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ABSTRACT

Growth in industrial, commercial, and medical applications for micro-fluidic devices has fueled heightened research and development into micro-fluidic design, materials, and increasingly manufacturing. Polymers (Poly(methyl methacrylate)-PMMA in particular) are the current material of choice given their low cost, wide range of material properties, and biocompatibility. Given most fabrication processes have focused on hard materials for the semiconductor industry, an alternate set of processes such as hot micro-embossing (HME) have received increased attention as manufacturing processes for high-volume polymer-based micro-fluidic production. An understanding of the equipment, process physics, control strategy, and metrology for part fabrication are required when moving from the lab to production level. An initial statistical analysis of PMMA parts fabricated on the first generation HME system showed the need to: (1) design a new HME system; and (2) establish alternative methods for characterizing micro-fluidic parts. A second generation HME system was constructed with fellow Manufacturing and Process Control Laboratory (MPCL) graduate students and a FTS (Functional Testing System) was developed to test whether HME parts from the new HME system were capable of flowing fluid and establish output metrics for process control based on fluid pressure and flow rate. The new characterization method was shown to have re-registration error as low as ± 1.03% (overall RMS uncertainty of ±1.51%). The experimental data from tests run on the FTS fit a fluid model developed to the expected accuracy of ±10% for all but the lowest aspect ratio micro-channel. Moreover, the FTS results were consistent with optical scans of a series of parts made with varying HME parameters. The FTS was able to detect differences that a few isolated optical scans could not. The FTS provided a bulk quantity to assess the geometry of the channel rather than at a specified location. These results and the deficiencies in existing metrology techniques warrant further exploration into functional-based testing for micro-fluidic devices to parallel well established testing methods in place in the IC industry. Functional testing does not have the capacity to replace traditional metrology; however, it can add an important output metric-a quantitative measure of the output parts fluid flow.

Thesis supervisor: David E. Hardt
Title: Professor of Mechanical Engineering
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First, I must thank my family and friends for their support and encouragement, without which this opportunity, much less its completion, would not have been possible.

I would also like to thank Professor Hardt for his technical consultation and his advice and guidance throughout my time here at MIT. It is a privilege to work for someone with such vast expertise in their field who takes the time to pass on that and other lessons to his students.

I would also like to acknowledge Grant Shoji for the work we did together on the HME heat transfer system, initial statistical analysis of micro-embossed parts, tool design, and the metrology analysis of the first series of HME characterization tests.

I would also like to acknowledge Wang Qi for her collaboration on the tool design and both Wang Qi and Matthew Dirckx for help on troubleshooting problems and suggesting alternatives for design and testing.

I must also thank: Hayden Taylor, for fabricating the silicon DRIE tools and testing PMMA-PMMA bonding; Dan Burns, for his help in obtaining AFM scans of parts; Sam Korb, for his assistance in depositing PDMS on PMMA; Catherine Nichols and Erica Daniels, for their help in navigating the maze that is MIT; and everyone in the LMP machine shop (Gerry Wentworth in particular) for their time and patience with yet another graduate student trying to meet a deadline.

I would also like to thank all my colleagues in 35-135 who made it an enjoyable place to work regardless of the time- day or night.

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## Nomenclature

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<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta Y/\delta a$</td>
<td>Sensitivity of the output of a process model to disturbances</td>
</tr>
<tr>
<td>$\delta Y/\delta u$</td>
<td>Sensitivity of the output of a process to changes in the input</td>
</tr>
<tr>
<td>A</td>
<td>Area or Amps</td>
</tr>
<tr>
<td>$A_2$</td>
<td>Smaller area in contraction/expansion</td>
</tr>
<tr>
<td>$A_1$</td>
<td>Larger area in contraction/expansion</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Conversion</td>
</tr>
<tr>
<td>AFM</td>
<td>Atomic Force Microscopy</td>
</tr>
<tr>
<td>ATE</td>
<td>Automated Testing Equipment</td>
</tr>
<tr>
<td>ATPG</td>
<td>Automatic Test Pattern Generator</td>
</tr>
<tr>
<td>C</td>
<td>Celsius</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Valve coefficient</td>
</tr>
<tr>
<td>cfm</td>
<td>Cubic Feet per Minute</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
</tr>
<tr>
<td>COM</td>
<td>Communications port</td>
</tr>
<tr>
<td>CCD</td>
<td>Central Composite Design</td>
</tr>
<tr>
<td>CRT</td>
<td>Cathode Ray Tube</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>d</td>
<td>Channel depth (equivalent to channel height)</td>
</tr>
<tr>
<td>DIB</td>
<td>Device Interface Board</td>
</tr>
<tr>
<td>DIN</td>
<td>Deutsches Institut für Normung</td>
</tr>
<tr>
<td>DIO</td>
<td>Digital I/O</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiments</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etching</td>
</tr>
<tr>
<td>DUT</td>
<td>Device Under Test</td>
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<tr>
<td>E</td>
<td>Elastic modulus</td>
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<tr>
<td>ESEM</td>
<td>Environmental Scanning Electron Microscopy</td>
</tr>
<tr>
<td>FTP</td>
<td>Functional Testing Platform</td>
</tr>
<tr>
<td>FTS</td>
<td>Functional Testing System</td>
</tr>
<tr>
<td>g</td>
<td>Gram</td>
</tr>
<tr>
<td>GPM</td>
<td>Gallons Per Minute</td>
</tr>
<tr>
<td>h</td>
<td>Channel height (equivalent to channel depth)</td>
</tr>
<tr>
<td>H</td>
<td>Fluid head (feet)</td>
</tr>
<tr>
<td>HME</td>
<td>Hot Micro-Embossing or Hot Micro-Embossed</td>
</tr>
<tr>
<td>HP</td>
<td>Horsepower</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>ILD</td>
<td>Inter-Layer Dielectric</td>
</tr>
<tr>
<td>$K_L$</td>
<td>Fluid loss coefficient</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>kN</td>
<td>Kilonewton</td>
</tr>
<tr>
<td>ksi</td>
<td>Thousand pounds per square inch</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>l</td>
<td>Liter</td>
</tr>
<tr>
<td>l₀</td>
<td>Initial length</td>
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<td>Final length</td>
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<tr>
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<td>Pounds</td>
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</tr>
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</tr>
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<td>Minute</td>
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</tr>
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<td>Millisecond</td>
</tr>
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<td>NEMA</td>
<td>National Electrical Manufacturers Association</td>
</tr>
<tr>
<td>NI</td>
<td>National Instruments</td>
</tr>
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<td>nm</td>
<td>Nanometer</td>
</tr>
<tr>
<td>NPSH</td>
<td>Net Positive Suction Head</td>
</tr>
<tr>
<td>NPN</td>
<td>N-P-N doped bipolar transistor</td>
</tr>
<tr>
<td>NPT</td>
<td>National Pipe Thread</td>
</tr>
<tr>
<td>N</td>
<td>Newton</td>
</tr>
<tr>
<td>n</td>
<td>Number of samples</td>
</tr>
<tr>
<td>Pa</td>
<td>Pascal</td>
</tr>
<tr>
<td>P</td>
<td>Pressure drop</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCI</td>
<td>Peripheral Component Interconnect</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate)</td>
</tr>
<tr>
<td>psi</td>
<td>Pounds per Square Inch</td>
</tr>
<tr>
<td>Q</td>
<td>Volume flow rate</td>
</tr>
<tr>
<td>R</td>
<td>Fluidic Resistance</td>
</tr>
<tr>
<td>R²</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>r</td>
<td>Radius</td>
</tr>
<tr>
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<td>Reynolds number</td>
</tr>
<tr>
<td>%RH</td>
<td>% Relative Humidity</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>S</td>
<td>Sample standard deviation</td>
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<tr>
<td>SCR</td>
<td>Silicon Controlled Rectifier</td>
</tr>
<tr>
<td>sec</td>
<td>Seconds</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SG</td>
<td>Specific Gravity</td>
</tr>
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<td>SPST</td>
<td>Single Pole-Single Throw</td>
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<tr>
<td>STM</td>
<td>Scanning Tunneling Microscopy</td>
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<td>Symbol</td>
<td>Description</td>
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<tr>
<td>T</td>
<td>Temperature</td>
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<td>$T_g$</td>
<td>Glass transition temperature</td>
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<td>TEFC</td>
<td>Totally Enclosed Fan Cooled</td>
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<tr>
<td>TTL</td>
<td>Transistor-Transistor Logic</td>
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<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
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<tr>
<td>v</td>
<td>Flow velocity</td>
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<tr>
<td>V</td>
<td>Volts</td>
</tr>
<tr>
<td>VAC</td>
<td>Volts Alternating Current</td>
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<td>Volts Direct Current</td>
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<td>Watts</td>
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<td>Width</td>
</tr>
<tr>
<td>$\bar{x}$</td>
<td>Sample mean</td>
</tr>
<tr>
<td>$\Delta a$</td>
<td>Disturbances to a process</td>
</tr>
<tr>
<td>$\Delta P_1$</td>
<td>Pressure drop across a fully open valve</td>
</tr>
<tr>
<td>$\Delta P_2$</td>
<td>Pressure drop across the rest of the system</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>Changes to the input of a process</td>
</tr>
<tr>
<td>$\Delta Y$</td>
<td>Changes in the output of a process</td>
</tr>
<tr>
<td>$\circ$</td>
<td>Degrees</td>
</tr>
<tr>
<td>$\varnothing$</td>
<td>Diameter</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Elastic strain</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity or micro</td>
</tr>
<tr>
<td>$\mu_m$</td>
<td>Population mean</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of a material</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Micro-fluidic Systems in Emerging Technologies

1.1.1 Technology Sectors and Growth Potential

The worldwide micro-fluidics market is currently ~$2 Billion USD per year [1,2]. Though speculation on the growth rate of this industry varies vastly from one source to another, most sources place the compounded adjusted growth rate between 10.3% and 27.3% [1,3]. Micro-fluidics traditional application has been in printing. This is most commonly seen in inkjet printers. However, new applications in power systems, propellant free aerosols, electronics, and most importantly the life sciences field are driving aggressive growth [1,4].

Despite the vast applications in industrial and commercial products, the dominant growth market is the life sciences field in general and the pharmaceutical industry, medical technology, and bio-technology industries in particular [5]. The cost and time savings with the use of micro-fluidic devices in drug discovery and analysis and the potential for micro-fluidics based drug delivery are emerging at the same time the cost for drug discovery and health care are reaching unprecedented heights. An analysis by the Tufts Center for the Study of Drug Development estimated the average cost of drug development at $897 million USD [6].

Micro-fluidics can be broken into several markets within life sciences industry: High throughput screening; Genomics; Proteomics; cell analysis; and drug delivery [2]. High-throughput screening is the dominant application at present, however,
developments in surface chemistry and material choice are expanding to encompass more complex analyses such as Genomics and Proteomics [2].

1.1.2 Need for Manufacturing-Related Development

There has been great emphasis within industry and academia to move toward the use of polymeric materials in micro-fluidic devices [7]. Initial work with micro-fluidics in the early 1990’s focused on the use of glass because of well established fabrication methods from the semiconductor industry [7]. However, the high cost and low flexibility of glass necessitated a shift to polymer-based devices. There are a range of polymers that are disposable, low cost, and biocompatible [7].

Until this time, most micro-scale processes focused on hard materials (silicon, quartz, etc). This shift in material choice drove development and characterization of processes to handle large scale production of polymer-based micro-devices. There are many processes that have been developed to attempt to meet this need: (1) Soft Lithography; (2) UV- Embossing; (3) Micro-Injection Molding; (4) Hot Micro-embossing (micro-embossing); etc [8]. However, micro-embossing, in particular, has shown great promise to potentially meet the need of fabricating low-cost high-volume nm-μm scale polymer-based micro-devices.

With this new toolbox of processes, several material choices arise. The demand for low cost, chemically resistant polymers that have the flexibility of surface modification limits these options. Poly(methyl methacrylate)-PMMA, Poly-carbonate, Poly-ester, poly-styrene, Poly vinylchrolide, and silicones are some of the major options [7]. PMMA, also known as acrylic, is one of the most commonly used thermoplastics. The low cost and well established material properties make it a natural first choice.
However, other more exotic materials with unique thermal, mechanical, and optical properties are constantly under development.

A key element to successfully addressing the hot micro-embossing (HME) manufacturing issues for micro-fluidic devices is developing methods for adequate process characterization, optimization, and control in a production environment. Prior work by Lee et al [9] and Hardt et al [10] assessed the variability of micro-embossing machines by measuring output part features of various dimensions and further work by Hardt et al [11] and Bacon et al [12] characterized the micro-embossing process by establishing relationships between equipment input parameters and output part metrics. Continued development of these quantitative models is required for HME to transition from a research to production level commercial process.

1.2 Background on HME Process Physics and Equipment

HME of thermoplastic polymers, at its most basic level, is a process where material is heated above its glass transition temperature \( T_g \), uni-axially pressed by a tool (with features inverse of those desired on the part), held for a certain time (hold time), and then released. According to the process taxonomy developed by Hardt [13], HME can be considered a Deformation>Parallel> (Thermal+Mechanical) process. Figure 1-1 explains the basic steps common to any HME system.
Though the basic principle of the process is rather straightforward, the details (time, temperature, force, extension, etc) of the processing conditions are extremely important to the quality of the output part. Figure 1-2 shows a plot of the temperature and force profiles of a typical HME process as a function of time. The process has five major steps: (1) the material is heated above $T_g$ ($\sim100\,^\circ C$ for PMMA) to the embossing temperature; (2) a force is applied on the tool into the part blank; (3) the force and temperature are held; (4) the temperature is brought down below $T_g$ to the de-embossing temperature under force; and (5) the force is released and the part is removed.
The details (time, temperature, force, extension, etc) of the processing conditions seen at the part are extremely important to the quality of the output part. However, given the difficulty of measuring these quantities at the part itself, the material states are often controlled indirectly by controlling the equipment states. The ability of the equipment to accurately maintain mechanical (position, force, velocity) and thermal (temperature, uniformity, etc) states is critical. Therefore, equipment that is robust to disturbances and can ensure repeatable material states for a given set of controllable equipment states is needed. The basic components of a HME system include a press, tool, platens, heating and cooling elements, and a control system. Force/position actuation is typically either through a motor-lead screw assembly or hydraulics. Heating and cooling is typically electrical or fluid based.
1.3 Manufacturing Cycle-to-Cycle Process Control in HME

Given the demand for micro-fluidic devices and the increased focus on polymer-based HME parts described in Section 1.1, there is a need to address the manufacturing issues that this demand will raise. Making a few parts in the laboratory is much different than implementing a full scale manufacturing process to fabricate a thousand or even a million devices. Manufacturing requires a much more precise understanding of the process physics to implement effective control strategies to maximize the effectiveness of the process. This underlies the need to develop a thorough understanding of manufacturing control in HME to identify, isolate, and reduce sources of process variation. Process variation can be represented by Equation 1-1.

\[ \Delta Y = \frac{\partial Y}{\partial a} \Delta a + \frac{\partial Y}{\partial u} \Delta u \]

Equation 1-1 [14]

The change in the output parameter is \( \Delta Y \). The change in the output is a function of the disturbance (\( \Delta a \)) and change in input parameters (\( \Delta u \)) multiplied by their respective sensitivities (\( \frac{\partial Y}{\partial a} \) and \( \frac{\partial Y}{\partial u} \)). An initial strategy is to reduce the magnitude of the disturbance or the processes sensitivity to that disturbance. This can be achieved with effective equipment design. The next step is to actively vary the input parameters to negate the effect of the disturbances on the output parameter. This is feedback control. Both methods should be applied to HME in a production environment.

Under ideal circumstances it would be preferable to control the output product parameters within cycle and not the equipment or material states. However, in-situ measurement of the functional performance or dimensions of a part during processing is extremely difficult. A way around this limitation is proposed by Hardt et al [13] in
Figure 1-3. The strategy involves six steps. Step one is to establish a first order relationship between equipment input parameters and output part metrics. Step one is also used to identify and reduce sources of noise [13]. Step two is to perform a statistical analysis of outputs with all equipment inputs held constant to assess the process variation [13]. Step three is to optimize equipment input parameters to minimize output variation and maximize the number of acceptable parts [13]. Step four is to implement closed-loop control of the equipment states [13]. Step five is to implement closed-loop control of the material states to help minimize the effects of material state/property variation [13]. Step six is to implement closed-loop cycle-to-cycle control of the output part metrics to minimize output variation and maximize the number of acceptable parts [13].

![Figure 1-3: General process control loops][13]

An important part of the cycle-to-cycle control strategy is to establish output metrics on which to assess the variation of the process and design equipment that is robust to noise factors. These two points are the central work of this thesis as described in Section 1.4.

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[13]: #
1.4 Thesis Scope

This work was supported by the Singapore-MIT Alliance and was carried out in the Manufacturing Process Control Laboratory (MPCL). The goal is in keeping with the larger objective of the MPCL to apply novel control strategies to manufacturing processes. Moreover, this work directly addresses Task 2 (HME equipment design) and Task 3 (metrology of HME micro-fluidic parts) of the Singapore-MIT Alliance Manufacturing Systems and Technology Research Proposal [15].

There are two objectives to the work of which this thesis is a culmination. The primary objective was to explore and develop alternative methods of characterizing micro-fluidic parts. The difficulty in extracting metrology-based measurements of parts made on the first generation HME system in the MPCL (described in Chapter 2) drove the need for an alternative characterization method. The proposed method is a Functional Testing System (FTS) which will be used to observe bulk fluid properties to determine the effect of HME processing parameters on output parts. The testing method involves flowing fluid through HME micro-channels and monitoring the variation in pressure between channels for a fixed flow rate of water. This work is a first step toward investigating the viability of the functional testing concept for application in micro-fluidics manufacturing process characterization and control. The technique will be assessed on its ability to detect differences in micro-channel geometry. This testing method will serve to both determine whether the fabricated channel is capable of flowing fluid (integral to its functionality) and also provide a quantitative bulk metric that can be used to assess HME process variation. The range, resolution, testing time, and sensitivity drawbacks of existing metrology techniques outlined in Chapter 4 warrant exploration.
into new characterization methods. Functional testing for micro-fluidic manufacturing process characterization and control is a new research area for which there is currently no published work. However, the idea of using a functional metric to assess a process has been used in the IC industry (outlined in Section 5.1). The proposed method has conceptual limitations in that it can detect whether there are defects of irregularities, but cannot detect their precise location along the channel. However, despite this limitation, adequate resolution and accuracy on commercially available pumps and pressure sensors for micro-fluidic testing (discussed in Section 5.3.2) suggest sufficient repeatability in the proposed FTS method that further exploration is warranted. The emphasis will be on HME PMMA parts. However, the technique is not necessarily limited to this material or fabrication method. The secondary objective of this thesis was the design and construction of a hot-oil heat transfer system for a second generation HME system.

1.5 Thesis Outline

The analysis to support the need for both a new characterization method and new HME system are explained in Chapter 2. Chapter 3, co-authored with Shoji [28], outlines the design of the second generation HME system designed by Dirckx [8], Shoji [28] and the author. Chapter 4 gives an overview of the proposed functional testing concept and an assessment of metrology techniques currently used to characterize micro-fluidic parts. Chapter 5 gives an overview of characterization methods used in the integrated circuit (IC) industry and outlines the requirements, preliminary calculations, sensitivity analysis, and conceptual design for the proposed FTS. Chapter 5 also describes the tooling developed for the second generation HME system with Shoji [28] and Wang [61]. Chapter 6 outlines the design, component selection, and integration of the FTS. Chapter
Chapter 7 describes the hardware connections and LabView program developed for control and data acquisition of the FTS components. Chapter 8 discusses the fluid model developed to predict the expected fluidic performance of parts tested in the FTS. Chapter 9 outlines the preliminary, re-registration, and model-fit tests run on the new FTS. Chapter 10 outlines the HME characterization tests used to compare the results of traditional metrology techniques with the FTS. Finally, Chapter 11 draws conclusions on the design, construction, and testing of the FTS and recommends future work that may further develop the concept of functional testing.

1.6 Background on Micro-Scale Device Testing and Packaging

Currently, there is no documented research on the use of functional performance metrics for process characterization, much less control of any micro-fluidics manufacturing process. However, other techniques using fluid flow to characterize channel geometry such as PIV (described in Section 4.2.6) are under development [16]. There is limited research on micro-fluidic testing and packaging which are essential to a designing and implementing a FTS. The need driving packaging research is the difficulty in flexibly integrating the micro-scale parts with large scale machinery and equipment. Moreover, it has been noted that packaging can account to up to 80% of the cost of a Micro-Electro-Mechanical Systems (MEMS) devices, of which micro-fluidics are a subset [17]. Work by Valentine [17] uses a sandwiching technique to seal off open PDMS channels and provide fluid I/O. Work by Tsai et al [18] uses Mylar polymer sealant in a layer deposition process to seal off capillary tubes connected to the fluid I/O. Work by Fredrickson et al [19] uses a surface micro-machined locking connector that expands when a tube is inserted to seal against a support platform which in turn directs
fluid to the part. More integrated products have been designed by Han et al [20], which have both electrical and fluid I/O. The options for macro-micro connectors range from modular to device specific and permanent (on-chip) to removable. However, the unique design of all micro-fluidic devices and the lack of any standards does not allow for a one solution fits all approach.

Most testing of micro-fluidic devices has focused on qualitative assessments of functionality. However, some groups have begun to quantify micro-fluidic performance for the purposes of validating models and determining the effect of geometry on flow characteristics. Lee et al [21] gathered pressure and flow rate data for nitrogen run through surface micro-machined micro-fluidic parts to assess the effect of constrictions on flow separation. Work by Chang et al [22] (blood) and Eason et al [23] (water) has focused on gathering pressure and flow rate data to validate CFD and analytical micro-scale fluid flow models. This fluid testing, however, has been carried out on hard materials, not polymer-based devices. However, the techniques, testing setup, and models generated by these groups lay the ground work for further development of functional fluidic testing as a characterization tool for manufacturing control.
2 Statistical Analysis of Micro-Embossed Parts: First-Generation HME System

2.1 Description of Tool and Parts

Ganesan [24] added significant work to the body of hot micro-embossing (HME) research by designing and constructing the first generation HME system described in depth in Section 3.1. Ganesan [24] fabricated several Poly(methyl methacrylate)-PMMA parts on this system to assess HME process variation with constant equipment input parameters. Figure 2-1 shows a sample tool and Table 2-1 outlines the six scales of tools that are on the etched silicon die based on the width of the feature 4 dimension. The tool had recessed features (~0.9 μm), so the parts made from this tool had raised features.

Figure 2-1: Close-up of silicon MIT tool used to fabricate parts on the first generation HME system [24]
Table 2-1: Summary of six scale of features based on feature 4 dimension in Figure 2-1

<table>
<thead>
<tr>
<th>Scale</th>
<th>Feature 4 Dimension ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>89</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

2.2 Effect of Measurement Resolution

Ganesan [24] measured the parts on a Zygo NewView Model 5000 Optical Interferometer (theory of operation described in Section 4.2.3). Scales 1-5 were measured because it was difficult to image the very small Scale 6 features in the Zygo. He concluded that there was: (1) an increase in mean and standard deviation of the die-part difference with increasing scale size; and (2) data to support process variation. However, further inspection of the instrumentation used to gather this data with Shoji [28] revealed that the change in the mean and standard deviation of die-part difference from scale-to-scale and feature-to-feature cannot be relied upon given the inherent measurement error from the Zygo. Figure 2-2 below shows the change observed in the standard deviation of the die-part difference for varying scales and features. Table 2-2 shows the change in resolution of the Zygo with scale size. Given the resolution of the Zygo, the observed changes in standard deviation and similarly mean are washed out. The differences are just as likely to be scale dependent measurement noise as evidence of a process trend. Moreover, Figure 2-3 shows a process run for Scale 1 feature 1 measurements with the measurement resolution error bars of $\pm 1.1 \mu$m included. What appears to be process variation cannot be verified because of the large measurement error embedded in the data.
Where $S_D$ stands for Standard Deviation Die-part difference (Left) in microns.

Figure 2-2: Change in tool-part difference standard deviation with changes in scale and feature size

Table 2-2: Zygo measurement resolution for scans at different scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Nominal Width (µm)</th>
<th>Horizontal Resolution (µm)</th>
<th>Scan Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170</td>
<td>2.2</td>
<td>1.43 mm x 1.07 mm</td>
</tr>
<tr>
<td>2</td>
<td>89</td>
<td>2.2</td>
<td>1.43 mm x 1.07 mm</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>0.85</td>
<td>0.45 mm x 0.34 mm</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>0.85</td>
<td>0.27 mm x 0.20 mm</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>0.85</td>
<td>0.18 mm x 0.13 mm</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>Not measured</td>
<td>0.18 mm x 0.13 mm</td>
</tr>
</tbody>
</table>
2.3 Re-Measurement Using Higher Resolution Imaging

In order to quantitatively establish if there is process variation (and to what extent) in the first generation HME system, a higher resolution surface imaging technique was used. Atomic Force Microscopy (AFM) measurements were taken on a Quesant Q-Scope Model 250 (theory of operation described in Section 4.2.1). AFM scans were taken of the Scale 6 parts and ten interpolations were performed on the width of the letter “I” as seen in Figure 2-4 (with the assistance of Dan Burns). An E-SEM (theory of operation described in Section 4.2.5) scan using a Phillips/ FEI XL30 FEG-SEM was taken to corroborate that the images from the AFM were indicative of the part geometry and not an artifact of the AFM measurement technique. Three parts were not included in the analysis because they had air bubbles. The data set of seven parts was analyzed to
determine whether the variation in the measurements from part-to-part was dominated by measurement or process variation.

Figure 2-4: AFM (a) and E-SEM (b) pictures of a Scale 6 part

The resolution of the AFM for these scans was 60 nm. The RMS uncertainty was calculated by combining the bias error introduced by the AFM−1/2 measurement resolution = 30 nm with the precision error (90% confidence student-t interval with degrees of freedom = 9) of the ten interpolations of the feature [25,26]. An interpolation is the act of re-measuring the AFM scan multiple times using the software provided by the manufacturer. This resulted in an overall RMS uncertainty error on the measurement
of 0.031-0.050 \mu m depending on the interpolation errors for each part. Figure 2-5 shows the high level of variation of the width of the letter “I” with run number. The RMS uncertainty is shown on the plot. Unlike the case of the Zygo data, the uncertainty is much smaller than the observed process variation.

Figure 2-5: Scale 6 width of the middle of the “I” for seven of the ten parts fabricated [10]

The summary of the AFM measurements taken is shown in Table 2-3. The coefficient of variance of the HME process for the fabrication of these features under identical equipment input conditions is \(~12.6\%\).

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Average (\mu m)</th>
<th>Standard Deviation (\mu m)</th>
<th>Coefficient of Variance (%)</th>
<th>Range (\mu m)</th>
<th>Overall RMS Uncertainty (\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle of the &quot;I&quot;</td>
<td>4.08</td>
<td>0.52</td>
<td>12.64</td>
<td>1.36</td>
<td>0.031-0.050</td>
</tr>
</tbody>
</table>
There may be several causes for this high variance, however, the inability of the
HME system to properly control equipment input parameters (de-embossing temperature,
cooling rate, etc), the high level of noise, and the variability in material properties are the
most likely causes.

2.4 Conclusions

Based on these results, two actions were warranted. First, a second generation
HME system to reduce the sensitivity of the machine to noise factors and have more
precise control of process parameters was needed. Moreover, added flexibility in terms
of part size and tooling could be added in this re-design. This re-design was carried out
by Dirckx [8] and the design and construction of the heat transfer for this new system was
completed by Shoji [28] and the author (outlined in Chapter 3). Second, an exploration
of alternative techniques to reliably detect HME process variation was needed. Given the
inherent difficulty in obtaining measurements at this scale (with the precision necessary
to obtain statistically significant data), alternative methods of understanding the
relationship between HME equipment input parameters and output part characteristics
had to be investigated. Functional testing (outlined in Chapter 5) was one proposed
method to help characterize micro-fluidic parts and provide feedback on the process
performance.
CHAPTER


This Chapter and all associated Appendices were co-authored with Shoji [28]. A statistical analysis of parts fabricated on the first generation HME system (described in Chapter 2) was the basis for the design of a second generation HME system described in the following subsections.

3.1 Background-First Generation HME System

The first generation HME system built in the Manufacturing Process Control Laboratory (MPCL) by Ganesan [24] has four main subsystems: (1) force and position actuation; (2) platens; (3) temperature actuation; and (4) control. An Instron model 5869 load frame provided force and position actuation. The platens, used to hold the work piece and tool, are made of copper. The platens are heated with two 200W cartridge heaters and cooled by running city water and/or pressurized air through tubing connected to the platens. The temperature is monitored by two thermocouples (one each in the top and bottom platen) and controlled with Chromalox 2110 controllers and the Instron is controlled with a hardware controller via its proprietary FastTrack and Merlin software’s. See Figure 3-1 for a close-up of the platen assembly.
The maximum force capacity is 50kN and temperatures up to 300°C are possible [8]. The Instron crosshead has a resolution of 0.0625 µm and can be controlled to speeds from 0.001 mm/min to 500 mm/min [27]. Typical heating time from ambient to 130°C is 15 minutes and cooling time back to ambient is 5 minutes [8]. The largest work piece that could be embossed was on the order of 40-45 mm [8]. Both copper and silicon tools can be used with this system.

The system has three main drawbacks: (1) large thermal mass and the resulting slow thermal cycle time; (2) limited control of key processing parameters; and (3) limited to small part sizes. These drawbacks led to a second generation HME system, designed by Dirckx [8], a graduate student in the MPCL.
3.2 Second Generation HME Subsystems

3.2.1 Platen Subsystem

Dirckx [8] designed and machined the platen subsystem, one of the three subsystems that underwent major changes. The main objectives of this platen design were to: (1) increase the work piece area to 100mm diameter; (2) accommodate a thermal-oil heat transfer system for rapid and uniform heating; and (3) provide more reliable platen alignment and flexible tool and work piece fixturing. Figure 3-2 to Figure 3-4 shows the various pieces in the platen assembly. For further details on the platen subsystem design and fabrication refer to Dirckx's SM thesis: Design of a Fast Cycle-Time Hot Micro-Embossing Machine [8].

