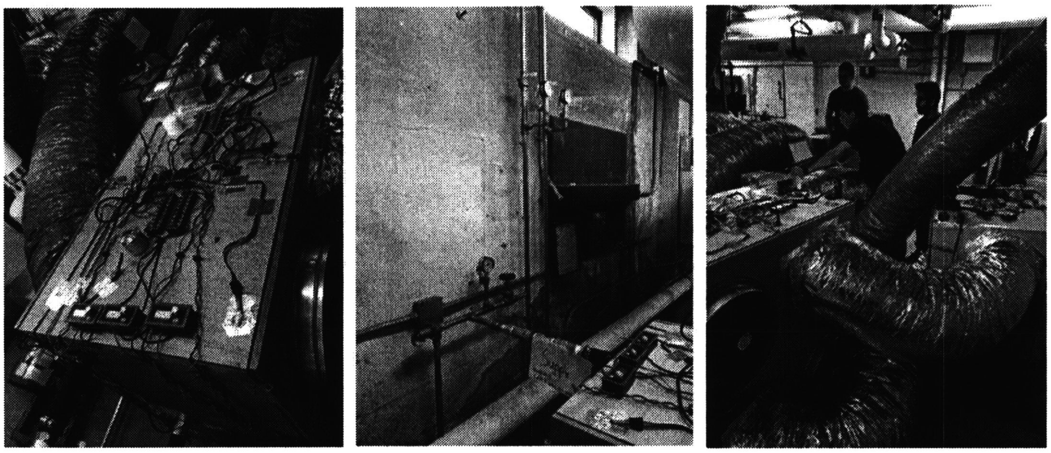


Figure 15: Images of the DW Module during data collection

3.1 Performance Metrics

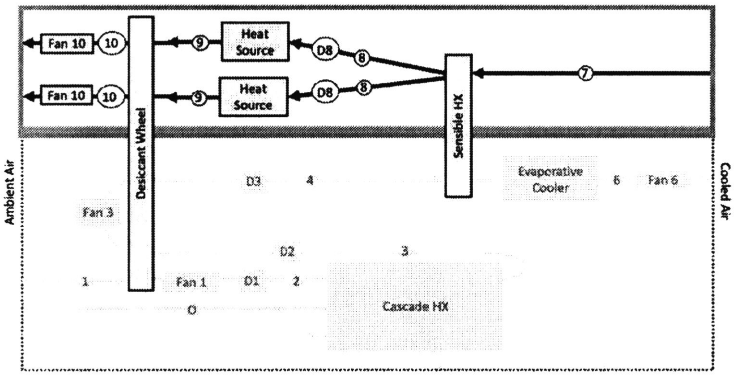


Figure 16: Block diagram of the overall system with green region being regeneration process

Table 2: Performance Metric from State 8 to 9

Metric	State 8 → 9a lower	State 8 → 9b upper	State 8 → 9
Air Temperature Change [°C]	1.874	43.797	N/A
Humidity Change [%]	4.719	12.627	N/A
Air Pressure Drop [Pa]	N/A	N/A	6496.47
Water Pressure Drop [psi]	N/A	N/A	1.3

For the intercoolers process, which is labelled as state 8 to 9 on the overall psychrometric chart as shown in earlier Fig. 5, the change in air temperature, humidity, and water pressure drop were analyzed as the overall performance metrics. The green boxed region in Figure 16 shows the regeneration path. Table 2 shows the performance metrics: change in air temperature, change in relative humidity, air pressure drop, and water pressure drop from state 8 to 9.

3.2 Theoretical Modeling of the Air Pressure Drop in the Intercoolers

One of the 2.014 teammates, Jose Padilla, did modeling analysis for the air pressure drop for the overall LORACS, including across the two intercoolers. Table 3 below shows results of the MATLAB modeling for the intercoolers and components adjacent to the intercoolers, which are crucial parts of the regenerative process [1]. Even though my thesis focuses on the water pressure drop and the flow rate, it is interesting to note the teammate's work on air pressure drop analysis.