Figure 3-2: Three-dimensional view of the full platen assembly [8]
Three major changes were made to the platen subsystem after initial construction. Omegatherm thermally conductive silicone paste Model OT-201 (Appendix B.1) was placed between the top platen and top spacer plate and between the bottom spacer plate and additional bottom spacer plate. This reduced the thermal resistance by eliminating the air gap between layers. Given difficulties with de-embossing using a silicon tool, Wang [61], a graduate student in the MPCL, designed a top spacer plate that could be used to affix copper tools. This plate is also needed when embossing a part with an unsecured silicon tool to keep the top and bottom manifolds from contacting one another prior to forming the part (see Figure 3-4). A vacuum pump to integrate with the vacuum chuck was also added.

Figure 3-3: The full platen assembly [8]
A vacuum pump was needed to apply a holding force on the tool in contact with the vacuum chuck. The suction force on the tool is proportional to the vacuum level of the pump. The theoretical limitation of any vacuum pump is 0 Torr (pure vacuum). No pump is capable of achieving this; however, several turbo molecular pumps can achieve $10^{-10}$ Torr. The objective is to maximize holding force, thus there is no need for a high vacuum pump, which would add unreasonable cost with minimal (fractions of a Torr) benefit. Therefore, the focus was on vacuum pumps with ~99% vacuum.

The important parameters to consider when specifying the vacuum pump are: (1) absolute pressure; (2) flow rate; (3) pump speed; (4) weight; (5) dimensions; (6) noise level; and (6) power requirements.
The most suitable vacuum pump for small volume evacuation is a roughing single-stage rotary vane pump. Other pumps offer higher vacuum but at much higher costs with negligible improvement in holding force. The rotary vane pump is the most common and economical mechanical pump for the transport of clean, dry, non-reactive gases, such as air. Oil lubrication, as opposed to dry lubrication, is recommended for a longer life and lower initial cost.

A 0.5HP Kinney-Tuthill KVO-5 capable of 3.1 cfm and an absolute pressure of 7.5 Torr was chosen because it met the aforementioned requirements at the most reasonable cost. The pump was wired to a switch mounted on the computer stand. A flexible stainless steel hose connects the vacuum pump to a brass barb epoxied with Duralco 4461 to the vacuum chuck (Figure 3-5). For further detail, see the vacuum pump user manual.

Figure 3-5: Vacuum pump and hose shown with vacuum chuck and barb
3.2.2 Force and Position Actuation Subsystem

The force and position actuation subsystem did not change from the first to the second generation HME system. The parameters for the Instron 5869 (Figure 3-6) shown in Table 3-1 are sufficient for the demands of the new 100 mm system. Refer to the Instron 5869 manual for further detail.

![Instron 5869 load frame and computer controller](image)

**Figure 3-6: Instron 5869 load frame and computer controller**

**Table 3-1: General specifications for the Instron 5869 [27]**

<table>
<thead>
<tr>
<th>Load Rating</th>
<th>Maximum Speed</th>
<th>Minimum Speed</th>
<th>Force Accuracy</th>
<th>Force Resolution</th>
<th>Position Accuracy</th>
<th>Position Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>50kN</td>
<td>500 mm/min</td>
<td>0.001 mm/min</td>
<td>0.4 -0.5%</td>
<td>0.001 N</td>
<td>0.02 mm or 0.05%</td>
<td>0.0625 μm</td>
</tr>
</tbody>
</table>

3.2.3 Temperature Actuation Subsystem

The temperature actuation subsystem is the second of three subsystems that underwent major changes. The thermal-oil heat transfer subsystem was designed by Dirckx [8] and integrated and constructed by the Shoji [28] and the author. This subsystem will be discussed in detail in the following subsections.
3.2.4 Software Control Subsystem

The third subsystem to undergo major changes was the control subsystem. The first generation HME system relied on hardware controllers to reach the desired platen temperature. Given the major changes in temperature actuation, Shoji [28] developed a new software program in LabView. Force and position are still controlled with the Instron hardware via its proprietary FastTrack and Merlin software’s. For further details, refer to Grant Shoji’s SM thesis: *Modeling and Control of a Hot Micro-Embossing Machine* [28]. Figure 3-7 is a screen capture of the new user interface used to control the system temperature.

![Screen capture of the LabView interface used to control the HME system temperature](image)

Figure 3-7: Screen capture of the LabView interface used to control the HME system temperature
3.3 Temperature Actuation Subsystem

3.3.1 Overview of the Temperature Actuation System

The temperature actuation system designed by Dirckx [8] utilizes heat transfer fluid flowing through mixing valves, heat exchangers, and a pump to command a certain temperature of a platen assembly. A layout of the system is shown in Figure 3-8.

![Figure 3-8: Thermal Control System Schematic [8]](image)

Thermal fluid is pumped through a hot and cold heat exchanger. The resulting flows out of the heat exchangers are split and the hot and cold streams of fluid combine in a mixing valve. This fluid is then circulated through a copper platen assembly, which is used to heat and cool a tool and polymer work piece. The fluid is then re-circulated and the process repeats itself.
3.3.2 Heat Transfer Fluid

A heat transfer fluid for the thermal system was selected based on good thermal properties, chemical and thermal stability in air, and non-toxicity. Dirckx [8] chose Paratherm MR, a paraffinic hydrocarbon oil, to be the working fluid. It has low viscosity, relatively high thermal conductivity, and a boiling point much higher than the system’s maximum temperature. Other favorable characteristics of the fluid are low toxicity, low odor, and stability in air. The last point enables the fluid to be used in a non-pressurized system. A complete list of Paratherm MR fluid properties can be found in Appendix B.2. Consult Dirckx [8] for a more detailed explanation of the fluid selection.

3.3.3 Hot Heat Exchanger

The hot heat exchanger selected by Dirckx [8] is a 30 kW circulation heater from Vulcan Electric Company (Figure 3-9). Internal to the heater are 18 U-tube heater elements enclosed within a 44” long and 8” diameter chamber. There are also baffles located in the heater to induce turbulence. A thorough explanation regarding the selection of this heater can be found in Dirckx [8]. A specifications drawing of the hot heat exchanger is in Appendix C.1.
3.3.4 Cold Heat Exchanger

The cold heat exchanger selected by Dirckx [8] is a plate and frame MaxChanger model MX-22 from Tranter PHE (Figure 3-10). This is a counter-flow heat exchanger with city water flowing in one direction and oil flowing in the other direction. A more detailed explanation behind the selection of this model can be found in Dirckx [8]. A specifications drawing of the cold heat exchanger is in Appendix C.2.

3.3.5 Fluid Flow Model

In order to specify the requirements on the major components of the system, a preliminary model was developed to approximate the thermal-fluid properties. According to ANSYS simulations by Dirckx [8], the system requires a flow rate of 40
GPM and a temperature to $T=200^\circ C$. The specified operating temperature range, however, is room temperature to $180^\circ C$. Each major component in the system was modeled in Matlab and the three key variables (pressure, flow rate, and temperature) are passed from one component to the next to find the pressure drop in the whole system for a desired platen temperature. This pressure drop was needed to select both the pump and the mixing valves. The model operates on the following assumptions:

1. Constant flow rate pump
2. The hot/cold heat exchangers and platens are the only sites for heat transfer
3. Estimated pipe length is 21 feet with a diameter of 1.5 inches
4. Pressure drop is considered in piping, cold/hot heat exchangers, and platens

The pressure drop in the platens was found by curve fitting data from Dirckx’s [8] ANSYS simulations. The pressure drop in the cold heat exchanger was obtained from manufacturer’s data and the pressure drop in the hot heat exchanger was calculated based on dimensional specifications obtained from the manufacturer. From this model, the required pressure drop in the mixing valve was calculated and then the pump was specified. The model was run for desired platen temperatures of $T=30^\circ C$ and $T=179^\circ C$. Table 3-2 shows the estimated pressure drop in the system for these two temperatures. As expected, the pressure drop is lower for the high temperature simulation because of the lower viscosity of the Paratherm MR and lower pressure drop through the heating subcircuit compared to the cooling subcircuit.
Table 3-2: Pressure drops from preliminary model used to specify pump and mixing valves

<table>
<thead>
<tr>
<th>Temperature</th>
<th>System pressure drop-Valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°C</td>
<td>30.0 psi</td>
</tr>
<tr>
<td>179°C</td>
<td>13.7 psi</td>
</tr>
</tbody>
</table>

As construction progressed, the Matlab model was modified to include the pressure drop in the: (1) Y-strainer; (2) an updated platen model; (3) flow meters; and (4) more accurate lengths, diameters, and fittings of pipe. This model was used to select pipe lengths and diameters to try to minimize the pressure drop of the system. Figure 3-11 shows the flowchart behind this model. Minor pipe losses and fittings between the major components were also included in the model. Appendix D outlines the subsections and equations used to generate this model.

Figure 3-11: Flow chart of the updated Matlab model
3.3.6 Mixing Valve Assembly

The mixing valve assembly consists of a mixing valve, actuator, and positioner. A photo of the mixing valve assembly is shown in Figure 3-12. The selection and sizing of these components are described in the following sections. A specification chart is listed in Appendix C.2.

![Photo of the mixing valve, actuator, and positioner](image)

Figure 3-12: Photo of the mixing valve, actuator, and positioner [8]

3.3.6.1. Mixing Valve

An initial design consideration for the control element in the thermal system involved using four individual globe style valves to mix hot and cold fluid streams to heat up two individual platens. This particular design allows flexible control of the flow rates through the platens. However, simulating and controlling the system with four valves can be quite complicated. A simpler way to control the fluid temperature is to use two mixing valves. One of the downsides to using mixing valves is little to no flexibility with
regards to changing the flow rate of fluid through a platen. However, this problem can potentially be eliminated by: (1) installing throttling valves or simple ball valves upstream from the mixing valves; or (2) varying the pump speed with a motor controller. Therefore, mixing valves were chosen as the control element in the thermal control system.

Proper sizing of the mixing valves was essential for optimal performance and ease of controllability. If the valve was too small, minute changes in valve position may cause the flows to drastically change. On the other hand, a valve too large might have unpredictable and little effect on temperature with changes in position [29]. Equation 3-1 is a valve authority equation used for sizing valves, where \( \Delta P_1 \) is the pressure drop across a fully opened valve, \( \Delta P_2 \) is the pressure drop across the remainder of the system, and \( N \) is the valve authority.

\[
N = \frac{\Delta P_1}{\Delta P_1 + \Delta P_2}
\]

Equation 3-1

It is good practice to design a system with a valve authority between 0.2 and 0.5, with better performance closer to 0.5 [29]. This is recommended because the mixing valve can only be expected to divert flow through different subcircuits of the system if it has a high pressure drop relative to the rest of the system. A mixing valve with a low pressure drop would be unable to command changes in subcircuit flow in the middle of the operating range (operation would be limited to the extremes of fully open or fully closed). Using the system simulation presented in Section 3.3.5, \( \Delta P_2 \) was calculated for cases where 179 °C and 30 °C fluid flows through both platens. The pressure drop for the system excluding the mixing valves comes out to 13.7 psi and 30 psi, respectively.
Given this range of pressures and a valve authority of $N = 0.5$, the pressure drop across the valve should be between 13.7 psi and 30 psi.

Once the pressure drop across the valve was known, the flow coefficient ($C_v$) for the valve was calculated using Equation 3-2. The flow coefficient $C_v$ is defined as the flow of water through a valve at 60°F in gal/min at a pressure drop of 1 psi. $Q$ is the flow rate in gal/min, $SG$ is the specific gravity = 1 for water at 60°F, and $\Delta P_1$ is the pressure drop across the valve.

$$C_v = Q \sqrt{\frac{SG}{\Delta P_1}}$$

Equation 3-2 [30]

Assuming a target flow rate through a single platen is 20 GPM, a $SG$ ranging between 0.68-0.8, and $\Delta P_1$ between 13.7 psi and 30 psi, the $C_v$ of the valve should be between 3.38 and 4.4. After consultation with Paxton Corporation, a control products and valve distributor, they recommended a ½" $C_v = 6.3$, model 2830 three-way mixing valve from Warren Controls. The justification for going with a higher $C_v$ was the fear of the total system pressure getting too high and a smaller valve might induce fluid velocities high enough to approach a point where it may damage the valve seating. The valve has a linear trim meaning that given equal fluid inlet pressures, the flows should be proportional to the position of the valve stem.

3.3.6.2. Pneumatic Actuator

One of the goals of the system was to reduce cycle time, so having the ability to move the mixing valve stem quickly is essential for a successful system. A pneumatic actuator has the response time necessary for quick and efficient control of the valve stem.
A DL49 spring-diaphragm actuator 49 in² was selected, which uses air pressure to move the valve stem in one direction and a spring to retract it back. More information on the DL49 can be found in the product specification manual [31].

3.3.6.3. Positioner

Another component necessary for controlling the mixing valves is an electro-pneumatic positioner. This gives the user the capability to control the mixing valves via computer. A Moore 760E positioner was selected with some of its properties shown in Table 3-3. The positioner accepts a 4-20 mA current signal over its full range and is assumed to be linear throughout. Mechanical feedback from the positioner actuator stem is provided by a feedback lever through a characterized cam to the spool valve which controls pressure to the actuator. Detailed information with regards to the Moore 760E positioner can be found in Appendix C.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity</td>
<td>0.75% of normal span</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>1.0% of normal span</td>
</tr>
<tr>
<td>Deadband</td>
<td>Less than 0.25% of span</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Within 0.5% valve travel</td>
</tr>
</tbody>
</table>

3.3.7 Positive Displacement Pump

Based on the system requirements, the pump must be capable of delivering 40 GPM of fluid in a temperature range of 25°C-200°C. The pump was specified based on
the highest system pressure drop expected (at lowest temperatures). The fluid model described in Section 3.3.5 indicated that a system pressure drop of 30 psi can be expected, not including the valves and other minor pipe losses. The mixing valve specification described in Section 3.3.6 showed that they would add another 30 psi. This puts the full system pressure drop estimate at 60 psi. However, given possible inaccuracies in the model and other design additions that could raise the pressure drop of the system, the pump was specified based on a possible 100 psi system pressure drop (safety factor of 1.8). Given that there is no downside in over specifying the pump (except for slightly higher initial capital costs), it was advisable to be cautious in selecting an adequately sized pump that can handle future pumping requirements.

Based on this number, two main types of pumps were investigated: centrifugal and positive displacement. Centrifugal pumps were considered first because they are much safer. As opposed to a positive displacement pump, which is essentially constant flow rate regardless of system pressure, according to a typical curve (see Figure 3-13), a centrifugal pump will not blow-out and cause physical injury because the pump flow diminishes with increasing system head. System head in feet (H) is equivalent to pressure (psi) according to Equation 3-3.
A positive displacement pump, however, can over pressurize and possibly explode under high pressure situations. Figure 3-13 also suggests that centrifugal pump flow rates are dependent on the change in the pressure of the system. As seen in the Matlab model in Section 3.3.5, the pressure drop in the system changes significantly with temperature. Therefore, centrifugal pumps pose a very difficult control problem. The flow rate would have to be controlled closed loop with a motor controller or a pressure regulating valve to ensure a constant flow rate as the process temperature cycles.

Positive displacement pumps, on the contrary, have pump curves more similar to Figure 3-14. The flow rate is almost constant with changes in the system curve (with the exception of some slip at higher pressures).
Based on this information, a positive displacement pump was specified. To ensure safe operating conditions, a pressure relief valve set below the pumps rated capacity was placed immediately downstream of the pump to avoid over-pressurization. Several pump manufacturers were investigated. However, based on advice from Paratherm corporation, Roper pumps was selected because of their compatibility with hot oil-systems and all steel and cast iron construction. The Roper model 3711W series of positive displacement pumps operate on a gear principle (see Figure 3-15) that forces the fluid from inlet to outlet through a series of gear teeth.
To size the pump, the required pump RPM for the pump was calculated. This calculation was done with the pump performance curves found in Appendix C.5. The first step was to determine the viscosity of the Paratherm MR. Based on the chart in Appendix B.2, the viscosity of Paratherm from 25°C to 180°C is ~5-0.5 centistokes. Given this viscosity, the slip GPM for the pump at its rated pressure of 100 psi was found to be ~6 GPM. Given this, the pump was specified for 46 GPM (40 GPM required plus 6 GPM slip). From this, the appropriate RPM was found to be ~400RPM. The next step was to calculate the motor size required. Based on a 400 RPM speed and 100 psi pressure, a base 2.5 HP was required in addition to another 0.5 HP for viscosity effects for a total of at least 3HP. Given start-up torque requirements a minimum of 4 HP motor would be required to power this pump. However, the manufacturer only had 5 HP pumps on hand, so a 5 HP motor unit was installed. A check of this calculation is Equation 3-4, which equates required pump horsepower (HP) to the flow rate (Q=40GPM), head (100 psi–H=288.75 feet), specific gravity at 30°C (SG~0.8) and (Motor/gear box and Pump)
Efficiency ~0.5. This standard efficiency for the motor-gearbox-pump assembly was recommended as a rule of thumb by the pump manufacturer (Roper pumps).

\[
HP = \frac{Q \cdot H \cdot SG}{3960 \cdot MP_{\text{efficiency}}}
\]

Equation 3-4 [33]

The selected pump has 2” NPT fittings and came mounted to a painted steel base with a coupling and guard connected to the motor through a gear reduction box. The motor is a three-phase 230-460V Totally Enclosed Fan Cooled (TEFC) inverter grade motor that is compatible with motor controllers, which will be required to change the flow rate of the system. The gear-reduction box has a 4.6:1 ratio and steps down the 1760 RPM motor to ~382 RPM (as close as possible to the rated 400 RPM given the discrete gear-box ratios). The pump is rated for the high temperature option and also has an in-built Relief Valve (RV) style pressure relief valve that bypasses the pump outlet if the pressure exceeds a user defined value 30-125 psi. The current installation of the valve is set to 125 psi. The motor-pump assembly rests on a PVC/fiber-reinforced vibration damping pad to reduce vibration and prevent the unit from moving during operation.

Another important consideration is the Net Positive Suction Head (NPSH) of the pump inlet. Cavitation could occur at the pump inlet if there is insufficient pressure head. This is not of concern in this application because a 4-6 foot head of fluid is present on the pump inlet. For further detail on maintenance and specifications, refer to the pump, gearbox, and motor manuals.
3.3.8 Motor Controller

Based on the positive displacement pump specified, a motor controller was required to control the speed of the motor to allow for variable flow rate. A variable flow rate is required to: (1) soft start the pump to ensure the motor does not overload caused by high start-up torque; and (2) change the flow rate through the platens at different points in the process cycle to maximize cycle time and reduce temperature non-uniformity at the platens. The minimum requirements for the motor controller were:

1. Variable power input to a 5 HP three-phase 460V motor
2. Manual speed control and on/off capability
3. Analog inputs to control motor speed and emergency on/off from a remote site
4. Capable of handling moderate vibration and robust to environmental changes found near a thermal-oil system
5. Full load amp delivery of at least 8.1 amps - given 5 HP (3.7 kW) motor and its 460V three phase power

Based on these requirements, several options were investigated and the Hitachi L100 was selected because it satisfied all the requirements at the most reasonable cost. Figure 3-16 below shows a front view of the motor controller.
The motor controller operates on the principle of sine wave Pulse Width Modulation (PWM) to convert the 60 Hz three-phase 480V input to a variable frequency (0-60 Hz) three-phase 460V output. The output frequency from the motor controller is approximately proportional to the motor speed and thus the flow rate of the pump. Every 1.3 Hz set on the motor controller corresponds to approximately 1 GPM of flow from the pump. The power wiring from the three-phase 480V 10 amp fuse box to the motor controller and the motor controller to the pump motor was done by the MIT facilities department.

The motor controller also has the ability to direct the motor to move in the forward and reverse direction, which may be useful in breaking up an obstruction, should debris clog the system. Moreover, the motor controller has dynamic braking and soft starting (to reduce the power spike to the motor and increase the motor and pump
lifetime). Constant or reduced motor torque settings as a function of motor controller frequency are also possible. This setting determines whether the full amp rating or a reduced amp rating will be permitted to be transmitted to the motor while running at reduced speeds. Several other more advanced features, such as the remote and local programming of preset trajectories of the motor, are possible with this motor controller. Reference the motor controller manuals for further detail.

3.3.9 Heater Controller

Based on the electric circulation heater specified, a heater controller to select the set point temperature of the fluid exiting the heater was required to ensure maximum flexibility when designing the HME process cycle. The minimum requirements for the heater controller are:

1. Variable power input to a 480V three-phase delta 30kW electric circulation heater
2. Two temperature inputs
   a. Set point output fluid temperature- feedback control
   b. Heater coil temperature (type J thermocouple)- auto shutoff
3. Analog and emergency remote inputs
   a. Alarm situations from the computer
   b. Startup/shutdown routines from the computer
4. Manual controls
   a. On/off switch
   b. Set point temperature
   c. Coil temperature shutoff
5. Analog output

a. Set point temperature

A review of the market of heater controllers showed that all the required functions listed above were not possible in one product, but rather, required the integration of three products: (1) a process controller; (2) an over-temperature controller; and (3) a power controller. These three products can be sold separately or combined in a power control box. These boxes have pre-wired communications and power in a NEMA 1 enclosure (well-insulated from ambient).

A Chromalox 4268 Silicon Controlled Rectified (SCR) Power Controller Box was chosen because it satisfied all the requirements at the most reasonable cost. This unit houses a 2104 Process Controller, a 1600 Over-temperature Controller and an SCR power controller. The SCR is a zero voltage switched unit that proportionally turns on and off a full cycle of the power line. The unit varies power to the heater by varying the number of AC power line cycles [37]. Figure 3-16 shows a front view of the heater controller installed on the system. The power wiring from the three-phase 480V 100 amp fuse box to the heater controller and the heater controller to the heater was done by the MIT facilities department. Reference the heater controller manuals for further detail.
3.3.10 Expansion Tank

The expansion tank serves as a multipurpose safety device found in thermal fluid systems allowing for thermal expansion of fluid, venting of vapor pressure, and maintaining a positive pressure into the entrance of the pump. Depending on the type of fluid used in the system there are a variety of designs for optimal performance and prevention of fluid degradation. Paratherm MR, the working fluid in the system, has a very low vapor pressure allowing the system to not be pressurized. A liquid phase systems design guide by Therminol detailed the most commonly used expansion tank designs and design rules [38]. The expansion tank can either have a single leg or double leg, the latter being more effective in venting non-condensable and purging of air/water upon start-up of the system. A cold seal tank used in conjunction with the double leg expansion tank is the best design to preserve the integrity of the fluid. Figure 3-18 details the final design used in the system.
Upon the initial charging of the fluid in the system, it is recommended to run the fluid through the expansion tank at a low flow rate to expel any entrapped air. This requires all of the valves to be opened except valve A. During normal operation of the system all of the valves should be opened except valve C. This will prevent the bulk of the fluid from entering the expansion tank and unnecessarily heating up the fluid and air which may result in oxidation of the fluid. The hose connection between the expansion tank and cold trap serves to mitigate air contact in the expansion tank, while allowing hot air within the expansion tank to exhaust. Another function of this design is to eliminate any non-condensables, such as water. The pipes branching from the main pipe to the expansion tank are raised 1” from the bottom of the tank, so water can settle out below into the piping between the expansion tank and cold trap. Disposing of the non-condensables requires shutting off valve D and E, then opening the cap on the right side.
of valve E. Proper sizing of the expansion tank and cold trap is recommended for system safety and keeping costs down. If the tank is too small, it may overflow during heating. If it is too large, a significant amount of the fluid needs to be purchased. Standard design rules suggest having the fluid level in the tank at 25% when the fluid is at room temperature and 75% when the fluid is at the highest system temperature. These conditions are taking into account the worst possible scenario, so the fluid level should typically operate between 25% and 50%. In the case of a system failure, either a backup in the system causing fluid levels to rise or a catastrophic loss of fluid, level sensors should be placed within the expansion tank to send a signal to shut down the pump and heater. A technical representative from Therminol suggested that the low level sensor should be placed at 10% of the tank capacity and the high level sensor at 90% of the tank capacity.

An initial calculation of the fluid volume within the system excluding the expansion tank was 10.7 gallons. This calculation is detailed in Appendix E.1. Assuming a system temperature ranging between 20 °C and 180 °C, a properly sized expansion tank using the rules stated above comes out to roughly 4.5 gallons. Staying on the conservative side of the design and using more fluid, a six gallon steel pail sealed with a lug cover serves as the expansion tank and a three gallon tin-plated steel pail is the cold trap. The dimensions of the expansion tank are 16” in height and 11.5” in diameter. The dimensions of the cold trap are 13.75” in height and 9” in diameter. Given some restrictions regarding the height differential between the expansion tank and cold trap, the side mounted stainless steel fluid level sensors from Madison Company were placed at heights of 3.5” and 11” in the expansion tank. An aluminum flexible-sight liquid-level
gauge 12" center-to-center with a 10.5" sight length was attached to the cold trap enabling the user to visually monitor the liquid level in the tanks. A flexible hose connected from the expansion tank into the cold trap exhausts gases and pressure from the system. A K-type thermocouple was also attached to the outside of the tank monitoring the temperature of the fluid in the tank.

3.3.11 Sensor Communication

When designing an automatic control system, the selection and placement of sensors, actuators, and data acquisition are critical to the performance of the system. A layout of the communication between the computer and components within the system is shown in Figure 3-19.
A total of 11 analog inputs were needed for the system, all of them thermocouple measurements. The locations of these temperature measurements are detailed in Table 3-4.

Table 3-4: List of analog inputs needed in the system

<table>
<thead>
<tr>
<th>Number of Analog Inputs</th>
<th>Description of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outlet of the Hot Heat Exchanger Fluid Temperature</td>
</tr>
<tr>
<td>1</td>
<td>Outlet of the Cold Heat Exchanger Fluid Temperature</td>
</tr>
<tr>
<td>2</td>
<td>Outlet of the Mixing Valve Fluid Temperature</td>
</tr>
<tr>
<td>5</td>
<td>Different Locations on Bottom Platen Temperature</td>
</tr>
<tr>
<td>1</td>
<td>Top Platen Temperature</td>
</tr>
<tr>
<td>1</td>
<td>Expansion Tank Temperature</td>
</tr>
<tr>
<td>Total=11</td>
<td></td>
</tr>
</tbody>
</table>

Four analog current outputs (4-20 mA) in the system are described in Table 3-5.

Table 3-5: List of current outputs needed in the system

<table>
<thead>
<tr>
<th>Number of Analog Outputs (4)</th>
<th>Description of Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Controls the speed of the pump motor</td>
</tr>
<tr>
<td>1</td>
<td>Controls the hot heat exchanger set point temperature</td>
</tr>
<tr>
<td>2</td>
<td>Controls the positions of the mixing valves</td>
</tr>
</tbody>
</table>

65
The system also required a number of digital inputs and outputs for the fluid level sensors and motor controller. Two digital input lines were needed to monitor the fluid level sensors in the expansion tank. They needed to be integrated with a simple electrical circuit, which will be detailed in Section 3.3.14.6. Two digital output lines were used for switching the motor on and off and also switching the type of signal sent to the motor controller. The digital outputs needed to be integrated with an additional electric circuit described in Section 3.3.14.1.

### 3.3.12 Computer Hardware

A National Instruments PCI-4351 card specifically designed for thermocouple measurements is the main sensor interface for the entire system. This board has 14 differential thermocouple inputs, an auto zero channel, and cold junction compensation. Its 24-bit ADC resolution and onboard signal conditioning provide extremely high precision temperature measurements; however, the trade-off being a slow maximum sampling rate of only 60 readings/second. In addition to the analog inputs, the board has 8 TTL digital I/O lines. The PCI-4351 was interfaced with a TC-2190 shielded isothermal rack mount with thermocouple mini-connector ports for ease of use. This board was sufficient for the 11 thermocouple readings and 4 digital I/Os needed for the system.

In addition to measuring analog inputs, the system required four analog current outputs to control two mixing valves, a pump motor, and heater. The NI PCI-4351 does not have any analog output channels, so an Adlinktech PCI-6208A card was selected. The Adlinktech PCI-6208A provides 8 current outputs, 4 digital inputs and 4 digital outputs. The pin assignment for the card is shown in Figure 3-20. Current sourcing is
possible because of additional onboard high-precision voltage to current transducers.

Performance of the board is adequate with a 4-20 mA range and current signals settling within 17 µs at a 15-bit resolution. Interfaced with the board is a DIN-37D terminal board with a 37-pin D-sub Connector and DIN-Rail Mounting.

![Pin assignment for the PCI 6208A](image)

Figure 3-20: Pin assignment for the PCI 6208A [39]

3.3.13 Sensors

3.3.13.1. Thermocouples

A variety of thermocouples were selected for measuring the temperature at different locations in the system. Directly measuring the temperature of the fluid required a thermocouple that could handle a substantial amount of pressure, since the fluid itself is pressurized. Therefore, rugged pipe plug probe K-type thermocouples with
1/4” NPT connections were placed after the two mixing valves and at the outlet of the cold heat exchanger. A dual K-type thermocouple with 1/8” NPT connection was placed at the outlet of the hot heat exchanger. Transition junction style K-type thermocouple probes 6” in length and 0.032” in diameter were used in all other locations. The bottom spacer plate, machined by Dirckx [8], has five channels and ports where the thermocouples can measure the temperature of the PMMA directly (Figure 3-21). High temperature ceramic cement from Omega was used to mount the thermocouples in the bottom spacer plate. See Appendix B.2 for properties of the adhesive. A hole was drilled into the side of the top spacer plate deep enough so that there are no thermal edge effects for the thermocouple reading. The last thermocouple was secured to the side of the expansion tank to monitor the temperature of the fluid.

Figure 3-21: Bottom spacer plate with five thermocouple ports designed and machined by Dirckx [8]
3.3.13.2. Level Sensors

Level sensors monitor the fluid level in the expansion tank to prevent overflow or catastrophic loss of fluid. A horizontally mounted stainless steel float type level sensor from Madison was used for the expansion tank. The basic operation of the sensor is to close a circuit when the fluid brings the float horizontal and breaks the circuit when the float is in air. These sensors can work in fluids with specific gravity down to 0.7, which corresponds to a Paratherm MR bulk fluid temperature of 150 °C. The temperature of the Paratherm MR within the expansion tank should never reach a temperature of 150 °C, because the temperature will typically be cycling between 55 °C and 150 °C. The sensors can also tolerate a temperature of up to 200 °C, so they should operate properly when the machine is running for an extended period of time.

Integrating the level sensors to work with the PCI-4351 digital inputs required some additional circuitry. Figure 3-22 shows the electric circuit used to get the sensors functioning properly. The PCI 4351 has a +5 V supply and a digital ground. The PCI 4351 requirement for a digital input is a maximum low level input of 0.8 V and a minimum high level input of 2.0 V with a current between -10 μA and 10 μA. Therefore, a 10 kohm resistor between the +5 V supply and digital input port will drop the high level by 0.1 V, which would not affect the range of voltages needed to detect a low and high level. Without the resistor, the voltage read by the digital input port would mostly be a high level reading whether or not the circuit is closed.
3.3.14 System Wiring

3.3.14.1. Motor Controller Wiring

Three functions that needed wiring of the motor controller were: (1) turning the motor on/off; (2) analog input to control the speed of the motor; and (3) analog current or voltage input signal switching. A diagram of the wire terminals on the motor controller is shown in Figure 3-23.
In order to turn the motor on and off via computer, wires needed to be connected to terminals P24 and 1. These wires were interfaced with the digital input/output terminals on the PCI-4351. Since terminal P24 is a +24 V source and the PCI 4351 has a +5 V source, the wires needed to be connected in series with a relay circuit. An external emergency button to turn off the motor was also hooked up in series with the relay circuit.

An analog current input signal to the motor controller was necessary for controlling the speed of the motor. A wire was connected to the OI terminal of the motor controller and the other end was connected to the positive analog output terminal (pin 15) in the PCI 6208A. The other wire was connected to the L terminal of the motor controller and the other end was connected to the negative (ground) terminal of the corresponding analog output terminal (pin 14) in the PCI 6208A.

In order to maintain flexibility with regard to potentially changing hardware, a switching function between sending a voltage or current analog output was used. Since the PCI 6208A sends out a current output, the current setting should always be on. But in the case of needing to switch to a card which sends voltage outputs, the option will be available. Wires were connected to the terminals P24 and 3 with a relay circuit in series because of the disparity in voltage supplies.

The relay circuit used for digital outputs is shown in Figure 3-24. An SPST reed relay with properties listed in Table 3-6 was used in the circuit. The transistor used is a 2N2222 NPN with properties listed in Table 3-7. Other constant variables were the +5 V power supply and the digital input signal. Since the PCI 4351 has a digital output low level logic maximum of 0.4 V and a minimum high logic level of 3.8 V with a maximum
current of 8 mA, the only variable that needed to be selected was the resistance into the base of the transistor. In order to determine the necessary resistance, a variable resistor was placed before the base of the transistor and 3.8 V was supplied to the input, then the resistance was turned down until it turned on an LED connected to the relay. Knowing this threshold resistance assisted in the selection of a resistor. Finally, a 1.8 kohm resistor proved to be an adequate design for switching.

![Relay circuit diagram](image)

**Figure 3-24: Relay circuit used to switch a +24V source to motor controller inputs**

**Table 3-6: Properties of the SPST reed relay**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Rating</td>
<td>5 VDC</td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>250 ohms</td>
</tr>
<tr>
<td>Contact Rating</td>
<td>0.5 A at 125 VAC</td>
</tr>
<tr>
<td>Nominal Current</td>
<td>20 mA</td>
</tr>
</tbody>
</table>
Table 3-7: Properties of the 2N2222 type transistor

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $h$</td>
<td>200</td>
</tr>
<tr>
<td>Max. $V_{ce}$</td>
<td>30 V</td>
</tr>
<tr>
<td>$I_c$</td>
<td>800 mA</td>
</tr>
<tr>
<td>Dissipation</td>
<td>1.8 W</td>
</tr>
</tbody>
</table>

3.3.14.2. Heater Controller Wiring

There are three sets of wires that needed to be connected to the heater controller. The functions are:

1. Switching between two set point temperatures with a digital signal
2. Controlling the set point temperature with an analog current signal
3. Monitoring the fluid outlet temperature of the heater

A diagram of the heater controller wiring terminals is shown in Figure 3-25.
The first set of wires was connected to terminals 1 and 2 and the other ends were connected to the top terminals of the emergency shutoff button. The wires were hooked up to the top terminals of the button.

In order to control the set point temperature of the heater via computer, wires were connected to terminals 5 and 6 of the heater controller. One end of a wire was connected to terminal 5 on the heater controller and the other end connected to pin 33 on the PCI 6208A, corresponding to a positive current output channel. The other wire was connected to terminal 6 on the heater controller and pin 32 on the PCI 6208A, which is the analog ground channel corresponding to pin 33.

A K-type thermocouple was used to measure the fluid outlet temperature of the heater. Since the particular thermocouple used has dual lead wires, a set was inputted to the PCI 4351 for computer monitoring and the other set was hooked up to terminals 8 and 9 on the heater controller. Since RF interference in the heater controller box causes a noisy signal, a shielded thermocouple attachment was necessary for stable measurements.
The thermocouple’s positive lead should be attached to terminal 8, the negative lead to terminal 9, and the ground lead to terminal 18.

3.3.14.3. **Heater Controller Over-temperature Wiring**

The over-temperature controller protects the heater coils from exceeding a maximum temperature. A diagram of the over-temperature controller is shown in Figure 3-26.

![Figure 3-26: Over-temperature terminal diagram](image)

The only terminals used on this controller are 9 and 10. A J-type thermocouple was attached to a heating coil within the heater. The positive lead was wired to terminal 10 and the negative lead to terminal 9. This thermocouple is shielded, so RF interference does not effect the measurement.
3.3.14.4. Mixing Valve Positioner Wiring

The two mixing valve positioners control the position of the valve stem with a 4-20 mA current signal. The Valve 1 (farthest from the wall) positioner was wired from its positive terminal to the PCI 6208A pin 18 and its negative terminal to the PCI 6208A pin 17. The Valve 2 (closest to the wall) positioner was wired from its positive terminal to the PCI 6208A pin 36 and its negative terminal to the PCI 6208A pin 35.

3.3.14.5. Thermocouple Wiring

All of the thermocouples in the system were inputted to the PCI 4351 through the TC 2190. A photo of the thermocouple inputs on the TC 2190 is shown in Figure 3-27. Table 3-8 shows the temperature readings and their corresponding inputs channels.

Figure 3-27: TC 2190 Thermocouple Inputs
Table 3-8: Description of the thermocouples interfaced with the TC 2190

<table>
<thead>
<tr>
<th>Thermocouple Channel</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Outlet of the cold heat exchanger</td>
</tr>
<tr>
<td>4</td>
<td>Valve1 outlet</td>
</tr>
<tr>
<td>5</td>
<td>Valve2 outlet</td>
</tr>
<tr>
<td>7</td>
<td>Expansion Tank</td>
</tr>
<tr>
<td>8</td>
<td>Outlet of the hot heat exchanger</td>
</tr>
<tr>
<td>9</td>
<td>Platen (Front Right)</td>
</tr>
<tr>
<td>10</td>
<td>Platen (Back Right)</td>
</tr>
<tr>
<td>11</td>
<td>Platen (Middle)</td>
</tr>
<tr>
<td>12</td>
<td>Platen (Front Left)</td>
</tr>
<tr>
<td>13</td>
<td>Platen (Back Left)</td>
</tr>
<tr>
<td>14</td>
<td>Top Platen</td>
</tr>
</tbody>
</table>

3.3.14.6. Miscellaneous Wiring

Since there is a large distance between the machine frame and the computer, a 25 wire cable was used to cover the distance. A picture of the 25 pin connector and its numbering is shown in Figure 3-28. Wires were distributed from the 25 pin connector mounted on the machine frame to the components within the frame. A 25 pin connector was also mounted to the computer stand, with wires distributed to their respective
components. A description of the wires connected to the 25 pins between the machine frame and computer stand is in Table 3-9. There are also a number of wires coming out of a circuit board located near the computer, which were also attached to a 25 pin connector. A description of the wire connections between the circuit board and other terminals is shown in Table 3-10.

![25 pin connector](image)

**Figure 3-28:** 25 pin connector used to link wires from the machine to the computer

**Table 3-9: Pin Identification for the interface between the machine frame and computer stand**

<table>
<thead>
<tr>
<th>25 Pin Port Number</th>
<th>Connection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DIO Ground Pin in 4351</td>
<td>Expansion tank high level sensor ground connection</td>
</tr>
<tr>
<td>2</td>
<td>DIO Pin 1 in 4351</td>
<td>Expansion tank high level sensor digital input</td>
</tr>
<tr>
<td>3</td>
<td>DIO Ground Pin in 4351</td>
<td>Expansion tank low level sensor ground connection</td>
</tr>
<tr>
<td>4</td>
<td>DIO Pin 2 in 4351</td>
<td>Expansion tank low level sensor digital input</td>
</tr>
<tr>
<td>5</td>
<td>Pin 18 in 6208A</td>
<td>Analog positive current output (channel 0) to control valve 1 (closest to front of the machine)</td>
</tr>
<tr>
<td>6</td>
<td>Pin 17 in 6208A</td>
<td>Analog ground (channel 0) to control valve 1 (closest to front of the machine)</td>
</tr>
<tr>
<td>7</td>
<td>Pin 36 in 6208A</td>
<td>Analog positive current output (channel 1) to control valve 2 (near the wall)</td>
</tr>
<tr>
<td>---</td>
<td>----------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>8</td>
<td>Pin 35 in 6208A</td>
<td>Analog ground (channel 1) to control valve 2 (near the wall)</td>
</tr>
<tr>
<td>9</td>
<td>Direct connection to Relay 1 and 2</td>
<td>Connects to the motor controller terminal P24. When this connection is shorted through the motor controller terminal 1 it turns the motor on and off and when it’s shorted through the motor controller terminal 3 it changes the accepted signal from voltage to current.</td>
</tr>
<tr>
<td>10</td>
<td>Direct connection to Relay 1</td>
<td>Connects to the motor controller terminal 1. When it is shorted with P24 it will be programmed to turn the motor on/off. The wiring is also routed to an emergency button so the motor can be turned off externally. The motor can also be turned on/off through the LabView program where it is hooked up to DIO Pin 3 in the 4351.</td>
</tr>
<tr>
<td>11</td>
<td>Direct connection to Relay 2</td>
<td>Connects to the motor controller terminal 3. When it is shorted with P24 it will be programmed to change the accepted analog signal from voltage to current. The wiring is routed to DIO Pin 4 in the 4351 so that control is through LabView.</td>
</tr>
<tr>
<td>12</td>
<td>Pin 14 in 6208A</td>
<td>Analog ground (channel 2) to motor controller terminal L</td>
</tr>
<tr>
<td>13</td>
<td>Pin 15 in 6208A</td>
<td>Analog positive current output (channel 2) to motor controller terminal Of</td>
</tr>
<tr>
<td>14</td>
<td>Hard wire to bottom of emergency button</td>
<td>This connection is to the heater controller terminal 1. This will be used to change the set point temperature, acting as an emergency shutoff.</td>
</tr>
</tbody>
</table>
15 | Hard wire to bottom of emergency button | This connection is to the heater controller terminal 2. This will be used to change the set point temperature, acting as an emergency shutoff.

16 | Pin 33 in 6208A | Analog positive current output (channel 3) to heater controller terminal 5

17 | Pin 32 in 6208A | Analog ground (channel 3) to heater controller terminal 6

**Table 3-10: Pin identification for the interface between the circuit board and other terminals**

<table>
<thead>
<tr>
<th>25 Pin Port Number</th>
<th>Connection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wire to the top of the button</td>
<td>Eventually connects to the motor controller terminal 1.</td>
</tr>
<tr>
<td>2</td>
<td>Pin 11 of main 25-pin connector</td>
<td>Connects to the motor controller terminal 3.</td>
</tr>
<tr>
<td>3</td>
<td>DIO 3</td>
<td>Digital output control for the motor controller terminal 1.</td>
</tr>
<tr>
<td>4</td>
<td>DIO 4</td>
<td>Digital output control for the motor controller terminal 3.</td>
</tr>
<tr>
<td>5</td>
<td>Pin 9 of main 25-pin connector</td>
<td>Connects to the motor controller terminal P24.</td>
</tr>
<tr>
<td>6</td>
<td>DIO +5 V</td>
<td>+5 V supplied by the 4351.</td>
</tr>
<tr>
<td>7</td>
<td>Pin 1 of main 25-pin connector</td>
<td>Ground connection for the expansion tank high level sensor.</td>
</tr>
</tbody>
</table>
8 | Pin 3 of main 25-pin connector | Ground connection for the expansion tank low level sensor.
9 | DIO Ground | Digital I/O ground supplied by the 4351.
10 | Pin 2 of main 25-pin connector | High voltage side connection for the expansion tank high level sensor.
11 | DIO 1 | Digital input for the expansion tank high level sensor.
12 | Pin 4 of main 25-pin connector | High voltage side connection for the expansion tank low level sensor.
13 | DIO 2 | Digital input for the expansion tank low level sensor.

3.3.15 System Frame/Support and Enclosure

Given the large dimensions of the major components and the safety risk posed by the motor-pump and the heater, an enclosure was needed. The requirements of the HME system frame and enclosure were to: (1) isolate the system from the rest of the laboratory for safety and appearance; and (2) provide support to components that will be positioned off the floor. A customizable framing product (Unistrut) was chosen to construct the frame of the enclosure and provide support to the piping, valves, cold heat exchanger, and expansion tank. Figure 3-29 shows the framing design.
An enclosure was affixed to the outside of this frame to protect the user from the motor-pump rotation and the chance of hot-oil leaks. This enclosure was made of aluminum sheet metal and plastic sheeting (see Figure 3-16). There are doors on each side to access the system for routine maintenance. Steel straps and pipe hangers were used to secure pipes, fittings, and the cold heat exchanger to the frame. The expansion tank and valves were directly bolted to the Unistrut frame.

3.3.16 Exhaust System

Vaporization of Paratherm MR at higher temperatures caused by leakage in the system creates an unsafe operating environment. In order to alleviate this situation a complete system enclosure and exhaust fan was required. A Kansas State University website provided an exhaust fan sizing equation for kitchens [42]. Using Equation 3-5 as a minimum CFM requirement for the fan should provide enough air movement to exhaust
most of the smoke generated by the system. The dimensions of the system enclosure are 5’ x 5.5’ x 5.5’ for a total volume of roughly 150 ft³. Using Equation 3-5, the minimum air flow required for the exhaust fan is 30 CFM. At high temperatures the system produces more smoke than a conventional kitchen, so it makes sense to size the fan for a larger air volume. Therefore, a 10” exhaust fan with a 350 CFM capacity should be adequate for the system. A 10” flexible duct connects the fan with the main exhaust line in the building. The 350 cfm unit installed was able to remove the smoke during normal system operation.

\[ \text{Minimum CFM} = \text{Room Volume} \times 0.2 \]

Equation 3-5

3.3.17 Miscellaneous/Minor Component Selection and Methods

In addition to the major components cited above, several minor components were specified to complete the system. Some relevant methods, such as pipe cleaning and installation are also briefly mentioned.

3.3.17.1. Pipe and fitting selection

In selecting the pipes and fittings, three main issues had to be addressed: (1) material choice; (2) connection type; and (3) pipe dimensions. Given that Paratherm MR is not corrosive, carbon steel (black steel) pipe and ductile iron and cast iron fittings were chosen because of their wide availability and low cost. Typical hot-oil systems offer two choices for the selection of piping: (1) high temperature flexible hose, and (2) rigid pipe. Moreover, the three main options for piping connections are: (1) NPT threaded; (2) welded; and (3) flanged.
Though welded fittings are generally recommended for hot-oil applications, Multitherm (a manufacturer of thermal hot oils) suggests that threaded fittings that are back-welded or using thread sealant are also acceptable (see Appendix E.2). Moreover, Paratherm was contacted and informed of the pressure (100 psi) and temperature range (25°C -180°C) of the specified system, and they indicated a threaded option may be viable given the low pressure. Furthermore, the hot and cold heat exchangers, as well as the mixing valves, most isolation valves, Y-type strainers, and pressure relief valves are readily available with threaded connections. With the exception of the pump, which is available in both flanged and threaded connections, all other components are most commonly and cost effectively found with NPT threaded. Given the relatively low pressure of the system and the difficulty posed by welded fittings, NPT connections were specified.

Given the wide availability of threaded rigid carbon steel pipe, this is the main piping component. However, at certain locations in the system, there was difficulty (in terms of location and orientation) in using rigid pipe. Here high temperature flexible hose with threaded fitting were used to ease connection problems. The pipe dimensions were largely dictated by component sizes:

1. Pump: 2” NPT fittings
2. Hot heat exchanger: 2.5” NPT fittings
3. Cold heat exchanger: 1.0” NPT fittings
4. Mixing Valves: 0.5” NPT fittings
5. Platens: 1.25” NPT fittings
Based on these sizes, rigid pipe in the largest available diameter was used to minimize the system pressure drop. Each major component was separated by at least one flexible hose with a female union (for easy installation/placement and removal). Reducers, diffusers, Y-junctions, T-junctions and 45° and 90° fittings were used to route the piping.

3.3.17.2. Isolation valves

Isolation of every major component of the fluid system was necessary. Therefore, ball valves serve as isolation valves before and after the mixing valves, platens, heat exchangers, pump, and expansion tank. These valves can be manually closed off when major components need removal or maintenance. Ball valves work well because of their minimal pressure loss when fully opened. Some locations, such as the cold heat exchanger output, where pressure loss is high relative to the rest of the system have full-port valves, while reduced-port valves were used in other locations.

3.3.17.3. Y-Strainer

A strainer was necessary to catch debris in the system before it is permitted to enter the pump. A 2” carbon steel Y-strainer with a 1/32” perforated Type 304 stainless steel screen (approximately equivalent to a 20 mesh screen) was selected. According to the manufacturer, based on a flow rate of 40 GPM, the strainer can be expected to have a 2-3 psi pressure drop.

3.3.17.4. Pressure Relief Valve

Given the choice of a positive displacement pump, a pressure relief valve was needed to ensure the system does not over-pressurize and damage the pump. The pump
itself has a built-in pressure relief valve that was set at 125 psi. However, given that the system is designed for 100 psi, a redundant pressure relief valve that has a blow-out pressure of <100 psi was needed. A 2" Cast Iron (30-100 psi) pressure relief was selected and installed directly downstream of the pump (set at 100 psi).

3.3.17.5. Component Layout

The last step before construction could begin was to determine a rough layout of the system. Figure 3-30 shows the conceptual layout of a single platen subcircuit.

![Figure 3-30: Schematic of a single platen subcircuit in the system](image)

Based on this information, the physical dimensions of the major components, and rough dimensions of the minor components, a model was generated in 3D Studio Max to approximate the system layout prior to the purchasing of parts. Figure 3-31 shows this model. The placement of some items, such as the heater controller were changed during construction, however, the modeled layout is generally consistent with the actual system.
Reference the HME System Bill of Materials for a full listing of all system components (Appendix E.4).

![Figure 3-31: 3D Studio Max model of the proposed system layout](image)

**3.3.17.6. Pipe Sealing**

Loctite 567 was used to seal the NPT threaded connections. It is an anaerobic sealant that sets in contact with an active material in the absence of air. For locations where an inactive pipe material was used (all pipes except carbon steel) Loctite 7649 structural adhesive primer was used as an activator. Loctite was placed only on the male ends of pipe 1” and smaller and both on the male and female ends of pipes larger than 1” diameter. After the system was assembled, leakage ensued and several other thread sealants were applied (Loctite 5900, Duralco Epoxy, Jetlock#2, GE high temperature silicone caulk, Permatex No.2 sealant, Loctite 294, X-Pando pipe sealant, etc) at different
locations in the system. No thread sealant either placed in the threads or around the perimeter of the pipe was able to stop leakage. Loctite 5900, however, was shown to significantly reduce leakage if applied in large amounts around the outside of the threaded connection (as seen at the platen-hose interface).

3.3.17.7. Insulation

There are two main alternatives for insulating hot-oil systems up to $T=200^\circ$C: (1) fiberglass; and (2) closed cell foam-glass. Though fiberglass is inexpensive and commonly available, there is the tendency of hot-oil (that may leak from the system) to wick into the open cells of the fiberglass and oxidize, which will generate heat and may cause a fire. Therefore, given that threaded connections are being proposed, closed cell Foamglas insulation (a product of Coming) is recommended by Paratherm to insulate the system piping and components to reduce the chance of fire.

A thickness of 1.5 inches is recommended by Corning to ensure proper insulation for a $T=200^\circ$C system. Jacketing material can either be aluminum (which will require securing the aluminum jacketing to the insulation with metal straps), or ASG (a type of high temperature fabric used to protect fiberglass insulation that is already attached to the Foamglas). Either option is acceptable, however, the ASG Foamglas will be easier to install and remove (simply slip fit the insulation over the pipe and secure with the adhesive tape provided on the insulation) then the aluminum (secure the aluminum over the pipe with metal straps). Foamglas can be purchased in standardized pipe lengths (0.5”-2.5” diameter and 1.5” -2” thickness) as well as specially shaped for other components such as valves. The material can be cut on-site with the use of a saw. Given leakage in the current system, no insulation has been purchased. Once the leakage has
been resolved, Foamglas should be installed. In the case of a fire, a Class ABC Dry Chemical Fire Extinguisher is located next to the system.

3.3.17.8. Pipe Installation

The pipes were installed by 2-3 people starting from the pump outlet and proceeding toward the heat exchangers, mixing valves, platens, and back to the pump inlet. Certain subsections were pre-assembled in a vice to ease installation. Strap wrenches were found to be ineffective at properly tightening the connections. Rather, large pipe wrenches were used to torque down the fittings, unions, and hoses.

3.3.17.9. System Cleaning

Prior to construction, each component was cleaned in a mineral spirit bath and scrubbed with wire brushes to remove any oils, lacquers and dirt. This was to ensure that the system remains free of debris for good heat transfer performance and to avoid clogging the 1/8” channels in the platen.
4 Micro-Part Metrology and Characterization

4.1 Need for Micro-Part Characterization

The same initial work described in Chapter 2 that indicated a second generation HME system was needed (Chapter 3) also introduced the difficulty of measuring micro-embossed parts at the scales of interest (lateral: \(<1\mu m\)-1000’s \(\mu m\) and depth: \(<1\mu m\)-100’s \(\mu m\)). There are several techniques currently in use to characterize micro-embossed parts. There is a need to characterize HME parts to: (1) ensure part compliance to a design specification; (2) establish a clear relationship between input parameters and output part metrics; and (3) monitor process variation. However, no existing technique addresses the essential functionality of the device. Given fluid will be flowed through the micro-channels, it is essential to determine whether a fluid can flow through a closed channel. The objective is not to mimic the intended application of the device, which would vary greatly from one design to another, but to determine the bulk fluid flow characteristics of the micro-channel (pressure vs. flow rate). This testing method can be used to both determine part functionality (ability to flow fluid) and assess HME process variation caused by deterministic (such as change in processing parameters) and non-deterministic (noise) factors. Table 4-1 outlines the major surface metrology techniques currently in use across the scientific community. The following subsection will discuss the major metrology options specifically related to the characterization of micro-fluidic parts.
Table 4-1: Summary of applications and limitations on existing surface metrology techniques [43]

<table>
<thead>
<tr>
<th>Technique</th>
<th>Main information</th>
<th>Vertical resolution (depth probed, typical)</th>
<th>Lateral resolution (typical)</th>
<th>Types of solid specimen (typical)</th>
<th>Use (popularity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical profiler and laser interferometry</td>
<td>3D and 2D imaging</td>
<td>-0.1 nm</td>
<td>A few sub μm to a few tens of μm</td>
<td>All</td>
<td>Medium</td>
</tr>
<tr>
<td>Confocal microscopy</td>
<td>3D and 2D imaging</td>
<td>Variable from a few nm to a few μm</td>
<td>Optical, 0.5 to 4 μm, SEM, 1 to 50 μm</td>
<td>Almost all</td>
<td>Medium</td>
</tr>
<tr>
<td>Optical scatterometry</td>
<td>Profilometry</td>
<td>20.1 nm</td>
<td>A few sub μm to a few tens of μm; ≥ laser wavelength λ/2 for topography</td>
<td>Almost all</td>
<td>Not common</td>
</tr>
<tr>
<td>Light microscopy (general)</td>
<td>Imaging</td>
<td>Variable</td>
<td>Variable</td>
<td>All</td>
<td>Extensive</td>
</tr>
<tr>
<td>Stylus profilometry</td>
<td>Profilometry</td>
<td>0.5 nm</td>
<td>100 nm</td>
<td>Almost all; flat smooth films</td>
<td>Extensive</td>
</tr>
<tr>
<td>Scanning tunneling microscopy (STM)</td>
<td>Topographic imaging</td>
<td>&lt;0.03 to 0.05 nm</td>
<td>Atomic</td>
<td>Conductors</td>
<td>Medium</td>
</tr>
<tr>
<td>Atomic force microscopy (AFM) or scanning force microscopy (SFM)</td>
<td>Topographic imaging</td>
<td>&lt;0.03 to 0.05 nm</td>
<td>Atomic to 1 nm</td>
<td>All</td>
<td>Medium</td>
</tr>
<tr>
<td>Variable-angle spectroscopic ellipsometry (VASE)</td>
<td>Film thickness Microstructure Optical properties</td>
<td>Tens of nm to μm</td>
<td>Millimeter</td>
<td>Planar surface and interface</td>
<td>Medium</td>
</tr>
<tr>
<td>X-ray fluorescence (XRF)</td>
<td>Film thickness (1 to 10 μm) Element composition (qualitative mapping)</td>
<td>10 μm</td>
<td>10 to 150 μm</td>
<td>All but low-Z elements: H, He, and Li</td>
<td>Extensive</td>
</tr>
</tbody>
</table>
4.2 Existing Metrology-Based Characterization Methods

4.2.1 Atomic Force Microscopy (AFM)

AFM is a surface characterization technique that brings a cantilevered tip with angstrom to nm scale diameter near a sample surface for scanning (see Figure 4-1). The AFM can operate in two different modes. Contact mode brings the tip in close contact with the sample surface (angstroms to several nm). The tip is then scanned across the surface and attractive and repulsive Vander Wall forces cause the cantilevered tip to deflect to account for changes in forces which are dependent on the distance of the tip from the surface [43]. The deflection of the tip is monitored and the topography data of the sample can be recorded. In non-contact or tapping mode, the AFM tip is excited at its resonant frequency and scanned slightly farther away from the sample surface. Therefore, the tip is only in intermittent contact with the surface, reducing lateral forces on the tip but still allowing for observation of the tip deflection, which can be used to back out the surface topography [43].

Figure 4-1: Diagram of an AFM cantilevered tip in contact with a sample and laser monitored [44]
AFM has a very high resolution; however, it has limited range in the lateral (100's of \( \mu m \)) and depth (10's of \( \mu m \)) directions. Moreover, the AFM is extremely sensitive to disturbances and scans take unusually long. Scans described in Chapter 2 took slightly longer than 30 minutes. Given the limited range, high noise sensitivity, and long scan times, AFM is not ideally suited to characterize micro-fluidic parts. There are several derivatives to this metrology method such as Scanning Tunnel Microscopy (STM), etc. STM operates by monitoring the tunneling current flow through the tip and surface at a constant voltage, which is distance dependent. This method however, requires a conductive surface, which is not possible without destroying the part in polymer-based micro-fluidic devices.

### 4.2.2 Confocal Microscopy

Confocal microscopy is a subset of traditional optical microscopy. Confocal microscopes use additional apertures to blur out reflected light from all but the specified focused plane on the sample [43]. Therefore, images of material sections can be taken and these sections can be collected to recreate the surface topography of the sample. Confocal microscopes have better resolution capabilities than most traditional optical microscopes and sufficient range, however, the lateral resolution may be insufficient to characterize the smallest scale micro-fluidic features. The depth resolution, which is a function of the ability to step through sections of the sample, is on the order of 10's of nm. Moreover, Poly(methyl methacrylate)-PMMA is transparent and the low reflectivity makes optical imaging very difficult. The equipment is not as sensitive to disturbances as the AFM.
4.2.3 Optical Profilometry

Optical profilometry is a technique based on white-light interferometry [10]. An input light source is split into two signals. One signal is sent to a reference surface and the other signal is reflected off the sample surface to the reference surface [10]. The difference in the optical path of the two signals creates light and dark fringes of constructive and destructive interference [10]. These fringes can be used to recreate an image of the sample. The objective lens can be moved in the vertical direction to scan a given depth of the sample to recreate the surface topography. This technique is very fast. Scans described in Chapter 2 took less than 45 seconds. As with confocal microscopy, the range is adequate, however, the lateral resolution may be insufficient to characterize the smallest scale micro-fluidic features (depth resolution is very high). Moreover, PMMA is transparent and the low reflectivity makes optical imaging very difficult. The equipment is not as sensitive to disturbances as the AFM.

4.2.4 Mechanical Stylus Profilometry

Stylus profilometry is in the same family as AFM. A stylus is brought in contact with the surface and scanned [43]. The deflection of the stylus is monitored and topography of the surface can be generated. In stylus profilometry, the tip comes in physical contact with the sample, rather than in AFM, where it does not come into full contact, only to a point where Vander Walls interactions can be detected. Stylus profilometry has slightly lower lateral resolution than the AFM, however, more than sufficient to characterize most micro-fluidic parts. Resolution is largely dependent on the size of the stylus tip. The range of the scans can be on the order of several cm. The only
major downsides are the sensitivity of the equipment to disturbances and the long scan times for full surface scans.

4.2.5 Scanning Electron Microscopy (SEM)

SEM is a technique where the surface of a conductive sample is bombarded with electrons and the secondary electrons from the sample are scattered and recorded on a Cathode Ray Tube (CRT) [45]. This technique can also be applied to non-conductive samples with the use of an Environmental –SEM, which has a gaseous environment that amplifies the secondary electron signal from the sample [45]. This technique has very high resolution, however, does not give quantitative data on the surface topography. Therefore SEM is useful to observe fabricated parts but not establish metrics for process control.