Table 3: Predicted Air Pressure Model from State 8 to 9 [1].

Regenerative Process	Average Velocity	Reynolds Number	Pressure Change [Pa]	Stations in Diagram
Sensible heat exchanger hot stream	2.07	484.34	84.887	7→ 8
Ducting 8	3.88	34,676	5.46	D8
Intercoolers	2.61	140.08	215.27	8→9
Desiccant wheel regenerative pass	1.35	72.454	97.415	9→ 10

3.3 Experimental Data of Pressure Drop and Flow Rate of Hot Water in the Intercoolers

The flow rate for the intercoolers was 2 *gallons per minute*, which is equivalent to 0.00012618 m^3/s. The water pressure was approximately 14.5 *psi* on the supply side as shown in Figure 17 and 13.2 *psi* on the return side as shown in Figure 18. From these two values, the water pressure drop was calculated to be approximately 1.3 *psi.*

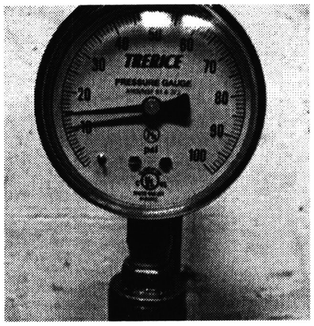


Figure 17: Supply Side Pressure Gauge

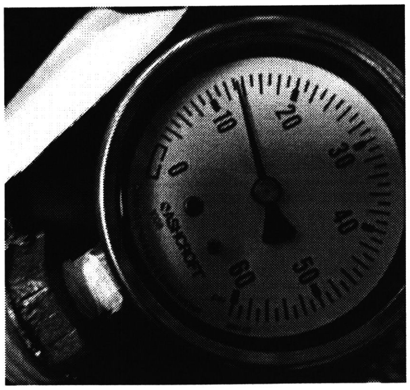


Figure 18: Return Side Pressure Gauge

4. Discussion

To validate the model, the predicted values of water pressure drop in Section 1.6 were compared to the measured values from the experiment. The total pressure drop assuming a smooth pipe was calculated to be 10.99 *kPa*, which is 1.59 *psi*. The total pressure drop assuming a rough pipe was calculated to be 11.03 *kPa*, which is 1.60 *psi*. The measured pressure drop was 1.3 *psi*. It is interesting to note that the measured pressure drop is slightly closer in value to the one with smooth pipe assumption.

There were limitations both in predictions and in testing. If given more time, more runs could have been done to get better results. The pressure drop calculations were based on approximations of certain models like assuming that the intercooler channels were equilateral triangular prisms even though in reality, they are closer to sinusoidal in shape.

Future implication of this experiment will be to optimize data collection to get more accurate measurement of all metrics since troubleshooting the sensors were troublesome on the day of the testing. There are many components that can be optimized in the testing environment itself, whether it be placing the modules in certain order and area, minimizing the length of ducts used, optimizing the path from the outlet to the inlet of the overall system, or minimizing electric power consumed. There is a great potential for this project from its initial testing.

Table 4: Overall Performance Metrics Comparison

	Predicted	Actual
Outlet Temperature (°C)	18.1	18.1
Cooling Power (W)	3500	2677
Electrical Power (W)	474	565
COP	7.37	4.74

5. Conclusion

The project has shown that the innovative lean operation rotary adsorption cooling system that uses a desiccant wheel to utilize the low-grade heat is feasible and more efficient than the currently available AC units. The results and limitations in the current set-up portrays a great potential for this project in the following years for further testing; it could eventually replace the current non-eco-friendly AC units and meet the demands of the growing population in different parts of the world like China and India other than MIT campus.

References

[1] Padilla, J, 2019. "Pressure Drop Analysis & Fan Selection for LORACS Cooling System," Cambridge, Massachusetts.

[2] USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

[3] Wasay, A., et al., 2018, "White Paper on Carbon-Neutral Cooling System," Cambridge, Massachusetts.