4.2.6 Particle Image Velocimetry (PIV)

PIV is a technique to characterize micro-channel geometry based on local fluid flow. PIV works by flowing a fluid with nano-particles that can be observed with a video imaging device (i.e. fluorescent tags) through the micro-channel [16]. The flow path of the particles is analyzed to determine the channel dimension based on a no-slip boundary layer model of the sidewalls [16]. Work on a device based on this concept (Nanoscope) by Stone et al. has shown promising results [16]. However, as expected, noise in the velocity measurements significantly raise the uncertainty of the wall measurements [16]. This technique is highly model driven. This technique was developed recently and may have great potential to characterize micro-fluidic parts. Moreover, with the addition of nano-particles in the fluid stream and a more sophisticated imaging system, this technique could be combined with the proposed functional testing method to both
quantify the bulk fluid performance of the micro-channel and the dimensions based on a no-slip boundary layer model. This technique, confocal microscopy, optical profilometry, and functional testing technique have the advantage of being able to establish metrics in closed channels. Other metrology techniques are only capable of characterizing open channels.

4.2.7 Metrology Overview

The advantages and disadvantages of each characterization method were discussed in detail and it is apparent that no single metrology technique is appropriate to characterize micro-fluidic parts. Rather, a combination of each technique is necessary to characterize parts under different circumstances. AFM could be used to characterize small features (<40-80 μm) in a laboratory setting, SEM could be used to corroborate other measurement techniques and verify results, and stylus profilometry and optical techniques (confocal and interferometry) could be used under most other conditions. Moreover, techniques such as PIV and the proposed bulk flow functional testing method holds promise to be used within a manufacturing environment to provide immediate data on the part for implementation in cycle-to-cycle control. The deficiencies in the current metrology methods and the need to test the ability of parts to actually flow fluid are the key points driving further inquiry into functional testing.
5 Overview of the Functional Testing System (FTS) Concept

5.1 Role of Functional Testing in the Integrated Circuit (IC) Industry

The problem of measuring micro-scale devices is not new to the field of microfluidics. The IC field has dealt with many of the same issues regarding the complication of measuring devices and establishing output metrics for both part compliance and equipment process control. The IC industry has addressed this issue with two major methods of characterization - traditional metrology and functional testing. The rule of ten is often cited as the main motivation to find defects as early as possible in the manufacturing process [46]. The cost C of finding a defect at the component level goes to 10C if found at the board level, 100C if found at the system level, and 1000C if found after the product is deployed in the field [46].

Traditional metrology techniques are limited to the wafer scale prior to packaging. They are used to determine the effectiveness of process steps such as layer deposition and etching. Typical methods to characterize micron scale structures include Scanning Electron Microscopy and Transmission Electron Microscopy (TEM) - an extremely high resolution electron imaging technique used to determine layer thickness on a diced sample [47]. Optical techniques and stylus profilometry are also used for larger scale structures where the precision of SEM and TEM are not required [47]. These techniques are largely used to characterize parts to assess equipment variation and determine the
ideal equipment parameters to deposit or etch to a particular specification. However, functional testing is more commonly used during production level to assess part functionality at different stages in the IC fabrication process.

The basic application of functional testing in the IC industry is outlined in Figure 5-1. Modeling is carried out after the initial design, and the device is tested after wafer processing, packaging, accelerated lifetime tests, and before product shipment for quality assurance [48].

![Diagram of functional testing applied to IC manufacturing](image)

*Figure 5-1: Overview of functional testing applied to IC manufacturing [48]*

There are two major types of functional tests. The first type is the electrical characterization of features by either resistive or capacitance measurements and the second is a more sophisticated suite of tests performed with Automated Testing Equipment (ATE). Figure 5-2 shows a diagram of test structure where a capacitance measurement between the top metal plate and underlying metal interconnects can be
correlated with the known material properties of the Inter-layer Dielectric (ILD) to determine the layer thickness [47].

![Diagram](image)

Figure 5-2: Test structure to determine the thickness of the Inter-layer Dielectric (ILD) by measuring the capacitance between the top metal plate and metal interconnects [47]

ATE is the mainstay of the IC fabrication industry. IC’s are often designed with testing in mind and some logic sites are built into the device design to facilitate testing during fabrication. There are two major issues related the use of ATE. First, the method of physical contact between the ATE and the Device Under Test (DUT) must be established. The second major issue is the algorithm used to test the logic, speed, and various metrics of DUT functionality. This testing method involves interfacing the bare wafer or the packaged chip to a Device Interface Board (DIB) as shown in Figure 5-3. The DIB is used to connect the wafer or packaged chip (with the use of a socket adapter) to the ATE [48]. The DIB can also be referred to as an interposer depending on the type of IC packaging tested [49]. Once physical contact has been established with the DIB or interposer several types of tests are run to test part functionality.
The ATE runs an Automatic Test Pattern Generator (ATPG) that directs AC and DC signals to the DUT and compares the output to expected reference values based on the design of the IC. The logic behind this testing method is shown in Figure 5-4.
The type of inputs are both systematic and random. The systematic algorithms seek to determine whether the most pervasive faults (such as stuck faults which are a logic gate stuck at one position 0 or 1) are present [46]. The random inputs are used to test for other errors. The results of the tests are used to differentiate between functional and non-functional devices and bin functional IC’s according to speed. The algorithms used for this testing are highly developed to find the most likely causes of IC malfunction with the least number of testing iterations. The DC and AC inputs are used to test the logic structure of the IC (gates) and determine which if any logic gates are not operational and whether that is critical to the performance of the device. The final step in the functional testing of IC’s is the accelerated lifetime tests. These tests are performed on ATE under harsher conditions (voltage, temperature, humidity, pressure, and loading) then expected in the field to accelerate the lifetime and test for failure [50].

Functional testing currently has no equivalent in micro-fluidics manufacturing. This is largely because micro-fluidics is an infant industry, however, increasing demand and application in this field as described in Section 1.1, justify the implementation of
functional testing within micro-fluidics manufacturing. The multiple lines of interconnects in an IC are similar to the multiple lines of micro-channels expected in micro-fluidic devices. In both cases, full inspection of interconnect or channel geometry is difficult and instead a bulk performance specification must be used. Functional testing has the potential to meet this need.

5.2 FTS Requirements

Though a combination of the existing metrology techniques have the potential to meet the range and resolution requirements for HME process control in a laboratory setting, existing metrology techniques lack the ability to quickly test the fluidic performance of the output part in a production environment, which is needed to control the hot micro-embossing (HME) process. Therefore, a functional testing system for micro-fluidic devices to establish: (1) Does the device flow fluid? and (2) How close is the device to meeting the required specifications for flow rate and pressure? is necessary to confirm the robustness of the HME manufacturing process. Tests will focus on the variation in pressure (for a fixed flow rate) or flow rate (for a fixed pressure) between channels.

The FTS must meet the following requirements: (1) provide fast results on the tests run; (2) be capable of handling a wide range of micro-channel geometries; (3) provide sufficient accuracy in pressure and mass/flow rate measurements to detect changes in micro-channel geometry; and (4) be robust to noise expected in a production environment. The FTS should be designed to accommodate parts fabricated from the second generation HME system to be tested for fluidic performance. The FTS should include five subsystems:
1. Off-part fluid source (pump)

2. Pressure sensor

3. Mass scale and humidity/temp sensor with enclosure
   - To corroborate the pump flow rate and ensure minimal fluid evaporation

4. Light microscope/ digital camera

5. Functional Testing Platform (FTP)
   - To load the test part, align, apply pressure to seal, and flow fluid to and from the part

6. Control and data acquisition
   - To control the pump and gather the required data for analysis of the fluid flow

5.3 FTS Preliminary Calculations and Sensitivity Analysis

5.3.1 FTS Preliminary Calculations

Based on the requirements described in Section 5.2, it was necessary to determine the feasibility of the proposed method within a laboratory setting. Prior to construction and initial testing it was important to determine the geometries, flow rates, and pressures that will be dealt with to ensure that the FTS was designed to meet the expected requirements and to ensure that unreasonable constraints were not placed on the equipment (pump, pressure sensor, mass scale, etc). A rough preliminary set of calculations was performed with sample input values shown in Table 5-1.
Table 5-1: Sample input values used for preliminary FTS calculations

<table>
<thead>
<tr>
<th>INPUT VALUES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity of Water ((\mu))</td>
<td>0.01 g/cm*sec</td>
</tr>
<tr>
<td>Density of Water ((\rho))</td>
<td>1 g/cm(^3)</td>
</tr>
<tr>
<td>Flow Rate (Q) = 1 ml/min</td>
<td>0.0167 cm(^3)/sec</td>
</tr>
<tr>
<td>Total Length of Micro-channel (L)</td>
<td>5 cm</td>
</tr>
<tr>
<td>Total Length of Reservoir (L)</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Width of Micro-channel (w)</td>
<td>0.05 cm</td>
</tr>
<tr>
<td>Height of Micro-channel (h)</td>
<td>0.005 cm</td>
</tr>
<tr>
<td>Diameter of Reservoir (D)</td>
<td>0.2 cm</td>
</tr>
</tbody>
</table>

The flow rate through the channel was set to \(~1\)ml/min. This flow rate was chosen based on a reasonable quantity of fluid that could aid in the mass/flow measurements (reduce time required to run the tests and allow for the accumulation of a sufficient amount of fluid to make measurements practical). This channel geometry was selected because it matched HME parts that had already been fabricated and observed with traditional optical profilometry and therefore would be a suitable comparison point to functional testing. The reservoir diameter= 2000 \(\mu\)m was chosen to aid in the integration of the micro-channels with the macro-scale connectors in the support platform used to connect the test chip to the rest of the fluid circuit. The calculations were performed assuming Hagen-Poiseuille laminar Newtonian flow (discussed in detail in Chapter 8).

Based on this assumption, the test chip was sectioned into two regions: (1) the micro-channel and (2) the reservoir. Fluidic resistance, Reynolds number (Re), fluid velocities, residence time, and pressure drops in each section were calculated independently. The data from the two sections was then complied to determine the total pressure drop and residence time outlined in Table 5-2.
Table 5-2: Summary of output values from the preliminary FTS calculations

<table>
<thead>
<tr>
<th>OUTPUT VALUES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity in Micro-channel (v) Q/A_{micro-channel}</td>
<td>66.80 cm/sec</td>
</tr>
<tr>
<td>Velocity in Reservoir (v) Q/A_{reservoir}</td>
<td>0.53 cm/sec</td>
</tr>
<tr>
<td>Re in Micro-channel ((\rho vD_h(nicro-channel)))/ (\mu)</td>
<td>60.73</td>
</tr>
<tr>
<td>Re in Reservoir ((\rho vD_h(reservoir)))/ (\mu)</td>
<td>10.64</td>
</tr>
<tr>
<td>Resistance in Micro-channel 12(\mu L/(wh^3))</td>
<td>9.60E+07 g/sec*cm(^4)</td>
</tr>
<tr>
<td>Resistance in Reservoir (8(\mu L)/(\pi r^4))</td>
<td>1294.27 g/sec*cm(^4)</td>
</tr>
<tr>
<td>Pressure Drop in Micro-channel R*Q</td>
<td>23.33 psi</td>
</tr>
<tr>
<td>Pressure Drop in Reservoir R*Q</td>
<td>3.14E-04 psi</td>
</tr>
<tr>
<td>Total Pressure Gradient</td>
<td>23.33 psi</td>
</tr>
<tr>
<td>Micro-channel Residence Time L_{micro-channel}/v_{micro-channel}</td>
<td>0.07 sec</td>
</tr>
<tr>
<td>Reservoir Residence Time L_{reservoir}/v_{reservoir}</td>
<td>9.55 sec</td>
</tr>
<tr>
<td>Total Residence Time (\sum (L_i/v_i))</td>
<td>9.63 sec</td>
</tr>
<tr>
<td>Area of Testing Platform (\pi(d=4in)^2/4)</td>
<td>12.56 in(^2)</td>
</tr>
<tr>
<td>Clamping Force (to ensure seal)</td>
<td>292.99 lbs</td>
</tr>
</tbody>
</table>

The micro-channel resistance equation assumes that the width >> height of the micro-channel. This assumption is correct for the geometries calculated (w=500 microns and h=50 microns). However, for channels where width is only slightly greater than height, another more precise derivation of the Navier-Stokes equation is Equation 5-1.

\[
R_{w\gg h} = \frac{12\mu L}{wh^3} [1 - \frac{h}{w} \left( \frac{192}{\pi^5} \sum_{n=1}^{\infty} \frac{1}{n^5} \tanh \left( \frac{n\pi w}{h} \right) \right)]^{-1}
\]

Equation 5-1 [52]

The calculations show that pressure drop of ~23 psi can be expected for the sample geometry. This is well below the 100 psi upper limit that would be both practical and safe for this testing application in a laboratory setting. Based on this calculation,
FTS equipment was specified to handle pressures on the order of 40 psi and flow rates from fractions of an ml/min to ten’s of ml/min. Moreover, the required clamping force is also reasonable (293 lbs). Therefore the implementation of this testing platform is practical within the laboratory setting for the range of geometries tens to hundreds of microns in width and depth. Smaller geometries would also be possible provided a lower flow rate were used or a shorter micro-channel were tested.

The calculations also showed that the pressure drop in the reservoir is approximately five orders of magnitude smaller then the pressure drop along the micro-channel. Given this and the fact that any external tubing used to connect the test chip to the rest of the fluid loop will have cross section on the order of the reservoir, it was reasonable to assume the proposed testing method has maximum sensitivity to the pressure drop across the micro-channel (not the rest of the fluid loop).

5.3.2 FTS Sensitivity Analysis

Given that the feasibility of functional testing within a laboratory setting was established the next step was to determine what sensitivity the test has to HME process variation. In order to determine this, it is important to look at the relationship between the dimensions of the channel, the flow rate, and the pressure drop. Note: Initial calculations were run assuming a constant pressure input of water; however difficulty in finding highly precise constant pressure sources later required a shift to a constant flow rate pump. If the tests were carried out with a constant pressure of water input and the mass/flow rate of the fluid loop was measured to establish a quantitative measure of process variation, then it is necessary to look at the variation in flow rate as a function of changes in channel depth and width. For a conservative estimate on testing sensitivity a
low aspect ratio was analyzed to determine the effect of changes in width on flow rate for a constant pressure input of water. Width on a low aspect ratio micro-channel was chosen because according to Hagen-Poiseulle flow, it is the least sensitive dimension given the micro-channel resistance equations shown in Table 5-2. The values cited in the preliminary calculations (Table 5-1) were also used to assess the functional testing methods sensitivity to changes in micro-channel geometry.

Commercial mass measurement devices can be obtained with resolution on the order of 0.001g (~0.001 cm$^3$ water). Assuming the test time is limited to 60 seconds, a mass measurement device could potentially detect a variation in flow rate of (0.001 cm$^3$/60 seconds) ~1.67 x 10$^{-5}$ cm$^3$/sec. The resolution would scale inversely with the length of the test (a longer test would be able to detect more subtle variation in flow rate-time additive). Figure 5-5 shows a plot of the flow rate as a function of width (assuming all other parameters are constant and an ideal water pressure source of P=23 psi).
As expected from the Hagen-Poiseulle equations, the plot shows a linear relationship between the width of the channel and the flow rate through the channel. The slope \( \frac{1}{2.994 \text{ sec/cm}^2} \) is \( \sqrt{\frac{0.05 \text{ cm}}{0.0167 \text{ cm}^3/\text{sec}}} \approx 2.994 \text{ sec/cm}^2 \). Given this slope \( \frac{1}{2.994 \text{ sec/cm}^2} \) and a flow rate measurement resolution of \( \sim 1.67 \times 10^{-5} \text{ cm}^3/\text{sec} \), the width measurement resolution is \( \sim (2.994 \text{ sec/cm}^2) \times (1.67 \times 10^{-5} \text{ cm}^3/\text{sec}) \approx 5 \times 10^{-5} \text{ cm} \) (0.5 microns).

Therefore, the testing process is theoretically capable of detecting a 0.5 micron variation (0.1%) in width for this particular micro-channel geometry at P=23 psi and a testing time of 60 seconds. This is the lowest resolution predicted by theory for this particular situation (as height would be expected to have a higher resolution given the cubic relationship between height and flow rate). Given this, we would expect that the sensitivity of the testing process would behave as follows:
1. An increase in the water supply pressure will increase the resolution of the testing process (higher flow rates for the same geometry translates to more sensitivity to geometry changes)

2. Longer test times will increase the resolution of the testing process (more time to detect subtle changes in flow rate-time additive)

The calculations above reinforce the following key points:

1. Functional testing is feasible within a laboratory setting

2. Functional testing has sufficient sensitivity to geometry variation (even when calculated for the lowest resolution dimension) that it should be further investigated for use in HME process characterization and control

The calculated sensitivity is the low-end theoretically expected value given limitations on commercially available mass scales. However, other factors such as pressure sensor accuracy/resolution and FTS leakage, alignment, and general testing repeatability will all serve to reduce this sensitivity. Therefore, the highest possible pressure sensor accuracy/resolution and proper FTP design to reduce testing induced error will be required to maximize sensitivity. The difficulty in finding a reliable constant pressure fluid source required a shift to a constant flow rate pump with pressure as the new metric to detect HME process variation. However, the feasibility and potential sensitivity of the process calculations are still valid and suggest further investigation is justified.

### 5.4 FTS Conceptual Design

Based on the need driving the development of the testing system and the requirements that the system must meet, a conceptual design as shown in Figure 5-6 was
The design of the FTS sought to reduce any secondary processes that would alter the fabricated part (therefore no additional processing steps were performed on the part to prepare for functional testing). This ensured the results of the testing match (as closely as possible) the variation of the micro-embossing process used to create the parts and not any secondary process or the testing variation itself.

Figure 5-6: Conceptual design of the FTS

The pump will supply fluid to the test part. The pressure sensor will record the pressure in the fluid circuit. The Functional Testing Platform (FTP) image capture will be via a light microscope and digital camera. The proposed FTP consisted of support platforms, an elastomeric gasket layer, and the test chip itself secured with fasteners. Macro-micro connectors will be threaded into the top support platform to ensure leak-tight delivery of fluid from the pump to the test chip. A mass scale and humidity/temperature sensor with enclosure will be used to monitor the flow of the fluid downstream of the
testing platform. Control and data acquisition from the pump, mass scale, and pressure sensor will be carried out by a PC running LabView.

Water was the chosen fluid because it: (1) is readily available, (2) safe to use, and (3) has the lowest viscosity of commonly available fluid that does not readily evaporate such as alcohols. Lower viscosity is important keep the pressure of the system down so a wide range of flow rates can be tested without driving up the pressure limits of the FTS.

Air was another alternative that was investigated, however, given the likelihood that most micro-fluidic channels will be used to flow liquid, water was chosen as opposed to air. Moreover, the difficulty in observing air leakage and pumping air leak free was also another point of concern. This having been said, as testing methods develop and the size of the micro-channels tested goes down, air (dynamic viscosity= \( \mu = 0.0182 \) centipoise~2% of water) may be a more attractive functional testing fluid [51]. Observing the change in pressure will allow for a quantification of HME variation.

5.5 Functional Test Part Tool Design

Given the need for functional test parts (with micro-channel and reservoirs for fluid I/O) and the design of the second generation HME system described in Chapter 3, a new tool was designed. Copper tools as shown in Figure 5-7 (designed by Wang [61]) were used in the first generation system. These tools were machined with a micro-end mill (635 \( \mu \)m). However, large tooling marks on the order of 5 \( \mu \)m, as well as burring problems drove the need to develop a more suitable tool for micro-fabrication. Given this need, a mask for use in Deep Reactive Ion Etched (DRIE) was designed and fabricated in collaboration with Shoji [28] and Wang [61]. DRIE silicon was chosen for several reasons: (1) tests using DRIE silicon tools were used by Ganesan [24] and found
to have well defined features; (2) the ability to fabricate several silicon tools from one mask master; (3) the vacuum chuck on the platen system was designed to accept surface micro-machined wafer tools; and (4) silicon tools are cost effective and have reasonably good thermal conductivity. The mask design was sent to Microtronics Corp. for fabrication on a 5" Soda-lime mask 0.09" thick (minimum 0.1 μm spot size). A smaller spot size would have been possible with a quartz mask, however, this was not required. The tools based on the new mask design were fabricated by Hayden Taylor in the Micro-Systems Technology Lab (MTL). See Appendix B.6 for detailed material properties of silicon.

![Figure 5-7: Copper platen used on the first generation HME system](image)

DRIE is a dry etching process where a silicon wafer is etched by the mechanical force of ions bombarding the surface of the wafer. Photo-resist is spun on the silicon wafer. The mask design is used to selectively shine high intensity light on the photo-resist. Those areas exposed by light dissolve away in a post-exposure developer while those not exposed to light remain. The silicon wafer with photo-resist is then hard baked
and dry etched for a given time based on the desired feature depth (areas without photo-resist etch while those with photo-resist remain) and then the remaining photo-resist is removed with solvent. This makes raised features. A major drawback with DRIE is sidewall roughness due the alternating nature of the DRIE process between etching and Teflon coating steps (to prevent undercutting of the features). Given this, when HME with the silicon tools, part sizes were kept as small as possible to aid de-embossing.

The new mask design had several requirements. The design had to include features to test the effect of the following tooling parameters on the HME process:

1. Spatial variation
2. Feature geometry
3. Feature density
4. Feature aspect ratio
5. Feature size (depth and width)

These design requirements allow for one mask design to be used to perform a $2^5$ Design of Experiments (DOE) of the parameters listed above. Moreover, functional test sites had to be included to allow for the fabrication of parts that had inputs and outputs in which to flow fluid. Based on these requirements, a 4” x 4” mask was designed to be fabricated on a 6” diameter silicon wafer and subsequently cleaved to fit in the HME system or on a 4” diameter silicon wafer with some features cut off. All tools to date have been fabricated on a 4” diameter silicon wafer.

Figure 5-8 shows a schematic of the light field mask. The mask has three distinct sections: (1) metrology test sites; (2) functional test sites; and (3) miscellaneous channels. The basic metrology pattern is replicated eight times across the mask. The width of the
features varies (300, 100, 30, 10, 3, and 1\(\mu\)m). The minimum space between features is 1 \(\mu\)m and the horizontal spacing between features range between 10x, 1x, and 0.1x feature size. Feature geometries include channels, circles, triangles, squares, and hexagons.

Figure 5-8: Schematic of the mask designed for the fabrication of DRIE silicon tools with close-up of a feature used in functional testing

The functional test site reservoirs are 2000 \(\mu\)m. This dimension was chosen to facilitate fluid connections from the macro-scale tubing and fittings to the micro-channel. The large fluid reservoirs make microscope and simple eye alignment of the test part for testing possible. The functional test sites lengths vary (1000, 2000, 4000, and 8000 \(\mu\)m). These lengths were largely determined by the layout of the mask and available space relative to the metrology test sites. The functional test sites widths vary (50, 100, 200, 400, and 800 \(\mu\)m). A large range of widths was chosen so tools of varying depth could be
made from the mask and a whole range of aspect ratio features could be HME with this single mask design. The functional test sites flow paths also vary (straight, constricted, diverging, and turning). These different flow paths were included to allow for the functional testing of parts with unique flow configurations.

The miscellaneous section of the mask was filled with large width and large length channels to simply fill out the remaining space on the layout. These features were not designed to form when the mask is used to fabricate a 4” diameter tool.

5.6 Description of Test Parts

All functional tests described hereafter were performed on HME PMMA functional test channels with 2000 μm reservoirs, a micro-channel length of 8000 μm, and varying depth and width (see Figure 5-8). Widths tested ranged the full spectrum of the mask (50, 100, 200, 400, and 800 μm). Depths tested were largely dependent on the variations in the DRIE process recipe used to create the tools. The approximate tool depths fabricated were 20, 30, 50, 65, and 100 μm. One tool, based on the mask design with 35 μm depth, was fabricated out of SU8 (a thermoset photo-resist epoxy commonly used in soft lithography processes). This tool was used for the fabrication of the 800 μm x 35 μm parts described in Chapter 9. All other parts were fabricated with silicon DRIE tools based on the mask shown in Figure 5-8. Table 5-3 summarizes the approximate micro-channel geometries and aspect ratios of all parts that have been tested with the FTS.

All parts tested were also observed in the Zygo Interferometer to determine the approximate channel geometries. Given the channels tested are much longer than they are wide, it is not practical to image the entire channel under the microscope to a
sufficient resolution to detect geometry differences. The channel dimensions were obtained by taking two scans and measuring the depth and top and bottom width of the micro-channel at each end of the channel. The depth of the channel was obtained by averaging the depth from each end of the channel and the width was obtained by averaging the average width at each end of the channel (average of top and bottom). The tools all have a natural draft angle that ranges from ~10° to ~30°. This creates a part with a smaller width at the bottom of the channel than at the top.

Table 5-3: Summary of parts made to date

<table>
<thead>
<tr>
<th>Feature Size</th>
<th>w* (μm)</th>
<th>d* (μm)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>65</td>
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<td>5</td>
<td>150</td>
<td>65</td>
<td>0.43</td>
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<td>6</td>
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<td>7</td>
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</tr>
<tr>
<td>8</td>
<td>800</td>
<td>35</td>
<td>0.04</td>
</tr>
</tbody>
</table>

* Intended tool dimension

Actual micro-channel dimensions are shown in Appendix G
6 Design of the Functional Testing System (FTS)

6.1 FTS Fluid Circuit Layout

Based on the FTS requirements, conceptual design, preliminary calculations, and sensitivity analysis explained in Section 5.2 and Section 5.3, all necessary components were assembled into a full system according to the fluid circuit shown Figure 6-1. Two syringes can be loaded into the syringe pump and connected to the fluid circuit. However, only one syringe was loaded for testing to date. The 1/8" ball valve connecting the second syringe to the circuit was closed to prevent fluid from flowing between syringes. The fluid flows from the syringe through the circuit passed the pressure sensor to the FTP and finally to the mass scale. The requirements and specification and selection of the major and minor components as well as the design of the Functional Testing Platform (FTP) are explained in the following subsections.

Figure 6-1: FTS fluid circuit layout
6.2 Specification and Selection of Major Components

6.2.1 Syringe Pump

An off-chip fluid delivery source was chosen to avoid the complication and secondary processes necessary to fabricate a pump and micro-channel on the same chip. The additional processing would have defeated the purpose of using functional testing to assess hot micro-embossing (HME) process variation. If on-chip pumping had been chosen, several options including, though not limited to the following could have been employed: bubble pumps; membrane pumps, diffuser pumps, rotary pumps, electro-hydrodynamic pumps, electro-osmotic/ electro-phoretic pumps, ultrasonic pumps, vacuum pumps [52]. Given this, the pump source had to meet several requirements: (1) deliver predictable steady flow in the range of hundredths to several ml/min; (2) repeatability < ± 1%; (3) accuracy < ± 1%; (4) manual control on the unit; (5) accept remote computer controls; (6) record relevant data during testing; and (7) deliver fluid with at least 40 psi.

Two types of pumps have the potential to meet these requirements: (1) syringe pumps; and (2) peristaltic pumps. Both are positive displacement pumps. A syringe pump operates with a motor-lead screw to push a block against a syringe filled with fluid at a rate defined by the user. A peristaltic pump operates using rollers that push against tubing which contains the fluid to be pumped. The rotation of the rollers physically pushes the fluid through the tubing. Figure 6-2 shows the operating principle of a peristaltic pump.
Though both pumps are available in the flow rate range needed for the FTS, the peristaltic pump has one major drawback. The rotation of the rollers creates a pulsed flow that is not steady and will therefore result in variable pressure readings. Given the objective is to define clear pressure to flow rate measurements, a peristaltic pump would not be acceptable. A syringe pump, however, has much more predictable flow that is dependent on the motor-lead screw pitch and motor speed.

Several manufactures were investigated and a Harvard Apparatus PHD 2000 Infusion pump was selected. The PHD 2000 was chosen because it was one of the few syringe pumps that met all communication requirements, came in a double syringe for added flow rate delivery, and provided adequate force for high pressure flow.

The pump, shown in Figure 6-3, has specifications outlined in Table 6-1. The syringe pump operates with an open loop stepper motor and lead screw assembly. The pump is angled during testing such that air bubbles rise to the back of the syringe and are not pumped into the rest of the fluid circuit.
Table 6-1: Summary of relevant specifications for the syringe pump

<table>
<thead>
<tr>
<th>Specification</th>
<th>Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate Range</td>
<td>0.0001 µl/min - 220.82 ml/min</td>
</tr>
<tr>
<td>Syringe Sizes Range</td>
<td>0.5 µl - 140 ml</td>
</tr>
<tr>
<td>Accuracy</td>
<td>(±) 0.35%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>(±) 0.05%</td>
</tr>
<tr>
<td>Maximum Force</td>
<td>66 lbs</td>
</tr>
<tr>
<td>Pusher Rate Range</td>
<td>0.18 µm/min - 190.676 mm/min</td>
</tr>
<tr>
<td>Step Resolution</td>
<td>0.082 µm/sec</td>
</tr>
<tr>
<td>Step Rate Range</td>
<td>27.3 sec/step - 416.7 µsec/step</td>
</tr>
</tbody>
</table>

6.2.2 Mass Scale and Humidity/Temp Sensor with Enclosure

The mass scale serves to verify the flow rate from the syringe pump. The mass scale had to meet the following requirements: (1) mass capacity of at least 200g; (2) resolution of at least 0.001g; and (3) output to data to a PC for recording. Given the flow rate may approach hundredths of ml/min or less, a precise measuring device was necessary. Several manufacturers were investigated and an ACCULAB VIC-303 (see
Figure 6-4) mass balance was selected because it had a high resolution at a reasonable cost.

![Mass Balance and Humidity Sensor](image)

**Figure 6-4: ACCULAB VIC-303 Mass balance and GENEQ Testo 625 Humidity/Temp Sensor**

In addition to the mass balance, a humidity enclosure and humidity/temperature sensor was required. In order to corroborate extremely low flow rates with the mass balance, some type of enclosure to prevent the loss of fluid through evaporation was required. Note: no test run to date was at a sufficiently low flow rates to require the use of the humidity enclosure. Nevertheless, this may be of concern for future tests. In order to ensure ~100%RH in the enclosure, a moisture absorbing foam structure saturated in water should be affixed to the inside of the humidity enclosure. This is a technique used to maintain small enclosures at or near 100%RH. The foam will have to be re-soaked each time after the enclosure is opened. The GENEQ Testo 625 humidity/temperature
sensor was chosen at the advice of Korb [62] because it was capable of measuring both humidity and temperature with reasonable accuracy and it included a probe which was necessary to measure inside the enclosure. Table 6-2 outlines the specification for both the mass scale and the humidity/temp sensor.

| Table 6-2: Summary of relevant specifications for the mass scale and humidity/temp sensor |
|-----------------------------------|------------------|------------------|
|                                   | ACCULAB Mass Balance | GENEQ Humidity/Temp Sensor |
| Capacity                          | 300g              | RH Range         |
| Resolution                        | 0.001g            | 0-100%RH         |
| Repeatability                     | 0.003g            | RH Accuracy      |
|                                   |                   | (±) 2.5%RH       |
| RH Resolution                     |                   | RH Resolution    |
|                                   |                   | 0.1%RH           |
| Temp Range                        |                   | Temp Range       |
|                                   |                   | -10 to 60°C      |
| Temp Accuracy                     |                   | Temp Accuracy    |
|                                   |                   | (±) 0.5°C        |
| Temp Resolution                   |                   | Temp Resolution  |
|                                   |                   | 0.1°C            |

6.2.3 Pressure Sensor

The pressure sensor, as the mass scale, had to have a high resolution and accuracy to measure the pressure in the system. Without reliable hardware the objective of establishing a repeatable testing process to characterize HME parts would not have been possible. The pressure sensor had to meet the following requirements: (1) pressures from 0-100 psi; (2) output data to a PC for recording; and (3) highest possible resolution within reasonable cost. Several manufactures were investigated and the 3D Instruments DTG-6000 high-accuracy digital test gauge was chosen to monitor the pressure of the fluid circuit. The gauge operates on a strain-gauge based principle with a stainless steel diaphragm. Deflection of the diaphragm is monitored with the strain gauge, displayed on
the digital readout and transmitted to the PC. Table 6-3 summarizes the relevant specification for the pressure sensor (Figure 6-5).

Table 6-3: Summary of relevant specifications for the pressure sensor

<table>
<thead>
<tr>
<th>Pressure Range</th>
<th>29.5” Hg to 100 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>0.01 psi</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-20 to 60°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accuracy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20-100 psi</td>
<td>(±) 0.1% (reading)</td>
</tr>
<tr>
<td>0- 20 psi</td>
<td>(±) 0.02% (full scale)</td>
</tr>
<tr>
<td>-14.5 psig to 0 psi</td>
<td>(±) 2.0% (full scale)</td>
</tr>
</tbody>
</table>

Figure 6-5: 3D Instruments DTG-6000 Pressure Gauge

6.3 Specification and Selection of Minor Components

6.3.1 Syringes

The tests to be run with the functional testing platform were not expected to require pressures in excess of ~40 psi. Therefore, the largest available syringe (140 ml) was chosen. Given the maximum force from the pump is 66lbs and the diameter of a 140
ml syringe is ~1.5 inches, the maximum pressure the pump can safely deliver with one
140 ml syringe loaded is ~37 psi. The largest possible syringe size for the required
maximum pressure was chosen to maximize the length of time a given test could be run
before the syringe had to be refilled. Testing showed that the pump was actually capable
of delivering on the order of 45 psi with the 140 ml syringe loaded (evidence that that it
can handle forces in excess of 66 lbs if necessary). Pressures in excess of this would
distort the syringe edge and cause the pump to stall. If higher pressures are required for
future testing, a smaller syringe size (which has a proportionally smaller syringe area)
could be used. The syringes have a Luer-lock female fitting on the ends to interface with
tubing (Figure 6-6). Two syringes were connected to the fluid circuit, however, one can
be isolated from the system by opening/closing a ball vale. This allows for added
flexibility in running at higher flow rates or longer test times.

Figure 6-6: 140 ml syringe used for all testing with Luer-lock fitting

6.3.2 Tubing

Tubing was selected to interface with the Luer-lock fittings on the syringe. The
tubing was cut to interface with the brass compression fittings. The tubing is rated to 200
psi. The smallest commonly available tubing has an internal diameter of 1/16” ~1590 µm. The outer diameter is 1/8”. This tubing was selected to keep the fluid circuit volume as low as possible (to reduce testing time needed to fill the circuit) and ensure negligible pressure drop. At low flow rates, if an unusually large tubing diameter was chosen than the fluid would only flow from the tube when a drop of sufficient size relative to the tubing formed. The smaller the tubing, the faster the fluid velocity and the more steady the flow rate into the mass scale. However, given the extremely low flow rates that will be tested, drop-based flow will still be seen.

6.3.3 Fittings

Brass fittings, as opposed to plastic fittings, were used to connect all major components of the system to the fluid circuit tubing caused by lower cost and higher pressure ratings. Compression fittings were chosen over barb fittings because the tubing selected was highly rigid and did not seal on a barb fitting. Moreover, compression fittings have a higher pressure rating and are less likely to leak. All fittings were wrapped with two revolutions of Teflon tape prior to tightening to ensure a leak free connection. See the FTS Bill of Materials in Appendix F for further details on all the minor components specified.

6.4 Mechanical Design of the Functional Testing Platform (FTP)

6.4.1 Support Platform Material Selection

The FTS required the specification and selection of several components and the construction of the FTP. Within the FTP, there were only two key pieces that required material selection, the support platforms and the gasket layers (see Section 6.4.2 for
details on the gasket layer specification). The top and bottom support platforms serve several purposes in the design of the FTP. First, they route the fluid to and from the test part. Second, the support platforms, with the aid of the fasteners and c-clamps, hold together the assembly. Third, they provide a backing against which the gasket layers can be compressed against the test part. The support platforms needed to be easily machinable, optically clear (to observe testing in progress), and maintain a rigid form under test loading. Given these requirements, a type of plastic was required. The three most commonly available plastics that are clear with no tint are acrylic, polycarbonate, and polyester. All three would be adequate for this application, however, polyester is most commonly found in thin sheets 1/4” and less in thickness and polycarbonate is substantially more costly than the other two alternatives because of its high impact resistance. Therefore, acrylic was chosen for the top and bottom support platforms.

6.4.2 Evolution of the FTP design

In all designs, there are several iterations until the design is crystallized and testing can begin. In the FTS, most components were specified and the task was in integrating, controlling and operating the equipment. However, the FTP did require some design iterations. There were five major design versions from start to completion. The defining features and the need driving the next version of the design are explained below. The objective of the FTP was to deliver fluid to and from a single test part leak free. The design scope was limited to a single-input single-output fluid connection.

6.4.2.1. FTP Version 1

FTP Version 1 (Figure 6-7) was made of two 1/4” thick pieces of acrylic 5” x 5” and secured with nine fasteners on the perimeter. A 1/16” silicone gasket layer was used
to seal the channel against the top support platform. Silicone was selected as the gasket material because of its Durometer rating of 40A— a hardness rating recommended for sealing commercial gaskets. Two brass fittings with tubing attached were screwed into a taped female NPT hole on the top support platform. The fittings only protruded 1/8” in the 1/4” platform. Two ~3 mm holes were then drilled 10 mm apart through the rest of the material (to fit the 8000 μm long channel with 2000 μm reservoirs). See Figure 6-8 for a schematic of this assembly.

Figure 6-7: FTP Version 1

Figure 6-8: FTP Version 1 schematic
The FTP Version 1 was tested with a test part and leakage was observed at the interface between the NPT fittings and the top support platform. Moreover, in an attempt to tighten the fitting, the acrylic cracked rendering the platform unusable.

6.4.2.2. FTP Version 2

FTP Version 2 (Figure 6-9) was fabricated along the same lines as Version 1, however, the size was reduced to 2.5” x 2.5” with four fasteners, given the parts to be tested are on the order of 1 in² and less. The method was kept the same to determine whether the quality of the NPT tap or the design was the cause of the leakage. The interface between the fitting and the top support platform leaked despite attempts to further tighten the fitting. As before, the support platform also cracked rendering the platform unusable.

Figure 6-9: FTP Version 2
6.4.2.3. FTP Version 3

Given the problems with leakage at the fitting-top support platform interface, a thicker top support platform was used for FTP Version 3 (see Figure 6-10 for a side view comparison with prior version). The logic here was to use a larger piece of acrylic less likely to crack and provide a longer engagement length for the NPT fitting to reduce the chance of leakage (see Figure 6-11). The new top support platform thickness was 1/2". Once again, upon testing the interface between the fitting and top support platform leaked. This led to a major re-design of the FTP in the subsequent version.

Figure 6-10: FTP Version 2 (left) and FTP Version 3 (right)
6.4.2.4. FTP Version 4

Given consistent leakage at the fitting-top support platform interface, the method of interfacing the FTP with the fluid circuit had to be revisited. The three main problems with Version 3 were: (1) insufficient engagement length for the NPT fitting; (2) cracking of the acrylic; and (3) close proximity of the fittings to one another making it difficult to tighten. Given these three problems, it was proposed that the fittings be attached to the side of the top support platform and channels be drilled into the acrylic to divert the fluid to and from the test part. This would allow the NPT fittings to tighten farther into the acrylic platform, reduce the likelihood of cracking, and permit the fittings to be tightened more easily.

Given this design, the thickness of the top support platform was increased to 1” to allow for the 1/8” NPT fittings to be inserted in a tapped hole on the side of the platform. The bottom support platform was kept at 1/4” thickness to keep the FTP as thin as
possible to allow it to fit under the microscope for observation. Figure 6-12 shows the FTP Version 4.

Figure 6-12: FTP Version 4 (channels drilled in the top support platform are visible)

Figure 6-13 shows a detailed schematic of the platform with dimensions shown in Table 6-4. Stock acrylic was cut with a band saw, the channels were drilled in a drill press, and the acrylic was tapped with a hand drill.

Figure 6-13: FTP Version 4 schematic
<table>
<thead>
<tr>
<th>Section</th>
<th>Channel Dimension</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15875 cm Ø</td>
<td>85.02 cm</td>
</tr>
<tr>
<td>2</td>
<td>0.6858 cm Ø</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>3</td>
<td>0.8 cm Ø</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>4</td>
<td>0.39 cm Ø</td>
<td>1 cm</td>
</tr>
<tr>
<td>5</td>
<td>0.3 cm Ø</td>
<td>1.4 cm</td>
</tr>
<tr>
<td>6</td>
<td>0.15875 cm Ø</td>
<td>45.72 cm</td>
</tr>
</tbody>
</table>

This design was tested with the same silicone gasket layer used in prior designs. Testing up to 40 psi showed there was no longer leakage between the fittings and top support platform. However, when part testing was begun, it was found that the fluid circuit pressure spiked up well beyond that expected from the model described in Section 8.1. Upon further investigation it was found that changes in the applied force from the fasteners drastically effected the fluid circuit pressure reading for a given flow rate. It was concluded that the chosen gasket layer deformed into the micro-channel and cut off fluid flow if the clamping force was too high and allowed fluid to leak if the force was insufficient. The problem of leakage at the fitting-platform interface was resolved, but new issues related to the proper method of fastening the FTP and the selection of the gasket layer were encountered.

6.4.2.5. Gasket Layer Material Selection

The problem of sealing the micro-channel was found to be more challenging then initially expected. The first 1/16” silicone gasket (40A Durometer rating) used in FTP Versions 1-4 was found to be too complaint. Both PMMA-PMMA bonding (to create a permanent closed channel) and a cast Polydimethylsiloxane (PDMS) layer on the PMMA (gasket alternative) were investigated (with the assistance of Taylor and Korb...
respectively). The bonding proved unreliable and the PDMS had insufficient adhesion and was prone to tearing. Two main classes of gasket layer materials were investigated to seal the micro-channel: rubbers and plastics. Gasket layers are typically specified according to their hardness rating. There are several scales of hardness. Figure 6-14 shows the relative hardness of commonly found rubbers and plastics on different hardness rating scales. The requirements for the gasket layer were:

1. Transparent or translucent
2. High tear resistance (robust to multiple tests without tearing or breaking)
3. Inexpensive and readily available
4. High degree of uniformity to seal against the micro-channel

![Figure 6-14: Hardness rating of commonly found rubbers and plastics](image)

Figure 6-14: Hardness rating of commonly found rubbers and plastics [54]
Hardness is a measure of a material's ability to resist permanent deformation when a concentrated load is applied [54]. Hardness is not an intrinsic material property, but rather a function of the method used to test hardness and the material's yield strength, tensile strength, and modulus of elasticity [54]. However, it is a useful quantity to compare the properties of materials relative to one another. The elastic region of the deformation of plastics is related to applied stress through Hooke's law (Equation 6-1). This linear relationship between stress and elongation holds true for the both the elastic compression and tension of most plastics. Given Equation 6-2 for material compression, it can be concluded that the deformation of the gasket layer for a given applied stress will go down with decreasing thickness of the gasket layer.

\[ \sigma = E\varepsilon \]

\[ \varepsilon = \frac{l_o - l_f}{l_o} \]

Given the high compliance of the first silicone gasket layer, additional gasket layers that were both thinner and had a higher hardness rating were purchased (see Table 6-5). Those gaskets specified by the Rockwell standard are much harder than those specified by the Durometer standard.
Table 6-5: Summary of all gasket layers tried on FTP Version 4

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness Rating</th>
<th>Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>Durometer 85A</td>
<td>0.015</td>
</tr>
<tr>
<td>Silicone</td>
<td>Durometer 50A</td>
<td>0.031</td>
</tr>
<tr>
<td>EPDM Rubber</td>
<td>Durometer 60A</td>
<td>0.031</td>
</tr>
<tr>
<td>Silicone</td>
<td>Durometer 40A</td>
<td>0.031</td>
</tr>
<tr>
<td>EPDM Rubber</td>
<td>Durometer 70A</td>
<td>0.031</td>
</tr>
<tr>
<td>EPDM Rubber</td>
<td>Durometer 80A</td>
<td>0.031</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Durometer 90A</td>
<td>0.02</td>
</tr>
<tr>
<td>White Delrin</td>
<td>Durometer M94</td>
<td>0.015</td>
</tr>
<tr>
<td>TPX® (polymethylpentene)</td>
<td>Rockwell R85</td>
<td>0.01</td>
</tr>
<tr>
<td>ABS Film</td>
<td>Rockwell R100</td>
<td>0.01</td>
</tr>
<tr>
<td>Acetal Film</td>
<td>Rockwell D85</td>
<td>0.01</td>
</tr>
<tr>
<td>Hytrel Film</td>
<td>Durometer D72</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Each gasket layer was loaded in the FTP Version 4 and tested to determine which could both seal the channel and be least sensitive to the fastening force. All materials specified by the Durometer rating, regardless of thickness, were found to be too complaint and sufficient force would cause the channels to be closed off. The three remaining Rockwell rated films were tested and leakage was observed regardless of the clamping force applied. However, the TPX film exhibited the least leakage. Leakage was observed between the gasket layer and the top support platform, not between the gasket layer and smooth test part. Therefore, it appeared that the gasket layer was adequately sealing the channel, but was allowing fluid to leak caused by roughness at the top support platform interface. Therefore, three layers of scotch tape were added between the top support platform and the TPX gasket layer. Moreover, a PMMA back piece and 1/16” highly complaint 40A silicone gasket layer were added to the underside of the test part to ensure force was applied evenly to the test part, which is known to be non-planar caused by alignment errors in the HME system (see Figure 6-15). This
assembly was tested and found to seal the channel and at the same time never close off the channel under any applied force possible with hand tightening. Therefore, all subsequent testing was carried out with this two-layer sealing method. See Appendix B.5 for details on the material properties of TPX® (polymethylpentene) gasket layer.

![Schematic of the FTP assembly with the two-layer sealing method](image)

**Figure 6-15: Schematic of the FTP assembly with the two-layer sealing method**

### 6.4.2.6. C-Clamps and Fasteners

In addition to the importance of the gasket layer, FTP Version 4 illustrated the need to quantify the clamping force applied to seal the test part in the FTP to ensure repeatable testing conditions. As in prior versions, four fasteners were used to hold the FTP together. However, these fasteners were not used to apply force. Rather, two c-clamps with precision springs rated at 46.58 N/mm (maximum 317.74 N) were used for force application. The calibration of the testing force and the resulting analysis of the deformation of the gasket layer and test part at that force are discussed in Section 9.1.
6.4.2.7. FTP Version 5

FTP Version 4, with the two-layer sealing method and c-clamp and springs was used for all tests described hereafter except the second series of HME characterization tests. Re-registration testing outlined in Section 9.2 showed that certain dimensions on FTP Version 4 may have been the cause of high re-registration errors. Therefore, a new FTP Version 5 was constructed to modify the diameter of the channel entering the test part reservoir from the top support platform. This channel dimension was changed from 3000 μm to 1000 μm to reduce alignment related re-registration errors. Moreover, as opposed to a 2000 μm hole in the gasket layers, a 1400 μm was made in the gasket layers. The data to justify this change in dimension and a discussion of the rationale can be found in Section 9.2. Figure 6-16 shows FTP Version 5 with a part loaded and c-clamps with springs attached.

Figure 6-16: FTP Version 5 with part loaded and c-clamps with springs attached
6.5 Microscope Imaging

An M-Series Labscope with a 4x objective was setup to observe the parts prior to testing, ensure alignment of the part reservoirs to the top support platform, and capture photographs of fluid in the micro-channel. The Labscope has a built-in 10x objective for a total 40x objective. The moveable stage was removed to make room for the FTP to be imaged. Light was provided from two directions: (1) from the microscope base; and (2) from the top with the use of a high-powered coaxial light. This secondary light source is necessary to image the FTP or almost any other object in the Labscope. The limited space under the microscope did not allow images to be taken during testing (FTP with c-clamps did not fit under the microscope).

Figure 6-17: M-Series Labscope
7 Hardware Connections and LabView Control & Data Acquisition of the FTS

7.1 Hardware Connections

The FTS has four devices that record/monitor conditions or require control. All but the humidity/temperature sensor have the ability to communicate with an external source. The humidity/temperature sensor data has to be recorded and monitored manually by the user. The syringe pump, mass scale, and pressure sensor each connect to a PC via the connection types identified in Figure 7-1. Each device both accepts data from the PC and transmits data back to the PC. Given that data from each device should be recorded simultaneously, the data record is dependent on the slowest of the three devices. The pump automatically outputs the actual dispensed volume, but the mass scale and pressure sensor have to be pinged by the computer. Therefore, to receive data from either the mass scale or the pressure sensor, a command has to be sent to the device. This greatly slows the process of data acquisition, however, the speed of 4 Hz was set to maximize data recorded and at the same time ensure the least corrupt data (data drop out).
Figure 7-1: Schematic showing the hardware connections and data stream for the control and data acquisition of the syringe pump, mass scale, and pressure sensor

7.2 LabView Program

An integrated LabView program was developed to control the syringe pump and acquire data from the syringe pump, pressure sensor, and mass scale during testing.

Figure 7-2 shows the programs front panel (divided into three sections for each of the three devices) where the user can enter all required information to run tests on the FTS.

The driver to control the syringe pump was provided by Harvard Apparatus. The LabView code for communication with the mass scale and pressure sensor were developed separately. The LabView code is divided into two distinct sections: (1) syringe pump control; and (2) mass scale and pressure sensor data acquisition. Both sections operate using NI Visa. NI Visa is a routine offered by National Instruments to communicate with serial port and USB devices. By entering the com port, baud rate, data
bits, parity, stop bits, and flow control parameters for the device, communication can be established. Table 7-1 outlines the parameters currently used in LabView to establish communication with the devices. If the devices are moved to another PC or the connection ports are changed, these parameters would have to be adjusted accordingly.

![Figure 7-2: LabView Program for syringe pump control and pressure sensor and mass scale data acquisition](image)

**Table 7-1: Parameters needed to establish LabView communication with FTS components**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Syringe Pump</th>
<th>Mass Scale</th>
<th>Pressure Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM Port</td>
<td>COM1</td>
<td>COM3</td>
<td>COM4</td>
</tr>
<tr>
<td>Baud Rate</td>
<td>9600</td>
<td>19200</td>
<td>9600</td>
</tr>
<tr>
<td>Data Bits</td>
<td>8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Parity</td>
<td>None</td>
<td>ODD</td>
<td>None</td>
</tr>
<tr>
<td>Stop Bits</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flow Control</td>
<td>None</td>
<td>RTS/CTS Hardware</td>
<td>RTS/CTS Hardware</td>
</tr>
</tbody>
</table>
7.2.1 Syringe Pump Control

The syringe pump control section of the LabView program takes the user inputs of: (1) syringe diameter; (2) flow rate; (3) units; and (4) stop volume and transmits them to the pump. The only input back to LabView is the actual dispensed volume, which is displayed on the screen while the program is running. Given the syringe pump operates with a stepper motor, the pump delivers very fine discrete amounts of fluid each step (refer to Section 6.2.1 for specifications). This does not allow the pump to deliver an exact amount of fluid because a discrete step may be slightly more or less than the desired quantity. This is why the actual dispensed volume is transmitted back to LabView, though this minor limitation does not have an effect on the testing carried out here because there is no need to deliver a precise quantity of fluid, only a precise flow rate of fluid. The pump can be turned on or off and parameters adjusted in real time at any point while the program is running. The VI prior to the case structure open the COM port to start communication with the pump and the case structure handles the control of the pump (within a while loop), error checking, and closes the COM port.

7.2.2 Mass Scale and Pressure Sensor Data Acquisition

The mass scale and pressure sensor data acquisition section of the LabView program relays the appropriate command (device specific: “P\r” for the mass scale and “?P,U\r” for the pressure sensor) to the devices to output data and displays the data on the programs front panel plots and dialog boxes. This section of the program operates similar to the syringe pump control section. The program opens the COM ports to establish communications and then iterates through a while loop constantly pinging the device to output data and then after a few hundred millisecond delay, recording the
output from the device. The COM port is then closed when the program is terminated. The program also writes and saves data to a folder specified by the user once the program is initiated (time, absolute msec counter, mass reading, pressure reading, and pressure units). The delay is necessary because each device requires a certain amount of time between when the signal to output data is sent and when the data is actually transmitted. For the mass scale a 200 msec delay is used and for the pressure sensor, a 100msec delay is used. This delay achieves two things: (1) allows sufficient time for the device to reliably transmit data back to the PC (high data integrity); and (2) the pressure sensor can be pinged two times for every one time the mass scale is pinged in the while loop. The pressure sensor had to be pinged and data recorded twice for every one ping of the mass scale because the pressure sensor, by design, outputs the numerical value of the pressure and then the pressure units. Therefore, data is only obtained every other ping. See Appendix J for details on the use of the LabView program during testing.
8 FTS Fluid Model

8.1 FTS Model Overview

In order to properly size the test equipment and to corroborate the results of the functional tests to be performed, a model was developed to estimate the expected fluidic resistance, pressure drop, residence times, velocities, and Reynolds number for all locations in the fluid circuit. The full Matlab code for this model is in Appendix I. The purpose of this model was to estimate the expected pressure drops and the effects of channel geometry changes.

There are three main components to the fluid model: (1) channels (including the micro-channel); (2) minor losses (entrance effects and flow turns); and (3) pressure head (static pressure caused by differences in fluid height). The Reynolds number is calculated according Equation 8-1, where \( \mu \) is the dynamic viscosity of water. The dynamic viscosity of water is assumed to be 0.010 g/cm\(^*\)sec or 1 centipoise (assumed operating temperature of \( \sim -20^\circ\)C) [56]. However, given the use of dyed water in these tests the modified viscosity of 1.004 centipoise was used in the model (see Section 9.1.3).

\[
Re = \frac{\rho v D}{\mu}
\]

Equation 8-1 [57]

In addition to the Reynolds number, the velocity and residence time in each section of the channel were also calculated.
8.2 Channel Model

Fluid flow in small channels (both the entrance channels and the micro-channel on the test part) was best approximated by Hagen-Poiseuille flow [49]. Hagen-Poiseuille flow models incompressible laminar flow in a closed channel with constant viscosity fluid. This model is based on a laminar Newtonian assumption from the Navier-Stokes Equation and has been shown to be accurate to within ~10% of experimental [55]. This error is largely caused by the inability to precisely represent the changes in flow caused by small changes in channel geometry analytically [56]. Equation 8-2 defines the fluidic resistance in a channel as the ratio of the pressure drop to the flow rate. For a constant resistance, this means the pressure drop increases linearly with flow rate in a channel.

\[ R = \frac{\Delta P}{Q} \]

Equation 8-2 [58]

Equation 8-3 to Equation 8-7 are derived from the Hagen-Poiseuille flow assumptions and they define the fluidic resistance as a function of the channel geometry. Equation 8-3 is for a circular channel while Equation 8-4 to Equation 8-7 are for a rectangular channel of varying aspect ratio [52]. Equation 8-4 (aspect ratios >5) and Equation 8-5 (aspect ratios<0.2) show that as aspect ratios become very high or very low, the pressure drop in the channel is most sensitive to the smaller of the two channel dimensions. Equation 8-6 (1<aspect ratio<5) and Equation 8-7 (0.2<aspect ratio<1) show that as the aspect ratio of the channel approaches one, the relative contribution of each of the channel dimensions is more equally weighted.
\[ R = \frac{8\mu L}{\pi^4} \]

Equation 8-3 [52]

\[ R_{w<\ll h} = \frac{12\mu L}{hw^3} \]

Equation 8-4 [52]

\[ R_{w\gg h} = \frac{12\mu L}{wh^3} \]

Equation 8-5 [52]

\[ R_{w\gg h} = \frac{12\mu L}{wh^3} \left[ 1 - \frac{h}{w} \left( \frac{192}{\pi^5} \sum_{n=1}^{\infty} \frac{1}{n^5} \tanh\left( \frac{n\pi w}{h} \right) \right) \right]^{-1} \]

Equation 8-6 [52]

\[ R_{w<\ll h} = \frac{12\mu L}{hw^3} \left[ 1 - \frac{w}{h} \left( \frac{192}{\pi^5} \sum_{n=1}^{\infty} \frac{1}{n^5} \tanh\left( \frac{n\pi h}{w} \right) \right) \right]^{-1} \]

Equation 8-7 [52]

### 8.3 Entrance Effects and Flow Turn Model

Unlike the micro-channel pressure drop model, which is dominated by viscous effects of the fluid, the entrance effects is dominated by bulk changes in the fluid momentum. Therefore, the equations governing pressure drops at expansions, contractions, and flow turns include the density of the fluid and not the viscosity (density of water at 20°C ~1.0 g/cm³) [59]. All expansions and contractions were assumed to be sudden to estimate the pressure drop in the fluid circuit (note: almost all expansions and contractions in the FTP are in fact sudden). This was a conservative approximation because there are several aspects such as roughness and deviations in wall geometry that were not modeled. Since these discrepancies would most likely raise the pressure drop in the fluid circuit, sudden expansions and contractions were modeled to compensate for factors not considered in the model. Equation 8-8 shows the expected pressure drop from
these minor effects. This equation is a macro-scale equation for predicting pressure loss caused by minor effects such as entrance effects and flow turns. However, Eason et al [23] show that this assumption is valid for smaller scale features. Eason [23] measured pressure and flow rate data for micro-channels from ~50 μm to >400 μm in dimension and verified Equation 8-8 is valid for mini-channels and micro-channels. This equation indicates that the pressure drop is quadratically related to the local velocity, which is proportional to the flow rate. $K_L$ is the loss coefficient and it is a function of the type of minor effect and the local geometry.

$$P = 0.5K_L \rho v^2$$  
Equation 8-8 [59]

In the case of expansions, $K_L$ can be found analytically according Equation 8-9, where $A_2$ expands to $A_1$. In the case of 90° turns, $K_L \sim 1.1$ (average of normal and long-radius 90° turns) [56].

$$K_L = (1 - \frac{A_2}{A_1})^2$$  
Equation 8-9 [56]

In the case of contractions, $K_L$ can be found according to Equation 8-10, which is a curve fit to data found in Munson et al. [59]. This is for the case $A_1$ contracts to $A_2$. Figure 8-1 shows the curve fit to the data ($R^2 = 0.999$).

$$K_L = 1.0417x^3 - 1.5446x^2 + 0.003x + 0.5007 \quad \text{Note: } (x = \frac{A_2}{A_1})$$  
Equation 8-10 [59]
Elevation effects (changes in the elevation of input and output) add a pressure head to the overall system pressure. This pressure is constant and independent of changes in flow rate and was observed to be $P \approx 0.24$ psi with a full fluid circuit. This was verified by measuring the difference in height (~6 inches) between the fluid circuit inlet (syringe pump) and outlet (into the mass scale). Given 28 inches of water equals approximately 1 psi, the measured difference in height yields an expected pressure head ~0.21 psi. The 0.24 psi measured by the pressure sensor was used in the fluid because this was determined to be more accurate than a simple height measurement, however, the close values obtained by the height measurement further reinforce the pressure sensor readings.
8.5 Model Summary

The model has three types of pressure drops:

1. Pressure head - constant with flow rate
2. Channel - linear with flow rate
3. Entrance effects - quadratic with flow rate

Figure 8-2 shows the contribution of each of these terms based on the flow path outlined in Table 8-1 (FTP Version 5) for a 200 μm x 100 μm micro-channel part. Figure 8-4 shows the addition of each of these three terms (constant, linear, and quadratic) in the full fluid model of the FTS. The pressure drop in the fluid circuit is dominated by the pressure drop in the channel (mostly micro-channel). This is expected; given the much smaller cross-sectional area in the micro-channel relative to the rest of the fluid circuit; and desired, so the FTS is most sensitive to the changes in micro-channel geometry.

With increasing flow rates, entrance effects start to grow as a percentage of fluid circuit pressure drop, however, in no case tested to date has the channel pressure drop contribution been less than 90%.
Figure 8-2: Model terms for pressure vs. flow rate of FTS with a 200μm x 100μm micro-channel part

Table 8-1: Summary of fluid circuit from the syringe pump through the FTP to the mass scale

<table>
<thead>
<tr>
<th>Section</th>
<th>Channel Dimension</th>
<th>Length</th>
<th>Minor Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15875 cm Φ</td>
<td>85.02 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>2</td>
<td>0.6858 cm Φ</td>
<td>1.5 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>3</td>
<td>0.8 cm Φ</td>
<td>0.8 cm</td>
<td>Contraction</td>
</tr>
<tr>
<td>4</td>
<td>0.39 cm Φ</td>
<td>1 cm</td>
<td>Contraction and 90° turn</td>
</tr>
<tr>
<td>5</td>
<td>0.1 cm Φ</td>
<td>1.4 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>6</td>
<td>0.14 cm Φ</td>
<td>0.0254 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>7</td>
<td>0.2 cm Φ</td>
<td>0.1 cm</td>
<td>90° turn</td>
</tr>
<tr>
<td>8</td>
<td>200 μm x 100μm</td>
<td>0.8 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>9</td>
<td>0.2 cm Φ</td>
<td>0.1 cm</td>
<td>Contraction and 90° turn</td>
</tr>
<tr>
<td>10</td>
<td>0.14 cm Φ</td>
<td>0.0254 cm</td>
<td>Contraction</td>
</tr>
<tr>
<td>11</td>
<td>0.1 cm Φ</td>
<td>1.4 cm</td>
<td>Expansion and 90° turn</td>
</tr>
<tr>
<td>12</td>
<td>0.39 cm Φ</td>
<td>1 cm</td>
<td>Expansion</td>
</tr>
<tr>
<td>13</td>
<td>0.8 cm Φ</td>
<td>0.8 cm</td>
<td>Contraction</td>
</tr>
<tr>
<td>14</td>
<td>0.6858 cm Φ</td>
<td>1.5 cm</td>
<td>Contraction</td>
</tr>
<tr>
<td>15</td>
<td>0.15875 cm Φ</td>
<td>45.72 cm</td>
<td>To Mass Scale</td>
</tr>
</tbody>
</table>
Figure 8-3: Full Model of pressure vs. flow rate for FTS with a 200μm x 100μm micro-channel part
9. Functional Test Results

9.1 Preliminary Tests

Preliminary tests were carried out on the functional testing system (FTS) to assess the integrity of the data and maximize testing repeatability. See Appendix H for a summary of all test runs. Two sets of data were obtained for all tests described hereafter. The first data set was pressure vs. time, as shown in Figure 9-1. The second data set was mass vs. time, as shown in Figure 9-2. To ensure an accurate assessment of flow rate, the slope of the mass vs. time plot is used to calibrate the pump flow rate. Tests were run to verify the accuracy of the flow rate (Section 9.1.1). All tests were carried out for at least three flow rates, as seen in Figure 9-1 to Figure 9-2.

Figure 9-1: Sample plot of pressure vs. time for a 100μm x 100μm channel test part in FTP Version 5
Figure 9-2: Sample plot of mass vs. time for a 100μm x 100μm channel test part in FTP Version 5

All pressures cited hereafter are the steady state values from plots like Figure 9-1. In order to expedite testing, the fluid circuit was quickly forced to the model expected pressure value by initially overshooting (10 ml/min) or undershooting (0 ml/min) the command flow rate. Then the proper command flow rate was input. The delay between the command flow rate and the observed flow rate was thought to be caused by: (1) trapped air near the pressure sensor and valve (compresses and acts as a delay in the response); (2) the expected delay to de-pressurize a pressurized fluid circuit; and (3) the expected delay to pressurize a circuit initially filled with air. All testing with parts loaded in the functional testing platform (FTP) was carried out according to the instructions in Appendix J.
9.1.1 Pump Flow Rate Calibration

The flow rate of the syringe pump was calibrated by setting a command flow rate of 10 ml/min through the FTS without the FTP. The slope of the mass vs. time plot however, yielded a flow rate of 9.635 ml/min based on a dyed water density measured at 0.998 g/cm³. The only way to calibrate the pump flow rate was by adjusting the syringe diameter. The syringe diameter was set to 38.4 mm at the suggestion of the manufacturer. However, given the actual flow rate was significantly less than the commanded flow rate, the syringe diameter was reduced to 37.693 mm (9.635/10*38.4). The test was then re-run and the new flow rate was measured at 9.997 ml/min. Figure 9-3 shows the mass vs. time before and after calibration (note: mass started at different levels for each test).

![Mass vs. Time](image)

**Figure 9-3: Plot of mass vs. time for flow rate calibration**

Both tests were run with the same time-position profile on the syringe to ensure comparable testing conditions. The linear curve fit to obtain the flow rate had an \( R^2 \) fit of
~1 for both tests, indicating very precise flow rate control. This calibration put the pump within the stated 0.35% accuracy. The accuracy of the pump flow rate was re-confirmed at other flow rates and pressures under testing conditions with parts.

9.1.2 Syringe Operating Range

Tests with no FTP were carried out to determine the proper syringe range in which to operate to ensure the most steady flow rate and pressure. Results showed that the syringe had a diameter profile that contracted towards the ends. Therefore, the most reliable syringe operating range was shown to be in the middle (105-45 ml). This range gave a flow rate variation of only ± 0.5-0.6% and pressure variation of ± 0.5-1.0% for multiple tests. To further ensure test repeatability all subsequent tests comparing parts of similar geometry were performed with the same syringe time-position profile.

9.1.3 Viscosity Effect of Dyed Water

In order to ensure dyed water had similar fluid properties to distilled water, two tests (one with each type of fluid) were run with no FTP and the fluidic resistance for a given flow rate were compared. Table 9-1 shows that the ratio of the fluidic resistance was ~1.004. This is a small difference; however, the adjusted dyed water viscosity of 1.004 centipoise was used in the model.

Table 9-1: Summary of distilled vs. dyed water tests

<table>
<thead>
<tr>
<th></th>
<th>Flow rate (ml/min)</th>
<th>Pressure (psi)</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water</td>
<td>80.14</td>
<td>8.38</td>
<td>0.105</td>
</tr>
<tr>
<td>Dyed Water</td>
<td>80.14</td>
<td>8.42</td>
<td>0.1046</td>
</tr>
</tbody>
</table>
9.1.4 Clamping Force Calibration

It was necessary to quantify the force needed to seal the channel to ensure test repeatability and verify the channel was not closed off. Given this need, clamping force calibration tests were run for two part sizes. Given the construction of the FTP, the area of the part tested will effect the required force to seal. However, given the full clamping pressure is not exerted on the part (caused by non-planarity of the parts) the required clamping force is not necessarily proportional to the part area. Two part sizes were tested here (large- 30 mm diameter x 1mm thick, and small- 15 mm x 5 mm x 1 mm thick). The cross-sectional area of the large and small part were 706.5 mm$^2$ and 75 mm$^2$ respectively. Tests on the large part indicated a required clamping force of $\sim$73 lbs from each of the two springs (spring length of 11mm) or leakage was observed. Only one large part has been tested to date. See Appendix G for a summary of all functional test parts fabricated on the hot micro-embossing (HME) system. Tests on the small parts indicated a required clamping force of $\sim$33 lbs from each spring (spring length of 15mm) or leakage was observed. Figure 9-4 shows a test with a part loaded in the FTP and a range of clamping forces as identified in Table 9-2.
Figure 9-4: Plot of pressure vs. time for a 800μm x 35μm part in FTP Version 4 for an arbitrary flow rate to test the required clamping force to seal the micro-channel

Table 9-2: Force conditions shown in Figure 9 5

<table>
<thead>
<tr>
<th>Condition</th>
<th>Spring Position (mm)</th>
<th>Force/Spring (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>55.68</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>33.41</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>22.27</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>11.14</td>
</tr>
</tbody>
</table>

The plot shows that at each condition the pump was shutoff and the outlet tubing was cinched to monitor for leakage. At conditions 1, 2, and 3 the pressure remained steady, while at condition 4, the pressure dropped off- a sign of leakage. Therefore, the minimum required force was approximately 22 lbs per spring. However, to remain on the conservative side, a spring position of 15mm- measured by calipers (33 lbs per spring) was specified. The variation in pressure output for the full range of the spring with no
leakage was observed to be ±3%. However, here a precise force was specified to make testing conditions more repeatable. This should help to keep the re-registration error as low as possible.

There were three methods employed to determine whether the part was leaking both during testing and after analyzing the data. Method one was to take fluid pressure to a high level (20-40 psi), shut off the flow rate and close off the fluid outlet by cinching the tubing. If the pressure remained constant, it was assumed there was no leakage. Method two was to simply observe the part by eye with the aid of the coaxial light to determine if leakage could be seen. Method three was to analyze the output flow rate data and confirm it was within the margin of error of the pump (if substantially lower, leakage could be assumed).

The exact clamping pressure seen at the part could not be accurately predicted because of the multiple points of contact in addition to the part itself. However, it was possible to estimate this value. Given leakage was observed at a total clamping force of 22 lbs for a flow of ~30 psi, that 22 lbs of clamping force must place less than ~30 psi of pressure on the part. This assumes clamping pressure has to equal fluid circuit pressure in order to properly seal against leakage. This would translate to <90 psi of force on the channel for a clamping force of 66 lbs. The compressive modulus of PMMA is ~2.9 MPa (420 ksi) [60]. The deformation of a 0.60 mm thick Poly(methyl methacrylate)-PMMA part (approximate thickness after HME) with ~90 psi pressure is <0.13 μm. The compressive stress modulus of the TPX® (polymethylpentene) gasket layer used is ~ 2.0 MPa (280ksi) according to the material properties in Appendix B.5. The deformation expected from a 0.010" thick TPX part is <0.1 μm. These small deformations show that
the effect of gasket and PMMA deformation testing is minimal and would only become of concern for features ~10 \( \mu \)m and less. No permanent deformation of the PMMA parts was detected from Zygo scans taken before and after functional testing. This is as expected based on PMMA’s high compressive strength (100MPa or 17 ksi). Reference Appendix B for PMMA and TPX® (polymethylpentene) material properties.

9.2 Re-registration Tests

The next step in the testing process was to assess the re-registration error of the FTS. Re-registration tests were carried out by re-loading a part in the FTP and running a pressure (P) vs. flow rate (Q) test for three flow rates. This test was then repeated an additional 2-3 times under identical testing conditions (force, time-syringe-position profile, etc) and the results were compared. A 95% student-t confidence interval was used to assess the re-registration error (Equation 9-1). The confidence interval on the population mean (\( \mu_m \)) is based on the sample mean (\( \bar{x} \)), number of samples (n), number of degrees of freedom (n-1) and sample mean (\( \bar{x} \)).

\[
\bar{x} - t_{\alpha/2,n-1} \frac{S}{\sqrt{n}} \leq \mu_m \leq \bar{x} + t_{\alpha/2,n-1} \frac{S}{\sqrt{n}}
\]

Equation 9-1 [14]

The confidence interval is then normalized as a percentage of the mean. Three part geometries were tested for re-registration in FTP Version 4 as shown in Table 9-3.
Table 9-3: Summary of parts used for FTP Version 4 re-registration tests

<table>
<thead>
<tr>
<th>Feature Size</th>
<th>( w^* ) (mm)</th>
<th>( d_e^* ) (mm)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>35</td>
<td>0.04</td>
</tr>
</tbody>
</table>

* Intended tool dimension

Actual micro-channel dimensions are shown in Appendix G

Figure 9-5 and Figure 9-6 show the re-registration errors for two parts in FTP Version 4. The trend from the plots is clear: (1) the re-registration error goes down with decreasing flow rate; and (2) the re-registration error goes down with increasing aspect ratio. Moreover, the re-registration errors for both test parts are excessively high (approaching 10-14%).

![Re-registration Error vs. Flow rate](image)

*Figure 9-5: Re-registration error for 800\(\mu\)m x 35\(\mu\)m part*
The flow rate dependence can be explained with the fluid model. Misalignment between the input channel and the part reservoir is the most likely cause of re-registration errors. Misalignment changes the entrance effects term in the model. At higher flow rates, the proportion of the fluid circuit pressure drop from entrance effects goes up. Therefore, the misalignment error would be most visible at higher flow rates. The re-registration going down with increasing aspect ratio is also expected given the greater effect clamping force will have on the fluid circuit pressure drop at lower aspect ratios. Figure 9-7 shows a schematic of the gasket layer closing in on channels with high and low aspect ratios. This effect can be explained by the fact that the deformation and warping of the gasket layer into the deeper channel will have less effect on the channel depth (as a percentage). This translates to a lower effect on the micro-channel pressure drop (according to Hagen-Poiseuille flow).
The high re-registration errors forced another design iteration of the FTP. Given the clamping force was reasonably quantified with the use of the precision springs, the other major source of error (misalignment) had to be mitigated. FTP Version 4 had the I/O from the top support platform coming into the test part with a diameter of 3000 μm. This is larger than the test part reservoir of 2000 μm. It was thought that a mismatch in dimension could be a cause of a large chunk of the re-registration error. A small misalignment could drastically change the fluid flow path and explain the highly variable testing results. A new FTP Version 5 was constructed with 1000 μm I/O expanding to a 1400 μm hole in the gasket layer to the 2000 μm reservoir. This step increase in diameter reduces the effect of misalignment errors because the overlap area between the I/O and reservoir remains constant so long as the 1000 μm I/O is positioned somewhere within the 2000 μm reservoir. This is a much more robust method than aligning an I/O.
and reservoir of the same diameter or an I/O with a larger diameter than the reservoir. Figure 9-8 shows a microscope image of the alignment of the I/O to the gasket to the reservoir.

Figure 9-8: Microscope image of the alignment of the reservoir to the gasket layer and fluid inlet

A re-registration test of the same part was run on both FTP Version 4 and FTP Version 5. Figure 9-9 shows the large reduction in re-registration error as a result of this design change. The behavior of the plot suggests that further reduction in re-registration error by lowering the flow rate even further may not be possible. The re-registration error appears to be settling off (in fact the 0.25 ml/min flow rate has a slightly higher re-registration error than the 0.5ml/min flow rate). Moreover, given the re-registration has become less dependent on flow rate suggests the ~1.03% re-registration error may be an intrinsic error in the current FTS components. The accuracy of the pressure sensor is ~±1% at these scales (repeatability assumed to be on the same order of magnitude). The
RMS uncertainty of the bias error from the equipment is \( \sim \pm 1.1\% \) \( \pm 1\% \) repeatability from pressure sensor and \( \pm 0.50\% \) repeatability from the mass scale), so a hardware limit appears to have been reached. The total RMS uncertainty of both the bias error and the precision error (from the 0.5 ml/min re-registration tests) is \( \sim \pm 1.51\% \). These results suggest that this FTS should be capable of detecting differences in micro-channel geometry.

![Re-registration Error vs. Flow rate](image)

**Figure 9-9:** Re-registration error for 100\( \mu \)m x 100 \( \mu \)m part in FTP Versions 4 and 5

### 9.3 Model Fit Tests

The model described in Chapter 8 was fit to all part geometries tested. The model was shown to be accurate to within \( \sim \pm 10\% \) of the experimental values for all but the lowest aspect ratio part. Below is a sample of model fits for tests run on FTP Version 4. Model fits for HME characterization tests on FTP Versions 4 and 5 are discussed in
detail in Chapter 10. This 10% error in the model is caused by two major factors: (1) difficulty in determining the full channel profile; and (2) the model is a theoretical approximation based on the channel geometries. The Hagen-Poiseuille equations do not account for minor changes in wall geometry (undulations, etc). Moreover, obtaining this information and integrating into an analytical model is cumbersome and prone to inaccuracies. This model accuracy is expected given the Hagen-Poiseuille equations have been shown to be accurate to within ~10% of experimental [55]. Figure 9-10 to Figure 9-12 shows the experimental data with the model prediction for three part geometries tested in FTP Version 4.

![Pressure vs. Flow Rate](image)

**Figure 9-10:** Pressure vs. flow rate for 200 μm x 100 μm part tested in FTP Version 4 with model and measurement RMS uncertainty
Figure 9-11: Pressure vs. flow rate for 300 μm x 50 μm part tested in FTP Version 4 with model

Figure 9-12: Pressure vs. flow rate for 800 μm x 35 μm part tested in FTP Version 4 with model and measurement RMS uncertainty
The model also calculates the predicted velocity, residence time, and Reynolds number in different sections of the fluid circuit. Table 9-4 summarizes this data to get an appreciation of the range of values for a 200 μm x 100 μm part tested at 1.5 ml/min. This data shows the fluid is always in the laminar region (<2300 Re) [59]. Moreover, the fluid velocity is highest and the residence time is the lowest in the micro-channel. This is expected given the substantially smaller cross section in the micro-channel. From this data, relative changes in the velocity, residence time, and Reynolds number with the micro-channel geometry can be seen.

Table 9-4: Summary of model predictions for change in velocity, residence time, and Reynolds number at 1.5 ml/min for a 200 μm x 100 μm test part loaded in FTP Version 4

<table>
<thead>
<tr>
<th>Area</th>
<th>Diameter (μm)</th>
<th>Velocity (cm/sec)</th>
<th>Residence Time (sec)</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>4.77</td>
<td>8.13</td>
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<td>0.35</td>
<td>3.95</td>
<td>10.57</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>0.80</td>
<td>0.13</td>
<td>15.86</td>
</tr>
<tr>
<td>7</td>
<td>200 μm x 100 μm</td>
<td>125.25</td>
<td>0.01</td>
<td>166.00</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
<td>0.80</td>
<td>0.13</td>
<td>15.86</td>
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<tr>
<td>9</td>
<td>3000</td>
<td>0.35</td>
<td>3.95</td>
<td>10.57</td>
</tr>
<tr>
<td>10</td>
<td>3900</td>
<td>0.21</td>
<td>4.77</td>
<td>8.13</td>
</tr>
<tr>
<td>11</td>
<td>8000</td>
<td>0.05</td>
<td>16.04</td>
<td>3.97</td>
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<td>22.11</td>
<td>4.63</td>
</tr>
<tr>
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<td>1588</td>
<td>1.27</td>
<td>36.11</td>
<td>19.98</td>
</tr>
</tbody>
</table>
The HME characterization tests focused on determining whether the FTS could detect changes in output parts with changes in HME parameters and to what degree they correlated with traditional metrology results. The parameters varied were embossing temperature and de-embossing temperature. This selection was based on work by Wang [61] that established these as significant control factors.

10.1 First Series of Tests

The first series of tests were run on FTP Version 4 with 800 μm x 35 μm micro-channel parts made with an SU-8 tool. The central composite design (CCD) processing conditions are outlined in Figure 10-1 (see Appendix G for a full account of other processing parameters). Three replicates of each corner, one for each axial point, and 12 for the center point were run for a total of 28 parts. The objective was to determine the effect of the processing parameters on the output part using the Zygo and compare that with the FTS results.
Figure 10-1: Central composite design parameters for the first set of HME characterization tests

Figure 10-2 shows the channel width of the parts under different processing conditions obtained by Shoji [28] using a measurement algorithm developed by Wang [61]. The RMS uncertainty shown in the plot (± 8.1 μm) is based on the Zygo resolution (± 1.1 μm biased error based on 2.2 μm resolution) and the channel width 95% precision error from re-registration (± 8 μm). It is apparent that no conclusions can be drawn about the between parameter variation for the location of these scans (approximately at the center of the micro-channel).
Figure 10-2: Channel width for eight HME processing conditions ($T_{Embossing}$: $T_{De-embossing}$):
(1) 110:55; (2) 110:75; (3) 130:55; (4) 130:75; (5) 134:65; (6) 105:65; (7) 120:51; (8) 120:79

Therefore, the full CCD was unnecessary given high measurement induced error. Moreover, the process variation of these parts was also indiscernible from the RMS uncertainty when the depth (which has nanometer scale resolution) was analyzed. The pressure used to fabricate these small parts was on the order of 4 MPa as opposed to 1 MPa used by Wang [61]. This higher force may have been the cause of the low process variation and low significance of the embossing and de-embossing parameters. Moreover, the very low aspect ratio of the embossed channel minimizes the width variation caused by lack of polymer fill and increases the re-registration error of the FTS. It would be expected that more variation would be detected for higher aspect ratio structures. The SU-8 tool used to make these parts broke at a reservoir (Figure 10-3) after the 21st run in the series. This would obviously not be visible in the Zygo scan.
which was isolated to the center of the channel. However, this may be observable by the FTS.

![Picture of the broken tool reservoir](image)

**Figure 10-3: Picture of the broken tool reservoir**

The FTS was used to test three random parts before and after the tool break to see if a statistically significant difference could be detected. Figure 10-4 shows that with the high re-registration error of the FTP Version 4 (as with the Zygo), there is no discernable difference between the pressure (P) vs. flow rate (Q) performance of the different parts (confirmed by error bar overlap). The overall RMS uncertainty for the 0.5, 1.5, and 4.5 ml/min flow rates are ±7.7%, ±11.0%, ±13.3% respectively. The model fit to the channel dimensions has good agreement (±10 %). Moreover, only half of the reservoir was broken to a depth of ~17 μm as opposed to the full tool depth of 35 μm. This change in geometry would be expected to have <1% effect on the P vs. Q performance, which would clearly be undetectable given re-registration errors in the FTP Version 4.
10.2 Second Series of Tests

The first series of tests were carried out on very low aspect ratio parts (where FTS re-registration is the highest) and with the FTP Version 4, which was shown to have higher re-registration error. Moreover, the parts were formed at P-4 MPa. These led to conditions where the part was well formed for all parameters and the FTS was unable to reliably detect changes in pressure. Based on the lessons learned from the first series of tests, a smaller $2^2$ DOE was carried out on embossing and de-embossing temperature on small parts with a more realistic micro-channel geometry of 100 $\mu$m x 100 $\mu$m. These parts were embossed at 1 MPa with a silicon tool to keep consistent with the existing body of work within the group. Moreover, the parts were tested in FTP Version 5. These conditions should give a good assessment of the ability of the FTS to detect changes in
micro-channel geometry. Figure 10-5 outlines the parameters for this experiment. Single part replicates were made at each corner of the square.

*Figure 10-5: $2^2$ design parameters for the second set of HME characterization tests*

In order to obtain a reliable measurement of the micro-channel, the channel dimensions were calculated by taking two scans and measuring the depth and top and bottom width of the micro-channel at each end of the channel. The depth of the channel was obtained by averaging the depth from each end of the channel and the width was obtained by averaging the average width at each end of the channel (average of top and bottom). Figure 10-6 outlines the metrology and FTS results for the four parts. The plot shows the change in pressure drop and micro-channel width for each part condition (micro-channel height was almost the same ~97.5μm for all parts). The correlation between width and pressure is strong, where a larger width corresponds to a smaller pressure drop and a smaller width corresponds to a larger pressure drop. This is expected given the Hagen-Poiseuille equations described in Chapter 8.
<table>
<thead>
<tr>
<th>Embossing Temp</th>
<th>De-Embossing Temp</th>
<th>~Channel Depth (µm)</th>
<th>~Channel Width (µm) and Top-Bottom Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 110°C</td>
<td>55°C</td>
<td>97.5</td>
<td>122.5 (80-180)</td>
</tr>
<tr>
<td>(a) 120°C</td>
<td>55°C</td>
<td>97.5</td>
<td>103.75 (70-137.5)</td>
</tr>
<tr>
<td>(b) 110°C</td>
<td>75°C</td>
<td>97.5</td>
<td>120 (80-180)</td>
</tr>
<tr>
<td>(ab) 120°C</td>
<td>75°C</td>
<td>97.5</td>
<td>100 (70-130)</td>
</tr>
<tr>
<td>Tool</td>
<td>-</td>
<td>97.5</td>
<td>107.5 (92.5-122.5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ml/min</td>
</tr>
<tr>
<td>0.5 ml/min</td>
</tr>
<tr>
<td>0.25 ml/min</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>(1) 7.145</td>
</tr>
<tr>
<td>3.735</td>
</tr>
<tr>
<td>2.1</td>
</tr>
<tr>
<td>(a) 8.94</td>
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<tr>
<td>4.6075</td>
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<td>(b) 7.475</td>
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<td>2.14</td>
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<td>(ab) 7.93</td>
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<tr>
<td>4.09</td>
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<tr>
<td>2.19</td>
</tr>
</tbody>
</table>

FTS Results vs. Metrology Results

Figure 10-6: Summary (c) of the metrology (a) and FTS (b) data for the four parts from the $2^2$ DOE

The overall RMS uncertainty for the 0.25, 0.5, and 1.5 ml/min flow rates are ±1.52%, ±1.51%, ±1.83% respectively. Given this low level of uncertainty, it is apparent that the FTS was able to detect process variation. There are however, two points of
inconsistency. First, the pressure values for all four parts are well above that expected according to the model (see Figure 10-7). Second, the pressure drop in the (ab) part was below expected relative to the (a) part which has similar dimensions.

![FTS Results vs. Model Predictions](image)

**Figure 10-7: FTS experimental results versus model predictions based on metrology data**

The parts were re-imaged in the Zygo and it was discovered that the parts were poorly formed at several locations along the length. There were various constrictions along the length that appear to be the result of poor filling (given the tool had a much cleaner profile). It appears localized geometry of constrictions and expansions played a large role in the experimental results. Figure 10-8 shows a blow-up of part (1) with the tool.
Figure 10-9 shows four screenshots of the types of defects observed on the four parts. Most defects showed cross sections narrowing to as little as ~60 μm. In addition to constrictions, there were some locations where the tended to bow out (to as much as 200 μm) as seen for part (ab). These images explain why the experimental values were so much higher than the model predicted values, especially at the higher flow rates.

Figure 10-10 shows the model predicted pressure drop for a channel width venturi contraction with radius of curvature/diameter ≥ 0.15 over a range of flow rates (K_L=0.04) [54]. The plot for expansion is similar caused by the similar loss coefficient for this entrance effect. This plot verifies that the pressure drop caused by constrictions/expansions is sufficiently large to explain the difference between the model and experimental data. Moreover, despite these constrictions, the bulk difference in the channel geometry between the 120°C and 110°C parts explain the higher pressure drop in
the 120°C parts. The difference in pressure drop between the two 120°C parts cannot be readily explained. However, it is apparent that given the deviation of the experimental data from the theoretical is on the order of the deviation between the two 120°C parts, differences in the constrictions between the two parts is the most likely cause of this pressure differential.

Figure 10-9: Screen captures of channel defects along the length (constriction and expansion defects shown)
Figure 10-10: Model predicted pressure drop for channel width venturi contraction from 100-60 μm

All four parts tested had a statistically different value based on the overall RMS uncertainty (bias error and 95% confidence interval on the re-re-registration error) for the 1.0 ml/min and 0.5 ml/min flow rates. This difference was present but not as great at the 0.25 ml/min flow rate, where the P vs. Q data was less sensitive to the entrance effects which, as seen above, play a large role in the pressure drop. These results show the FTS is capable of detecting variation in the output part as a function of equipment input parameters to a sufficient degree that measurement induced error does not overshadow the physical differences in the parts.
Conclusions and Possible Future Work on the FTS

11.1 Conclusions

The initial statistical analysis of Poly(methyl methacrylate)-PMMA parts fabricated on the first generation hot micro-embossing (HME) system showed the need to: (1) design a new HME system; and (2) establish alternative methods for characterizing micro-fluidic parts. A second generation HME system was constructed with fellow Manufacturing and Process Control Laboratory (MPCL) graduate students and a Functional Testing System (FTS) was developed to test whether micro-embossed parts from the new HME system were capable of flowing fluid and establish output metrics for process control based on pressure (P) vs. flow rate (Q) fluid performance.

The new characterization method was shown to have re-registration error as low as ±1.03%, approaching the hardware limitations of the components in the system (overall RMS uncertainty of ±1.51%). The initial statistical analysis also showed HME process variation was on the order of 12.6% (coefficient of variance). Though a large cause of this variation may have been caused by deficiencies in the first generation HME system, this order of process variation should be detectable by the new FTS. The experimental data from tests run on the FTS fit a fluid model developed to the expected accuracy of ~±10% for all but the lowest aspect ratio micro-channel. Moreover, the FTS results were consistent with Zygo scans of a series of parts made with varying HME parameters. The latest version of the FTS was capable of detecting process variation
caused by the change in input equipment parameters. In fact, the FTS was able to detect differences that a few isolated optical scans could not. The parts had to be observed over the entire length to determine the cause of higher than expected pressure drop in the channels. It was determined that constrictions/expansions at localized sections of the channel were responsible for this FTS result.

The FTS performed as expected, providing a bulk quantity to assess the geometry of the channel rather than at a specified location. The FTS has the potential to provide fast testing results (tests to date of ~60 minutes were largely dependent on the part loading and unloading time which can be reduced). The FTS also can be easily adapted to handle any range of micro-channel geometry. However, very low aspect ratio structures were shown to have much higher re-registration errors. Moreover, there would be a substantive cost involved in integrating this type of testing method in a production environment. These results and the deficiencies in existing metrology techniques warrant further exploration into functional-based testing for micro-fluidic devices to parallel well established testing methods in place in the IC industry. Functional testing does not have the capacity to replace traditional metrology; however, it can add an important output metric-a quantitative measure of the output parts fluid flow. Further development of failure criteria and other testing methods to extract more data on the dimensional compliance of the micro-channel is justified.

11.2 Future Work

11.2.1 Tests to Characterize Parts of Other Processes and Materials

The FTS was designed to accommodate the testing of HME PMMA parts. However, other HME materials such as polycarbonate could be easily tested in the
existing system with little to no modification. Moreover, parts manufactured from other processes such as micro-injection molding could also be easily tested in the existing system with little to no modification. The FTS was used by Korb in testing the effect of multi-layer alignment of PDMS made with soft lithography [62]. The FTP was removed and the PDMS device was directly connected to the rest of the FTS via metal tubes used to create a seal against the compliant PDMS reservoirs [62]. This is an example of how the FTS can be used for purposes beyond the characterization of HME PMMA parts.

11.2.2 Larger Part Dimensions

The last FTP Version 5 has overall dimensions of 2.5" x 2.5". This was sufficient for the parts of less than 1in² tested to date. However, given the potential to fabricate 4" diameter parts with the second generation HME system, a FTP that can accommodate a similar size part is warranted.

11.2.3 Test FTS to Detect HME Process Variation

To date, tests run have focused on assessing the re-registration error of the FTS and fitting the experimental data to a fluid flow model. Moreover tests have also been run to determine whether the FTS is capable of detecting differences in micro-channel geometry caused by changes in HME process parameters. These results were then compared to optical scans and good correlation between the two techniques was found. It may be useful to test the ability of the FTS to detect HME process variation. Based on initial metrology assessments of HME variation, discussed in Chapter 2, the coefficient of variance of the first generation HME system was found to be on the order of 12.6%. Given that a new HME system was constructed based on this high level of process
variation, a new round of tests to assess the metrological and functional variation of the system may be warranted.

11.2.4 Varied Micro-Channel Geometry and Multiple Input or Output

The current FTP was designed to accommodate single-input single-output straight functional test channels with 2000 μm reservoirs, a micro-channel length of 8000 μm, and varying channel widths and depths. However, this concept can be expanded to design a FTP that is capable of testing all the functional test sites on the current mask design. This would encompass varying micro-channel lengths as well as different flow paths. Moreover, this would allow for the testing of the converging/diverging functional test site which would involve either two inputs or two outputs.

11.2.5 Automated Part Handling

A drawback with the current FTP design is the high degree of user input required in loading the part to be tested. Though the uncertainty associated with this was shown to be as low as ±1.51%, further improvement could be achieved if the part loading and unloading is automated and even more precise hardware is used. This would require a significant upgrade to the FTS design and would only be warranted if functional testing were to be implemented for high throughput.

11.2.6 New FTS to Test Parts on Other Metrics

The current FTS is limited to testing the fluidic performance of parts. However, further inquiry into the functional testing concept can be directed toward other tests such as optical testing. HME parts can be assessed based on their ability to meet certain optical diffraction specifications as opposed to fluid flow characteristics.
Appendix
A HME System Operation and Use Manual

This Appendix was co-authored with Shoji [28].

A.1 Standard Use of the System

The following protocol is used to create a Poly(methyl methacrylate)-PMMA part using a silicon wafer. The most up-to-date software file automatically controls the temperature control system, but not the force subsystem.

Pretest Instructions

1. Make sure the air supply to the mixing valve positioners is set to roughly 27 psi.

2. Five ball valves are closed when the machine is not running to mitigate leakage of the Paratherm MR. Open the ball valves after the two mixing valve outlets, one at the outlet of both platens, the return to the pump inlet, and the pump outlet.

3. Check the fluid level in the cold trap tank and make sure it’s around the room temperature level mark.

4. Hook up the water hose from the cold heat exchanger to the faucet and make sure the other end is going straight down the drain. If the waste doesn’t go straight down the drain, the sink will overflow. Turn on the cold water to its maximum flow rate (5 GPM).

5. Turn on the exhaust fan to expel any vaporized Paratherm within the machine enclosure.
6. Turn on the heater controller, but do not increase the set point temperature above room temperature.

7. Open the LabView program called “Automate2.vi,” in the Grant_Labview folder on the desktop.

8. Make sure within the Motor Controls panel that the Motor Heating and Motor Cooling buttons are ON. Also, the Motor Signal Heating and Motor Signal Cooling buttons should both read Current.

9. Open the Instron software and set the Instron to manual control.

10. Open the Merlin software and set the desired force profile needed to create the part. Maintain the end force for a long time (12 minutes) to ensure the Instron holds the force during an indefinite amount of cooling time.

11. For the top platen, input the embossing set point temperature in Heat SP Top and the de-embossing set point temperature in Cool SP Top.

12. For the bottom platen, input the embossing set point temperature in Heat SP Bottom and the de-embossing set point temperature in Cool SP Bottom. Make sure the controller setting in the program is set to Heating.

13. Make sure the controller setting in the program is set to Heating.

14. Place a 4” wafer size piece of acrylic on the bottom spacer plate and a 4” aluminum machined wafer on the acrylic. The purpose of the acrylic is to compensate for the misalignment of the platens.

Test Instructions
1. Run the program, save the file to some user defined directory and increase the set point temperature on the heater controller to 180 °C.

2. Monitor the temperature of the platens on the chart on the right side of the screen.

3. Once the temperature of both platens is near the embossing set point temperature (± 5°C), register the PMMA sample on the desired feature of the tool. (Note: Using PMMA too large in area may cause problems with de-embossing).

4. Quickly bring the top platen in close contact with the PMMA so it can heat up from both sides. This also prevents the PMMA from curling.

5. Wait approximately three minutes to ensure the PMMA reaches its equilibrium temperature.

6. Once the three minutes are up, switch over to the Merlin program and start the force/displacement profile. Also, record the timestamp on the LabView program when the Merlin program is started. This will allow for coordination of data during analysis.

7. When the force reaches its set point, monitor the displacement.

8. When the speed of the crosshead reaches a threshold of 1 μm/3 sec., go back to the LabView program and switch the controller to Cooling.

9. Monitor the temperature of both platens on the chart on the right side of the screen.

10. When the temperature reaches the cooling set point, stop the Instron from applying a force and manually disengage the top platen from the work piece.
11. De-emboss the PMMA from the tool. Practice has shown that using a razor while delicately handling the silicon wafer ensures the lowest probability of the tool breaking.

12. Once the PMMA is off the tool, the cycle can be repeated.

**Posttest Instructions**

1. Run the program called “55to120_3.vi,” in the folder located in
   
   `>>Desktop>>Grant_Labview>>DOE` using Cooling control and keep the cooling set point around 50 °C.

2. Turn up the motor speed to 49 Hz to increase cooling.

3. Turn down the set point of the heater controller to 10 °C.

4. Monitor the temperature of all components in the system.

5. When the temperature of all components is below 50 °C, stop the motor in the program and then the LabView program can be stopped.

6. Turn off the power to the heater controller.

7. Turn off the water to the cold heat exchanger.

8. Turn off the exhaust fan.

9. Close the ball valves after the two mixing valve outlets, one at the outlet of both platens, the return to the pump inlet, and the pump outlet.

**A.2 Operation of Controllers**

**A.2.1 Motor Controller Operation**

The motor controller comes with a number of different options. The figure below describes some parameters that may want to be configured at some point. The only two
function codes which need to be changed when switching from manual to computer control are A_01 and A_02.

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<tr>
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<th>Name/SRW Display</th>
<th>Description</th>
<th>Run Mode</th>
<th>Setting</th>
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<td>01</td>
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<td>A_02</td>
<td>Run command source setting</td>
<td>Two options; select codes: 01...Control Terminal 02...Run key on keypad, or digital operator</td>
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<td>01</td>
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<td>The ending point (offset) for the active analog input range</td>
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<td>C_13</td>
<td>IN-TM O/C-3 NO</td>
<td>X 00</td>
<td></td>
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</tbody>
</table>

**Modified Programmable Drive Parameters**

**A.2.2 Motor Controller Notes**
1. Make sure all of the inverter vents are opened before operation to prevent overheating.

2. Speed in RPM = (Frequency x 120)/# of poles.

3. The potentiometer and control terminal cannot be used at the same time. There is no override option.

4. There is an option of setting up to three jump frequencies with bounds. Since there are known resonant frequencies of the system, we can eliminate the motor from staying those frequencies.

A.2.3 Heater Controller Operation

It has been found that computer control of the heater is not necessary for normal operation of the machine. None of the features have been implemented, but the wiring is setup. The following paragraphs describe the procedures for gaining computer control of the heater controller.

The heater controller has different security levels, which gives access to certain menus. The security code is entered on the control PAGE Ctrl, at the MENU Loch. To access and enter the Security Code, press and hold RESET for more than 3 seconds to enter Setup mode. Security Lock is the first menu that will appear.

In order to gain computer control of the heater, switch #4 on the bottom of the controller needs to be down. Enable the remote set point by entering MENU rSP on the Ctrl PAGE and select ON. To scale the input signal, go to the ScAl PAGE, MENUs rSPL (remote set point low) and rSPH (remote set point high). Enter the sensor span low and high ranges. For example, for a 100 to 500 °F range, 4 mA would equal 100 °F, and 20 mA would equal 500 °F.
In order to utilize the digital input function, the rSP should be selected in the Ctrl PAGE. When the function is selected, the controller uses the Local Setpoint (Ctrl PAGE, SP) when the digital input switch is open. The remote set point is used when the switch is closed. The remote set point must be enabled (Ctrl PAGE, rSP=on) for this function to operate. The AUX indicator is ON when the remote set point is selected and OFF when the local set point is selected.

A.3 Troubleshooting the System

A number of problems occur on occasion when running the machine and the following sections should describe some problems that have been encountered. This list is not exhaustive, so consult the appendix or component manuals if the problem is not stated in one of the following sections.

A.3.1 Instron Instability

**Problem:** The Instron makes a grinding noise when it is in force control. It may also stop.

**Solution:** Tune the PID gains using the Instron software. Different materials being embossed change the effective stiffness of the system dynamics. Therefore, try to place a material of comparable stiffness you want to emboss with when tuning the PID gains.

A.3.2 Leakage near Platens

**Problem:** Paratherm Leaks at the interface between the hoses and platens.

**Solution:** Clean off the Paratherm from the surface of the interface as much as possible. Apply Loctite 6900 generously around the area of interest and try to get it to
flow in most of the cracks. Let the Loctite cure at room temperature for at least 48 hours before running the machine again.

A.3.3 Possible Valve Closure

Problem: The pump makes an unusual sound and the temperatures being recorded in LabView do not reflect what should happen.

Solution: These clues typically indicate that a ball valve is closed. Sometimes the steps for operating the machine are not followed closely and a ball valve remains closed preventing normal operating flow. Check the flow meters to see if the flow is consistent with the motor setting.

A.3.4 Water is not Turned On

Problem: The temperature of the cold heat exchanger outlet remains at the same temperature as other components in the system.

Solution: It is not uncommon to forget to turn on the water to cool the cold heat exchanger. If the cold heat exchanger fluid outlet temperature is the same as other components within the system, or the system does not cool down when commanded to, it is a good indication that the water is not turned on. If this is the case, take caution when turning on the water because it can vaporize and burn you.

A.4 Draining the Hot Micro-Embossing (HME) System

Maintenance, repair, or other factors may require the system to be drained of Paratherm MR fluid. The steps below outline the general procedures that should be followed to drain the system. Most fluid in the system will be removed with this
technique; however, some fluid will remain in the lines leading to the platen because of the lower relative height.

1. Ensure power is off to all the major powered components of the system (heater, pump and exhaust fan). Turn off power at both the controllers and the junction boxes found on the ceiling (by pulling the boxes open).

2. Remove the aluminum panel on the front of the system (see Figure on next page) to access the bottom right side of the heater body. Note: The right side aluminum panel is a door which can simply be opened to access the heaters right side.

3. Set the mixing valve positions to half cold using the LabView Control program.
4. Ensure all valves in the system (including those near the expansion tank) are open.

5. Obtain: (1) two large buckets that can be easily placed and removed from under the heater body directly under the opening nut which allows the heater to be drained; and (2) two pairs of gloves resistant to organic liquids. Wear gloves and complete all subsequent steps with the help of two people if possible.

6. Place the first bucket underneath the heater opening nut and slowly open the nut until a steady and manageable flow of fluid drains from the system. If flow out of the heater is too high to manage, close a valve in the system to reduce the pressure head on the fluid exiting the heater (will reduce the flow rate). Once the flow rate has sufficiently subsided again, open the system valve that was closed to ensure the entire system is drained.

7. Switch out one bucket for the other quickly as they are filled and pour the Paratherm MR from the buckets back in the storage containers with the use of the mesh-funnel.

8. Repeat Step 6 until all the Paratherm MR is removed from the system. Note: as more fluid is removed from the system, the pressure head on the fluid remaining in the system is lower and the opening nut will have to be opened further to maintain a steady flow, until the opening nut can be removed completely to allow the last remaining amounts of Paratherm MR to drain from the system.
9. Once flow of fluid out of the heater ceases, power should be restored to the pump and it should be operated at an extremely low flow rate (on the order of 1-2 GPM) for only a few minutes. This is to ensure no fluid remains backed-up in the system behind the pump.

10. Once all flow from the heater ceases, turn off the pump and cut its power.

11. Place Teflon tape around the opening nut and tighten the drain in the heater.

12. Clean all spilled Paratherm MR.

13. Replace the front aluminum panel that was removed to access the heater.

Note: The next time the system is drained a 1/8” ball valve and stop plug should be installed at the heater drain. A hose can then be connected to make it easier to drain the system in the future.

A.5 Re-filling the HME System

After the system has been drained and necessary maintenance, repair or other actions have been taken, the system has to be re-filled with Paratherm MR. The steps below outline the general procedures that should be followed to re-fill the system.

1. Ensure power is off to the heater and exhaust fan. Turn off power at both the controller and the heater junction box found on the ceiling (by pulling the box open).

2. Ensure all valves in the system (including those near the expansion tank) are open.
3. Ensure the fluid circuit is closed and no openings are present (missing sensors or pipe sections).

4. Begin pouring the Paratherm MR directly from the buckets to the cold baffle of the expansion tank until the tank is nearly full.

5. Wait for the level of the fluid in the system to go down and repeat Step 4 until the fluid level appears to have stabilized.

6. Turn on the pump and initially operate at 1-2 GPM. The fluid level should start going down. Repeat Step 4. Continue gradually increasing the flow rate of the pump (up to and not exceeding 39GPM) while adding fluid to the system until the fluid level in the expansion tank no longer changes. Note: monitor the noise from the pump. If excessive noise is emitting from the pump, reduce the pump flow rate or turn the pump if necessary and wait until the more fluid has time to work its way into the system. This may be a sign of pump cavitation.

7. Turn the pump off and close the valve connecting the expansion tank outlet to the pump inlet (normal operating position).

### A.6 Switching out the Load Cell (1KN-50KN)

1. Place a compliant material between the top and bottom platen assemblies. Bring the two assemblies together until the top assembly is resting on the complaint material.

2. Remove the clevis pin holding the top assembly to the load cell. Use a small rubber headed hammer if necessary.
3. Disengage the top crosshead (the top assembly, now disconnected from the load cell, should remain resting on the bottom assembly).

4. Remove the three screws holding in the load cell and disconnect the communications cable between the load cell and the Instron frame.

5. Store the load cell.

6. Place the new load cell in the opening in the top crosshead and secure with the same three screws.

7. Connect the cable from the load cell to the Instron frame.

8. Open the Load Cell Calibration Protocol in the Instron software on the PC and calibrate the load cell.

9. Unscrew the top anvil from the top assembly and replace with the appropriate anvil for the new load cell.

10. Bring the top crosshead down until the pin in the top anvil enters the opening on the load cell and the holes for the clevis pin are aligned.

11. With the help of two people, one person should adjust the alignment of the top assembly while the other forces the clevis pin through the pin in the anvil and the load cell. Once the pin has been inserted, the securing device should be installed.

12. The top crosshead can now be raised and the top assembly and top anvil should be secured. The compliant gasket layer can now be removed and tests can be carried out.

A.7 Changing the Platen Subsystem
1. The four screws securing the bottom steel plate to the Instron frame should be removed (this will allow the entire bottom platen assembly to move freely).

2. Place a compliant material between the top and bottom platen assemblies. Bring the two assemblies together until the top assembly is resting on the complaint material.

3. Remove the clevis pin holding the top assembly to the load cell. Use a small rubber headed hammer if necessary.

4. Disengage the top crosshead (the top assembly, now disconnected from the load cell, should remain resting on the bottom assembly).

5. Both the top and bottom assemblies are now free to move. Two people should move the entire table holding the Instron frame until the top and bottom assemblies can be moved out toward the back left of the Instron base (away from the load cell axis as shown below). This will allow the first generation system to be mounted in the Instron frame while still allowing the second generation system to rest on the Instron base and remain connected to the thermal-oil heat transfer system loop.
Top and bottom platen assemblies for the first generation HME system and the location the second generation HME system should rest when not in use

6. Replace the centering ring on the Instron base where the bottom assembly rested.

7. Mount the bottom anvil and the first generation system bottom platen assembly.

8. Change out the load cell if required (see instructions 4-8 in Section A.6 for more details).

9. If using the same load cell, remove the top anvil still connected to the second generation system and mount it to the first generation system top platen assembly. If using a new load cell, mount the new load cells anvil to the first generation system top platen assembly.
10. Attach the top platen assembly (with top anvil attached) to the load by placing the assembly on a compliant layer resting on the bottom assembly and moving the Instron until the pin in the top anvil enters the opening on the load cell and the holes for the clevis pin are aligned.

11. Adjust the alignment of the top assembly and force the clevis pin through the pin in the anvil and the load cell. Once the pin has been inserted, the securing device should be installed.

12. The top cross head can now be raised and the top assembly and top anvil should be secured. The compliant gasket layer can now be removed and tests can be carried out.
B Material Properties

B.1 Properties of OT-201

From the Omega product webpage:

Typical Properties

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*M = Metal  
C = Ceramic  
PL = Plastic  
PA = Paper Products  
W = Wood

B.2 Properties of Paratherm MR

From the Paratherm product webpage:
http://www.paratherm.com/Paratherm-MR/MRtabdataSI.asp

Paratherm MR™

Tabular Data (SI Units)

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<tr>
<td>260</td>
<td>500</td>
<td>0.6145</td>
<td>615</td>
<td>0.545</td>
<td>0.335</td>
<td>0.6776</td>
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<td>265</td>
<td>509</td>
<td>0.6105</td>
<td>611</td>
<td>0.535</td>
<td>0.327</td>
<td>0.6809</td>
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<td>270</td>
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<td>0.6065</td>
<td>606</td>
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<td>0.319</td>
<td>0.6841</td>
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<td>275</td>
<td>527</td>
<td>0.6025</td>
<td>602</td>
<td>0.518</td>
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<td>0.6874</td>
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<td>280</td>
<td>536</td>
<td>0.5985</td>
<td>598</td>
<td>0.510</td>
<td>0.305</td>
<td>0.6906</td>
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<tr>
<td>285</td>
<td>545</td>
<td>0.5944</td>
<td>594</td>
<td>0.503</td>
<td>0.299</td>
<td>0.6938</td>
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<td>554</td>
<td>0.5904</td>
<td>590</td>
<td>0.500</td>
<td>0.295</td>
<td>0.6972</td>
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<td>295</td>
<td>563</td>
<td>0.5863</td>
<td>586</td>
<td>0.496</td>
<td>0.291</td>
<td>0.7005</td>
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<td>300</td>
<td>572</td>
<td>0.5823</td>
<td>582</td>
<td>0.493</td>
<td>0.287</td>
<td>0.7038</td>
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<tr>
<td>305</td>
<td>581</td>
<td>0.5782</td>
<td>578</td>
<td>0.490</td>
<td>0.283</td>
<td>0.7071</td>
<td>0.1194</td>
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<tr>
<td>310</td>
<td>590</td>
<td>0.5742</td>
<td>574</td>
<td>0.487</td>
<td>0.279</td>
<td>0.7104</td>
<td>0.1189</td>
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<tr>
<td>316</td>
<td>601</td>
<td>0.5701</td>
<td>570</td>
<td>0.483</td>
<td>0.276</td>
<td>0.7137</td>
<td>0.1185</td>
</tr>
</tbody>
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### B.3 Properties of CC High Temperature Cement

From the Omega product webpage:
http://www.omega.com/Temperature/pdf/CC_CEMENT.pdf

#### Physical Properties

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>OMEGABOND 600</th>
<th>OMEGABOND 700</th>
<th>CC High Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Cement (One or Two Part)</strong></td>
<td>One Part</td>
<td>One Part</td>
<td>Two Part</td>
</tr>
<tr>
<td><strong>Coefficient of thermal expansion, in/in°F</strong></td>
<td>2.6 x 10⁻⁶</td>
<td>12.4 x 10⁻⁶</td>
<td>4.6 x 10⁻⁶</td>
</tr>
<tr>
<td><strong>Color</strong></td>
<td>Off White</td>
<td>White</td>
<td>Tan</td>
</tr>
<tr>
<td><strong>Compressive strength, PSI</strong></td>
<td>4500-5500</td>
<td>3500</td>
<td>3800</td>
</tr>
<tr>
<td><strong>Density, Ib/ft³</strong></td>
<td>160</td>
<td></td>
<td>141</td>
</tr>
<tr>
<td><strong>Dielectric constant</strong></td>
<td>3.0 - 4.0</td>
<td></td>
<td>5.0 to 7.0</td>
</tr>
<tr>
<td><strong>Dielectric strength at 20°C (70°F), Volts/mil</strong></td>
<td>76.0</td>
<td>25.0 to 36.0</td>
<td>12.5 to 25.0</td>
</tr>
<tr>
<td><strong>Dielectric strength at 795°C (1475°F), Volts/mil</strong></td>
<td>12.5 to 25.0</td>
<td></td>
<td>≤1.3</td>
</tr>
<tr>
<td><strong>Maximum service temperature, °C (°F)</strong></td>
<td>1426 (2900)</td>
<td>871 (1600)</td>
<td>843 (1550)</td>
</tr>
<tr>
<td><strong>Modulus of rupture, PSI</strong></td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tensile strength, PSI</strong></td>
<td>250</td>
<td></td>
<td>425</td>
</tr>
<tr>
<td><strong>Volume resistivity at 20°C (70°F), ohm-cm</strong></td>
<td>10⁻¹⁰</td>
<td>10⁻¹⁰</td>
<td>10⁻¹⁰</td>
</tr>
<tr>
<td><strong>Volume resistivity at 40°C (75°F), ohm-cm</strong></td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td><strong>Volume resistivity at 795°C (1475°F), ohm-cm</strong></td>
<td>10⁻⁶</td>
<td></td>
<td>10⁻⁶</td>
</tr>
<tr>
<td><strong>Flexural strength, PSI</strong></td>
<td>435</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Absorption, %</strong></td>
<td></td>
<td></td>
<td>10 - 12</td>
</tr>
<tr>
<td><strong>Shrinkage, %</strong></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Thermal Conductivity, Btu-in/ft²°F</strong></td>
<td>10 - 12</td>
<td>4.5 to 5.9</td>
<td>8</td>
</tr>
<tr>
<td><strong>Mix Ratio</strong></td>
<td>Mix 100 Parts powder with 13 parts water by weight.</td>
<td>Mix 75-80% powder with 20-25% water by weight.</td>
<td>Mix 3 parts powder to 1 part liquid by weight, or 2 parts filler to 1 part liquid by volume.</td>
</tr>
</tbody>
</table>

#### Curing Schedule

**OMEGABOND 600°** cures at room temperature by internal chemical action in 18-24 hours. Cure time can be accelerated by low temperature oven drying at 82°C (180°F). If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 82°C (180°F) and for an additional 4 hours at 105°C (220°F). This helps to prevent spilling.

**OMEGABOND 700°** cures at room temperature with a chemical action in 18-24 hours. Cure time can be accelerated by low temperature oven drying at 92°C (180°F). If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 92°C (180°F) and for an additional 4 hours at 105°C (220°F). This helps to prevent spilling.

**CC High Temperature Cement** cures at room temperature with an internal chemical-setting action with an initial set in approximately 30 minutes. The final set is reached in 18 to 24 hours when cured at room temperature. If it is desired to accelerate the curing time, set the drying oven to 105°C (220°F), then oven dry for 4 hours. The drying oven is set to 105°C (220°F), the cement will cure in 3 hours.

#### Distinguishing Characteristics and Applications

**High dielectric strength**
Used to pot nickel chromium resistance heating wire. Won't stick to smooth quartz.

**Used on metals or other materials which have a high coefficient of thermal expansion. Excellent bonding characteristics.**
Used to cement on and insulate thermocouples for surface temperature measurement.

---

*These physical properties were determined under laboratory conditions using applicable ASTM procedures. Actual field data may vary. Do not use physical properties data for specifications. Air Set Cements are also available. See OMEGABOND® 300, OMEGABOND® 400 and OMEGABOND® 500. These cements set or cure through loss of moisture by evaporation. Atmospheric conditions therefore affect the drying rate. Air Set Cements are used mainly in the thin film applications (less than 1/16" thickness). Porous substrates may require dampening with Thinning Liquid before application of mixed cement. For OMEGABOND® 600 and OMEGABOND® 700 (one part cements), order OMEGABOND® Thinning Liquid, Model No. OB-TL, Price $36 (8 fluid oz). For CC High Temperature Cement, use CC High Temperature Cement Liquid Binder to dampen porous substrates.*

---

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### B.4 Properties of PMMA

From MatWeb page on Cast Acrylic:


<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.19 - 1.2 g/cc</td>
<td>0.043 - 0.0434 lb/in³</td>
<td>Average = 1.19 g/cc; Grade Count = 4</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>0.13 - 0.35 %</td>
<td>0.13 - 0.35 %</td>
<td>Average = 0.22%; Grade Count = 4</td>
</tr>
<tr>
<td>Water Absorption at Saturation</td>
<td>1.1 %</td>
<td>1.1 %</td>
<td>Grade Count = 1</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Barcol</td>
<td>49</td>
<td>49</td>
<td>Grade Count = 1</td>
</tr>
<tr>
<td>Hardness, Rockwell M</td>
<td>90 - 94</td>
<td>90 - 94</td>
<td>Average = 92; Grade Count = 2</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>60 - 83 MPa</td>
<td>8700 - 12000 psi</td>
<td>Average = 73.2 MPa; Grade Count = 4</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>60 MPa</td>
<td>8700 psi</td>
<td>Grade Count = 1</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>4.2 - 5.5 %</td>
<td>4.2 - 5.5 %</td>
<td>Average = 4.8%; Grade Count = 4</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>2.8 - 3 GPa</td>
<td>406 - 435 ksi</td>
<td>Average = 2.9 GPa; Grade Count = 2</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>3 - 3.3 GPa</td>
<td>435 - 479 ksi</td>
<td>Average = 3.2 GPa; Grade Count = 2</td>
</tr>
<tr>
<td>Flexural Yield Strength</td>
<td>100 - 114 MPa</td>
<td>14500 - 16500 psi</td>
<td>Average = 110 MPa; Grade Count = 2</td>
</tr>
<tr>
<td>Compressive Yield Strength</td>
<td>100 - 124 MPa</td>
<td>14500 - 18000 psi</td>
<td>Average = 110 MPa; Grade Count=2</td>
</tr>
<tr>
<td>Izod Impact, Notched</td>
<td>0.22 - 0.25 J/cm</td>
<td>0.412 - 0.468 ft-lb/in</td>
<td>Average = 0.23 J/cm; Grade Count = 2</td>
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<table>
<thead>
<tr>
<th>Electrical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Electrical Resistivity</td>
<td>1e+015 - 1.6e+016 ohm-cm</td>
<td>1e+015 - 1.6e+016 ohm-cm</td>
<td>Average = 9E+15 ohm-cm; Grade Count = 2</td>
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<tr>
<td>Surface Resistance</td>
<td>1.9e+015 ohm</td>
<td>1.9e+015 ohm</td>
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<td>Dielectric Constant</td>
<td>2.7 - 4</td>
<td>2.7 - 4</td>
<td>Average = 3.3; Grade</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Count = 2</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Dielectric Constant, Low Frequency</strong></td>
<td>3.5 - 4</td>
<td>3.5 - 4</td>
<td>Average = 3.8; Grade Count = 2</td>
</tr>
<tr>
<td><strong>Dielectric Strength</strong></td>
<td>17 kV/mm</td>
<td>432 kV/in</td>
<td>Grade Count = 2</td>
</tr>
<tr>
<td><strong>Dissipation Factor</strong></td>
<td>0.02 - 0.055</td>
<td>0.02 - 0.055</td>
<td>Average = 0.038; Grade Count = 2</td>
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<tr>
<td><strong>Dissipation Factor, Low Frequency</strong></td>
<td>0.055 - 0.06</td>
<td>0.055 - 0.06</td>
<td>Average = 0.057; Grade Count = 2</td>
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<tr>
<td><strong>Thermal Properties</strong></td>
<td></td>
<td></td>
<td>Grade Count = 3</td>
</tr>
<tr>
<td><strong>CTE, linear 20°C</strong></td>
<td>61 - 130 μm/m-°C</td>
<td>33.9 - 72.2 μm/in-°F</td>
<td>Average = 98.3 μm/m-°C; Grade Count = 3</td>
</tr>
<tr>
<td><strong>Heat Capacity</strong></td>
<td>1.5 J/g-°C</td>
<td>0.359 BTU/lb-°F</td>
<td>Grade Count = 3</td>
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<tr>
<td><strong>Thermal Conductivity</strong></td>
<td>0.19 - 0.25 W/m-K</td>
<td>1.32 - 1.74 BTU-in/hr-ft²-°F</td>
<td>Average = 0.2 W/m-K; Grade Count = 4</td>
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<tr>
<td><strong>Maximum Service Temperature, Air</strong></td>
<td>65 - 112 °C</td>
<td>149 - 234 °F</td>
<td>Average = 94.5°C; Grade Count = 4</td>
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<tr>
<td><strong>Deflection Temperature at 1.8 MPa (264 psi)</strong></td>
<td>99 - 112 °C</td>
<td>210 - 234 °F</td>
<td>Average = 100°C; Grade Count = 4</td>
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<tr>
<td><strong>Vicat Softening Point</strong></td>
<td>110 °C</td>
<td>230 °F</td>
<td>Grade Count = 1</td>
</tr>
<tr>
<td><strong>Minimum Service Temperature, Air</strong></td>
<td>-40 °C</td>
<td>-40 °F</td>
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</tr>
<tr>
<td><strong>Glass Temperature</strong></td>
<td>100 °C</td>
<td>212 °F</td>
<td>Grade Count = 1</td>
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<tr>
<td><strong>Optical Properties</strong></td>
<td></td>
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<td>Grade Count = 3</td>
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<tr>
<td><strong>Refractive Index</strong></td>
<td>1.49</td>
<td>1.49</td>
<td>Grade Count = 1</td>
</tr>
<tr>
<td><strong>Haze</strong></td>
<td>0.6 - 1 %</td>
<td>0.6 - 1 %</td>
<td>Average = 0.77%; Grade Count = 3</td>
</tr>
<tr>
<td><strong>Transmission, Visible</strong></td>
<td>92 %</td>
<td>92 %</td>
<td>Grade Count = 3</td>
</tr>
<tr>
<td><strong>Processing Properties</strong></td>
<td></td>
<td></td>
<td>Grade Count = 1</td>
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<tr>
<td><strong>Processing Temperature</strong></td>
<td>180 °C</td>
<td>356 °F</td>
<td>Grade Count = 1</td>
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</tbody>
</table>
B.5 Properties of TPX® (polymethylpentene) Gasket Layer

Material Properties Data Sheet obtained from Westlake Plastics Company:

TPX® Film (polymethylpentene)

TPX has a remarkable and unique combination of transparency and resistance to heat and chemicals. It also has unique acoustical properties. It is used in a wide variety of applications including speaker cones, gas separating membranes, release films and carrier films for ceramic slurry. The following physical property information is based on typical values of the base TPX® DX845 resin as well as test results obtained from actual film testing.

Applications Include:
- Speaker cones
- Gas separating membranes
- Release films
- Carrier films for ceramic slurry
- Antennas
- Medical instrument covers
- Ultrasonic imaging equipment

Advantages of TPX Film:
- Lowest specific gravity of any known thermoplastic
- Low moisture absorption
- Exceptional electrical properties
- Good chemical resistance
- High heat resistance
- Excellent acoustical properties
- Transparency
- Resin FDA-compliant

Manufacturing Capabilities:
- Thicknesses and Widths: .002" to .029" up to 24" wide
- Finishes: all thicknesses available polished one side, matte the other (PIM)

In addition to our standard capabilities, Westlake also has the ability to process custom resins in various sizes and colors with some exceptions.

<table>
<thead>
<tr>
<th>Mechanical</th>
<th>Units</th>
<th>ASTM Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength @ yield</td>
<td>psi</td>
<td>D882</td>
<td>4,110</td>
</tr>
<tr>
<td>Elongation @ break</td>
<td>%</td>
<td>D882</td>
<td>10</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>psi</td>
<td>D882</td>
<td>280,000</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>psi</td>
<td>D790</td>
<td>210,000</td>
</tr>
<tr>
<td>Tear Strength - prop.</td>
<td>g/mil</td>
<td>D1004</td>
<td>125</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Thermal</th>
<th>Units</th>
<th>ASTM Test</th>
<th>Result</th>
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</thead>
<tbody>
<tr>
<td>Continuous Use Temp. - UL</td>
<td>°F</td>
<td>—</td>
<td>212</td>
</tr>
<tr>
<td>Heat Deflection Temperature @66 psi</td>
<td>°F</td>
<td>D648</td>
<td>212</td>
</tr>
<tr>
<td>Melt Temp. - DSC</td>
<td>°F</td>
<td>D3418</td>
<td>—</td>
</tr>
<tr>
<td>Glass Transition Temp.</td>
<td>°F</td>
<td>—</td>
<td>—</td>
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<table>
<thead>
<tr>
<th>Flammability</th>
<th>Units</th>
<th>ASTM Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL Rating - UL94</td>
<td>—</td>
<td>—</td>
<td>HB</td>
</tr>
<tr>
<td>L.O.I.</td>
<td>%</td>
<td>D2863</td>
<td>&lt;25</td>
</tr>
<tr>
<td>NBS Smoke</td>
<td>Dmax</td>
<td>E662</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical</th>
<th>Units</th>
<th>ASTM Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Resistivity</td>
<td>Ohms</td>
<td>D257</td>
<td>&gt;10 16</td>
</tr>
<tr>
<td>Dielectric Strength @ .003&quot;</td>
<td>V/mil</td>
<td>D149</td>
<td>3,710</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>1 kHz</td>
<td>D150</td>
<td>2.12</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>1 MHz</td>
<td>D150</td>
<td>0.00025</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other</th>
<th>Units</th>
<th>ASTM Test</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>—</td>
<td>D792</td>
<td>0.035</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>½/24 hr.</td>
<td>D570</td>
<td>0.01</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>—</td>
<td>—</td>
<td>1.463</td>
</tr>
<tr>
<td>Haze</td>
<td>%</td>
<td>D1003</td>
<td>2</td>
</tr>
<tr>
<td>Area Factor</td>
<td>in²/lb/mil</td>
<td>—</td>
<td>32.725</td>
</tr>
</tbody>
</table>

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## B.6 Properties of Silicon

From MatWeb page on Silicon:

http://www.matweb.com/search/SpecificMaterial.asp?bassnum=AMESi00

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.329 g/cc</td>
<td>0.0841 lb/in³</td>
<td></td>
</tr>
<tr>
<td>a Lattice Constant</td>
<td>5.43072 Å</td>
<td>5.43072 Å</td>
<td></td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>28.086 g/mol</td>
<td>28.086 g/mol</td>
<td></td>
</tr>
<tr>
<td>Volume Compressibility, 10⁻⁵ m²/N</td>
<td>0.306</td>
<td>0.306</td>
<td></td>
</tr>
</tbody>
</table>

### Mechanical Properties

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knoop Microhardness</td>
<td>11270</td>
<td>11270</td>
<td>N/mm²</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>112.4 GPa</td>
<td>16300 ksi</td>
<td></td>
</tr>
<tr>
<td>Compressive Yield</td>
<td>120 MPa</td>
<td>17400 psi</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>98.74 GPa</td>
<td>14300 ksi</td>
<td></td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.28</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>43.9 GPa</td>
<td>6370 psi</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

### Electrical Properties

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Resistivity</td>
<td>0.01 ohm-cm</td>
<td>0.01 ohm-cm</td>
<td></td>
</tr>
<tr>
<td>Magnetic Susceptibility</td>
<td>-3.90E-06</td>
<td>-3.90E-06</td>
<td>Atomic (cgs)</td>
</tr>
<tr>
<td>Critical Superconducting</td>
<td>6.7 - 7.1 K</td>
<td>6.7 - 7.1 K</td>
<td>6.7-7.1 K</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td>from 12.0-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.0 GPa</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>11.8</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>Band Gap</td>
<td>1.107 eV</td>
<td>1.107 eV</td>
<td></td>
</tr>
<tr>
<td>Electron Mobility, cm²/V-</td>
<td>1900</td>
<td>1900</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hole Mobility, cm²/V-s</td>
<td>500</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>

### Thermal Properties

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of Fusion</td>
<td>1800 J/g</td>
<td>774 BTU/lb</td>
<td></td>
</tr>
<tr>
<td>CTE, linear 20°C</td>
<td>2.49 μm/m-</td>
<td>1.38 μin/in.-°F</td>
<td>at 25°C</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
<td>Units</td>
<td>Temperature</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>CTE, linear 250°C</td>
<td>3.61 μm/m-°C</td>
<td>2.01 μin/in-°F</td>
<td>at 227°C</td>
</tr>
<tr>
<td>CTE, linear 500°C</td>
<td>4.15 μm/m-°C</td>
<td>2.31 μin/in-°F</td>
<td>at 527°C</td>
</tr>
<tr>
<td>CTE, linear 1000°C</td>
<td>4.44 μm/m-°C</td>
<td>2.47 μin/in-°F</td>
<td>at 1027°C</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>0.702 J/g-°C</td>
<td>0.168 BTU/lb-°F</td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity Gas</td>
<td>0.794 J/g-°C</td>
<td>0.19 BTU/lb-°F</td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>124 W/m-K</td>
<td>861 BTU-in/hr-ft²-°F</td>
<td></td>
</tr>
<tr>
<td>Melting Point</td>
<td>1412 °C</td>
<td>2570 °F</td>
<td></td>
</tr>
<tr>
<td>Boiling Point</td>
<td>3265 °C</td>
<td>5910 °F</td>
<td></td>
</tr>
<tr>
<td>Heat of Formation Crystal</td>
<td>0 kJ/mol</td>
<td>0 kJ/mol</td>
<td></td>
</tr>
<tr>
<td>Heat of Formation Gas</td>
<td>450 kJ/mol</td>
<td>450 kJ/mol</td>
<td></td>
</tr>
<tr>
<td>Debye Temperature</td>
<td>372 °C</td>
<td>702 °F</td>
<td></td>
</tr>
</tbody>
</table>

**Optical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index</td>
<td>3.49</td>
<td>3.49</td>
<td>at 589 nm</td>
</tr>
<tr>
<td>Reflection Coefficient Visible</td>
<td>0.3 - 0.7</td>
<td>0.3 - 0.7</td>
<td>varies irregularly with wavelength.</td>
</tr>
</tbody>
</table>

**Descriptive Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS Number</td>
<td>7440-21-3</td>
<td></td>
</tr>
<tr>
<td>Crystal Structure</td>
<td>Cubic</td>
<td>Diamond Structure - Space Group Fd3m</td>
</tr>
<tr>
<td>Solubility</td>
<td>Insoluble in H₂O and Acid; Soluble in Alkaline</td>
<td></td>
</tr>
</tbody>
</table>
Component Specifications

C.1 Hot Heat Exchanger by Vulcan

These specifications are provided by Vulcan.

Design Specifications:
8"-150# Circulation Heater - Bolied Flange Construction

1. Carbon steel flanges and shell assembly
2. (16) .475" diameter nickel alloy elements.
3. Moisture resistant terminal housing
4. (2) 2 1/2" NPT externally threaded inlet/outlet connections
5. (8) B0.15 & nuts (3/4-10) equally spaced on a 11 3/4" O.D.C.
6. Shell body wrapped with 1" fiberglass insulation and secured with heavy gauge outer jacket.
7. Heavy duty mounting lugs (with tapped holes) welded to shell body
8. (1) 1/2" NPT drain plug
9. Housing includes an over- temp type "J" thermocouple
10. Hydrostatic test at 225 psi (MIN)
1. Baffles must be placed in a manner in which thermocouple is not obstructed.

2. Stamp on flange below main conduit hub: Vulcan, watts, volts, phase and date code.

3. Paint flange with heat resistant black paint, paint cover and housing with red paint.

4. Bake out unit and seal elements with 3-W before installing rubber insulators and terminal hardware.

5. Hydrostatic test at 225 PSI (min.).

6. Assemble plastic plug in 1/2" NPT hub.

8" Flanged IMM. Heater

Massachusetts Institute of Technology

Electric Company

Porter, Maine 04048

Vulcan

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C.3 Mixing Valve Whole Assembly Specifications

From the Warren Controls Webpage:

```
Component 2820 Dimension (IN) by Valve Size (IN)
Variable
A 25THD 4-7/8 6-3/4 6-1/2
B 25THD 3-3/4 3-3/4 3-5/8
C 50THD 3 5-1/2 5-7/8
DL40 Direct* 15-1/4 17-7/8 16-1/8
DL40 Reverse 15-1/4 15-1/4 15-1/8
DL40 Direct 15-1/4 19-7/8 20-1/8
DL40 or DL40R Direct 19-7/8 19-7/8 19-1/2
DL40R 3-3/4 2-3/8 2-3/4
W/DL40 DL40 or DL40R 5-5/8 4-1/4 4-1/2

Item 1/2, 3/4, 1 3/4 & 1 1/2 2
Variable 50THD 5-1/2 6-1/2 6-3/8
S60THD 8 10-1/2

Component 2830 Dimension (IN) by Valve Size (IN)
Variable
A 25THD 4-7/8 6-3/4 6-1/2
B 25THD 3-3/4 3-3/4 3-7/8
C 50THD 3 5-1/2 5-7/8
DL40 Direct* 15-1/4 17-7/8 16-1/8
DL40 Reverse 15-1/4 15-1/4 15-1/8
DL40 Direct 15-1/4 19-7/8 20-1/8
DL40 or DL40R Direct 19-7/8 19-7/8 19-1/2
DL40R 3-3/4 2-3/8 2-3/4
W/DL40 DL40 or DL40R 5-5/8 4-1/4 4-1/2

Item 1/2, 3/4, 1 3/4 & 1 1/2 2
Variable 50THD 5-1/2 6-1/2 6-3/8
S60THD 8 10-1/2

Component 2832 Dimension (IN) by Valve Size (IN)
Variable
A 25THD 4-7/8 6-3/4 6-1/2
B 25THD 3-3/4 3-3/4 3-7/8
C 50THD 3 5-1/2 5-7/8
DL40 Direct* 15-1/4 17-7/8 16-1/8
DL40 Reverse 15-1/4 15-1/4 15-1/8
DL40 Direct 15-1/4 19-7/8 20-1/8
DL40 or DL40R Direct 19-7/8 19-7/8 19-1/2
DL40R 3-3/4 2-3/8 2-3/4
W/DL40 DL40 or DL40R 5-5/8 4-1/4 4-1/2

Item 1/2, 3/4, 1 3/4 & 1 1/2 2
Variable 50THD 5-1/2 6-1/2 6-3/8
S60THD 8 10-1/2

* Includes 1-3/8 inch for air fitting
H = Centerline of pipe to bottom of positioner
CF = Consult factory
NA = Not Available

Allow 4-7/8 inch clearance above actuator for removal.
Actual shipping weights may vary.

Component 2833 Dimension (IN)
Variable D DL40 11 DD4 or DD4R 11 DL40 11
D DL40 11 DD4 or DD4R 11 DL40 11
D DL40 11 DD4 or DD4R 11 DL40 11

Positioner Weight (LB) 260 15

RADIUS is from centerline of actuator to outside edge of positioner

Positioner Removal Clearance
Allow 3-1/4 inch clearance beyond 260 for cover removal

2-WAY or 3-Way w/DL40 & 760 Positioner
2-WAY or 3-Way w/DL84 or DL84R & 760 Positioner

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## C.4 Valve Positioner Series 760E

From the Siemens Webpage:

<table>
<thead>
<tr>
<th></th>
<th>760P Pneumatic Positioner</th>
<th>Common *</th>
<th>760E Electro/Pneumatic Positioner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Range</td>
<td>-40 to 85°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingress</td>
<td>NEMA 4X, IP65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connections</td>
<td>Pneumatic - 1/4&quot; NPT, 1/8&quot; NPT, 1/4&quot; NPT, 1/8&quot; NPT</td>
<td></td>
<td>Pneumatic - 1/4&quot; NPT, 1/8&quot; NPT, 3/4&quot; NPT, M25 (optional), 1/4&quot; NPT, 3/4&quot; NPT, M25 (optional)</td>
</tr>
<tr>
<td>Finish</td>
<td>Epoxy/Polyester powder coat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Configuration</td>
<td>Single or double acting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Action</td>
<td>Direct or reverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Pressure</td>
<td>150 psig max.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Consumption</td>
<td>0.5 scfm (typical)</td>
<td></td>
<td>0.6 scfm (typical)</td>
</tr>
<tr>
<td>Flow Capacity Standard Spool</td>
<td>9 scfm (Cv = 0.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Capacity High Flow Spool</td>
<td>18 scfm (Cv = 0.6) Supply (1/2 pressure gain of std.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Capacity Lo Flow Spool</td>
<td>9 scfm (Cv = 0.3) Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Signal</td>
<td>3-15 psig, 3-27 psig</td>
<td></td>
<td>Up to 50% Split range 4-20 mA</td>
</tr>
<tr>
<td>Feedback Signal</td>
<td>90 degree rotary standard 1/2&quot; to 6&quot; rectilinear optional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedback Configuration</td>
<td>Cam characterization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Gain</td>
<td>160 %% @ 60 psig supply std. (800 psi/psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span</td>
<td>Adjustable -60 to +25% of normal span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero</td>
<td>Adjustable -10 to +60% of normal span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linearity (Independent)</td>
<td>0.5% of normal span (typical)</td>
<td></td>
<td>0.75% of normal span (typical)</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.75% of normal span (typical)</td>
<td></td>
<td>1.0% of normal span (typical)</td>
</tr>
<tr>
<td>Deadband</td>
<td>Less than 0.25% of span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repeatability</td>
<td>Within 0.5% valve travel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Pressure Effect</td>
<td>Less than 0.2% valve travel for a 5 psig change in supply pressure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C.5 Roper 3711 Positive Displacement Pump

From Roper Pumps 3600 Series Manual
Fluid Flow Model MATLAB Code

D.1 Main File

This is the most up-to-date fluid flow model for the system. It includes the following components: mixing valves, platens, hot heat exchanger, cold heat exchanger, pipes, pipe fittings, y-strainer, flow meters, and pump.

```matlab
global t
global interval
global finalt
global PumpPressure

interval=1000;
finalt=40;
count=1;
len=linspace(0,finalt,interval);
Z=zeros(size(len));

%initialize vectors for mixing valve 1
Pout1o=Z;Qout1o=Z;Tout1o=Z;percent1o=Z;
%initialize vectors for mixing valve 2
Pout2o=Z;Qout2o=Z;Tout2o=Z;percent2o=Z;

%initialize vectors for platen2 output 1
Pout11ao=Z;Qout11ao=Z;Tout11ao=Z;Tsout11ao=Z;
%initialize vectors for platen2 output 2
Pout11bo=Z;Qout11bo=Z;Tout11bo=Z;Tsout11bo=Z;

%initialize vectors for other pipeTcombine1 output 1
Pout15o=Z;Qout15o=Z;Tout15o=Z;

%initialize vectors for pump1 output
Pout25o=Z;Qout25o=Z;Tout25o=Z;Pdiff0=Z;

%initialize vectors for PipeTSeparate1 output
Pout27ao=Z;Qout27ao=Z;Tout27ao=Z;Pout27bo=Z;Qout27bo=Z;Tout27bo=Z;

%initialize vectors for coldhex_new output
Pout30bo=Z;Qout30bo=Z;Tout30bo=Z;

%initialize vectors for hotwatt output
Pout30ao=Z;Qout30ao=Z;Tout30ao=Z;

%initialize vectors for PipeTSeparate2 output
Pout37alo=Z;Qout37alo=Z;Tout37alo=Z;Pout37alo=Z;Qout37a2o=Z;Tout37a2o=Z;

%initialize vectors for PipeTSeparate2c output
Pout34b1o=Z;Qout34b1o=Z;Tout34b1o=Z;Pout34b2o=Z;Qout34b2o=Z;Tout34b2o=Z;

%User defined parameters
```
Q=0.0025236; %Volumetric flow rate defined at Temperature=T
PumpPressure=5e5; %Initial Condition on the pump output pressure
Tdesired=170; %Temperature desired into Platen 1
Tdesired2=170; %Temperature desired into Platen 2
T=25; %Temperature at which the volumetric flow rate Q is defined
Tsinitial=25; %Initial temperature of the platens

for t=1:length(len)
    t=t-1;
    if t=0

%MIXING VALVE SECTION-----------------------------------------------

%Setting Initial conditions for the mixing valve 1
Thl=180; Til=Tdesired; Tcl=25; percent1=0;
%Setting the initial condition for the flow rate through platen 1 as
%half the mass flow rate into
%the system
[rho, mu, cp, k]=props(T);
[rhol, mu1, cp1, k1]=props(Til);
Qil=(Q*rho)/rhol/2;
[Qh1, Qc1]=tempratios(Til, Qil, Thl, Tcl);
Phl=0;
Pc1=0;
%Executing the mixing valve
[Poutl, Qoutl, Toutl, percentl] =
valvemixing(Qil, Til, Phl, Qh1, Thl, Tcl, percentl);

%Setting Initial conditions for the mixing valve 2
Th2=180; Ti2=Tdesired2; Tc2=25; percent2=0;
%Setting the initial condition for the flow rate through platen 1 as
%half the mass flow rate into
%the system
[rho, mu, cp, k]=props(T);
[rho2, mu2, cp2, k2]=props(Ti2);
Qi2=(Q*rho)/rho2/2;
[Qh2, Qc2]=tempratios(Ti2, Qi2, Th2, Tc2);
Ph2=0;
Pc2=0;
%Executing the mixing valve 2
[Pout2, Qout2, Tout2, percent2] =
valvemixing(Qi2, Ti2, Ph2, Qh2, Th2, Tc2, percent2);

%Executing the Pipel file after mixing valve 1 (User can define the
%diameter and length of the pipe)
[Pout3a, Qout3a, Tout3a] = Pipel(Poutl, Qoutl, Toutl, 0.3125, 0.5);

%Executing the fittings file after mixing valve 1 for an expansion in
%area
[Pout4a, Qout4a, Tout4a] = fittings(Pout3a, Qout3a, Tout3a, 11, 0.5, 1);

%Executing the flowmeter file after the expansion in area
[Pout5a, Qout5a, Tout5a] = flowmeter(Pout4a, Qout4a, Tout4a);

%Executing the fittings file after mixing valve 1 for a reduction in
%area
[Pout6a, Qout6a, Tout6a] = fittings(Pout5a, Qout5a, Tout5a, 1, 1, 0.75);
% Executing the Pipel file after mixing valve 1 (User can define the diameter and length of the pipe)
[Pout7a, Qout7a, Tout7a] = Pipel(Pout6a, Qout6a, Tout6a, 0.375, 0.75);

% Executing the fittings file after mixing valve 1 for an expansion in area
[Pout8a, Qout8a, Tout8a] = fittings(Pout7a, Qout7a, Tout7a, 11, 0.75, 1.25);

% Executing the fittings file after mixing valve 1 for a 90 degree turn
[Pout9a, Qout9a, Tout9a] = fittings(Pout8a, Qout8a, Tout8a, 2, 1.25, 1.25);

% Executing the Pipel file after mixing valve 1 (User can define the diameter and length of the pipe)
[Pout10a, Qout10a, Tout10a] = Pipel(Pout9a, Qout9a, Tout9a, 2, 1.25);

% Executing the fittings file after mixing valve 2 (User can define the diameter and length of the pipe)
[Pout3b, Qout3b, Tout3b] = Pipel(Pout2, Qout2, Tout2, 0.3125, 0.5);

% Executing the fittings file after mixing valve 2 for an expansion in area
[Pout4b, Qout4b, Tout4b] = fittings(Pout3b, Qout3b, Tout3b, 11, 0.5, 1);

% Executing the flowmeter file after the expansion in area
[Pout5b, Qout5b, Tout5b] = flowmeter(Pout4b, Qout4b, Tout4b);

% Executing the fittings file after mixing valve 2 for a reduction in area
[Pout6b, Qout6b, Tout6b] = fittings(Pout5b, Qout5b, Tout5b, 1, 1, 0.75);

% Executing the Pipel file after mixing valve 2 (User can define the diameter and length of the pipe)
[Pout7b, Qout7b, Tout7b] = Pipel(Pout6b, Qout6b, Tout6b, 0.375, 0.75);

% Executing the fittings file after mixing valve 2 for an expansion in area
[Pout8b, Qout8b, Tout8b] = fittings(Pout7b, Qout7b, Tout7b, 11, 0.75, 1.25);

% Executing the fittings file after mixing valve 2 for a 90 degree turn
[Pout9b, Qout9b, Tout9b] = fittings(Pout8b, Qout8b, Tout8b, 2, 1.25, 1.25);

% Executing the Pipel file after mixing valve 2 (User can define the diameter and length of the pipe)
[Pout10b, Qout10b, Tout10b] = Pipel(Pout9b, Qout9b, Tout9b, 2, 1.25);

% PLATEN SECTION
---------------------------------------------------------------

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%Executing the Platen 1 (User can define the initial platen temperature)
%(Assumption: same for both platens)
[Pout11a,Qout11a,Tout11a,Tsout11a] = platen2(Pout10a,Qout10a,Tout10a, Tinitial);

%Executing the Platen 2 (User can define the initial platen temperature)
%(Assumption: same for both platens)
[Pout11b,Qout11b,Tout11b,Tsout11b] = platen2(Pout10b,Qout10b,Tout10b, Tinitial);

%Executing the Pipel file after the Platen 1 (User can define the diameter and length of the pipe)
[Pout12a,Qout12a,Tout12a] = Pipel(Pout11a,Qout11a,Tout11a, 2.66, 1.25);

%Executing the fittings file after the Platen 1 for a Long Radius 90 degree elbow
[Pout13a,Qout13a,Tout13a] = fittings(Pout12a,Qout12a,Tout12a,3,1.25,1.25);

%Executing the fittings file after the Platen 1 for a reduction in area
[Pout14a,Qout14a,Tout14a] = fittings(Pout13a,Qout13a,Tout13a,1,1.25,1);

%Executing the fittings file after the Platen 1 for a 45 degree elbow
[Pout15a,Qout15a,Tout15a] = fittings(Pout14a,Qout14a,Tout14a,4,1,1);

%Executing the Pipel file after the Platen 2 (User can define the diameter and length of the pipe)
[Pout12b,Qout12b,Tout12b] = Pipel(Pout11b,Qout11b,Tout11b, 2.66, 1.25);

%Executing the fittings file after the Platen 2 for a Long Radius 90 degree elbow
[Pout13b,Qout13b,Tout13b] = fittings(Pout12b,Qout12b,Tout12b,3,1.25,1.25);

%Executing the fittings file after the Platen 2 for a reduction in area
[Pout14b,Qout14b,Tout14b] = fittings(Pout13b,Qout13b,Tout13b,1,1.25,1);

%Executing the fittings file after the Platen 2 for a 45 degree elbow
[Pout15b,Qout15b,Tout15b] = fittings(Pout14b,Qout14b,Tout14b,4,1,1);

%PIPETCOMBINE1 SECTION---------------------------------------------
%Executing the PipeTCombine1 bringing the two pipes together after the platens
%(User can define the diameter entering the PipeTCombine1)
\[\text{[Pout15, Qout15, Tout15]} = \text{PipeTCombinel(Pout15a, Qout15a, Tout15a, Pout15b, Qout15b, Tout15b, 1)};\]

\% Executing the Pipe1 file after the PipeTCombinel bringing the two pipes together after the platens
\%(User can define the diameter and length of the pipe)
\[\text{[Pout16, Qout16, Tout16]} = \text{Pipe1(Pout15, Qout15, Tout15, 0.5, 1)};\]

\% Executing the fittings file for an expansion in area
\[\text{[Pout17, Qout17, Tout17]} = \text{fittings(Pout16, Qout16, Tout16, 11, 1, 2)};\]

\% Executing the Pipe1 file after the PipeTCombinel bringing the two pipes together after the platens
\%(User can define the diameter and length of the pipe)
\[\text{[Pout18, Qout18, Tout18]} = \text{Pipe1(Pout17, Qout17, Tout17, 5.5, 2)};\]

\% Executing the fittings file after for a 90 degree elbow
\[\text{[Pout19, Qout19, Tout19]} = \text{fittings(Pout18, Qout18, Tout18, 2, 2, 2)};\]

\% Executing the Pipe1 file after the PipeTCombinel bringing the two pipes together after the platens
\%(User can define the diameter and length of the pipe)
\[\text{[Pout20, Qout20, Tout20]} = \text{Pipe1(Pout19, Qout19, Tout19, 0.5, 2)};\]

\% Executing the fittings file after for a 90 degree elbow
\[\text{[Pout21, Qout21, Tout21]} = \text{fittings(Pout20, Qout20, Tout20, 2, 2, 2)};\]

\% Executing the fittings file after for a 90 degree elbow
\[\text{[Pout22, Qout22, Tout22]} = \text{fittings(Pout21, Qout21, Tout21, 2, 2, 2)};\]

\% Y-STRAINER SECTION
\% Executing the ystrain file after the pipe
\[\text{[Pout22, Qout22, Tout22]} = \text{ystrain(Pout21, Qout21, Tout21)};\]

\% Executing the fittings file after for a 90 degree elbow
\[\text{[Pout23, Qout23, Tout23]} = \text{fittings(Pout22, Qout22, Tout22, 2, 2, 2)};\]

\% Executing the Pipe1 file
\%(User can define the diameter and length of the pipe)
\[\text{[Pout24, Qout24, Tout24]} = \text{Pipe1(Pout23, Qout23, Tout23, 0.7, 2)};\]

\% PUMP SECTION
\% Executing the Pump (User can define the flow rate desired at T=25C)
\[\text{[Pout25, Qout25, Tout25, Pdiff]} = \text{Pump1(Pout24, Qout24, Tout24)};\]

\% Executing the Pipe1 file after the Pump (User can define the diameter and length of the pipe)
\[\text{[Pout26, Qout26, Tout26]} = \text{Pipe1(Pout25, Qout25, Tout25, 1.7, 2)};\]

\% Executing the fittings file after for a 90 degree elbow
[Pout27, Qout27, Tout27] = fittings(Pout26, Qout26, Tout26, 2, 2, 2);

% %------------------------------------------------------------- ---

% %PIPETSEPARATE1 FILE------------------------------------------

% %Executing the PipeTSeparate1 (User can define the diameter entering
the PipeTSeparate1)
[Pout27a, Qout27a, Tout27a, Pout27b, Qout27b, Tout27b] =
PipeTSeparate1(Pout27, Qout27, Tout27, Qhl, Thl, Qh2, Th2, 2);

% %Executing the Hot Pipe1 file after the PipeTSeparate1 (User can define
the diameter and length of the pipe)
[Pout28a, Qout28a, Tout28a] = Pipe1(Pout27a, Qout27a, Tout27a, 2, 2);

% %Executing the fittings file after the Hot Pipe1 file for an expansion
in area
[Pout29a, Qout29a, Tout29a] =
fittings(Pout28a, Qout28a, Tout28a, 11, 2, 2.5);

% %Executing the Cold Pipe1 file after the PipeTSeparate1 (User can
define the diameter and length of the pipe)
[Pout28b, Qout28b, Tout28b] = Pipe1(Pout27b, Qout27b, Tout27b, 2, 2);

% %Executing the fittings file after the Cold Pipe1 file for a reduction
in area
[Pout29b, Qout29b, Tout29b] =
fittings(Pout28b, Qout28b, Tout28b, 1, 2, 1);

% %HOT AND COLD HEAT EXCHANGER FILES-------------------------------

% %Executing the cold heat exchanger
[Pout30b, Qout30b, Tout30b] = coldhex_new(Pout29b, Qout29b, Tout29b);

% %Executing the hot heat exchanger
[Pout30a, Qout30a, Tout30a] = hotwatt(Pout29a, Qout29a, Tout29a);

% %Executing the fittings file after the Hot Pipe1 file for a reduction
in area
[Pout31a, Qout31a, Tout31a] =
fittings(Pout30a, Qout30a, Tout30a, 1, 2.5, 2);

% %Executing the Pipe1 file hot heat exchanger (User can define the
diameter and length of the pipe)
[Pout32a, Qout32a, Tout32a] = Pipe1(Pout31a, Qout31a, Tout31a, 0.75, 2);

% %Executing the fittings file after the Hot Pipe1 file for a 90 degree
elbow
[Pout33a, Qout33a, Tout33a] =
fittings(Pout32a, Qout32a, Tout32a, 2, 2, 2);

% %Executing the fittings file after the Hot Pipe1 file for a 45 degree
elbow

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% Executing the fittings file after the Cold Pipel file for a 90 degree elbow
[Pout31b,Qout31b,Tout31b] = 
fits(Pout30b,Qout30b,Tout30b,2,1,1);

% Executing the fittings file after the Cold Pipel file for a reduction in area
[Pout32b,Qout32b,Tout32b] = 
fits(Pout31b,Qout31b,Tout31b,1,1,0.75);

% Executing the Pipe1 file cold heat exchanger (User can define the diameter and length of the pipe)
[Pout33b,Qout33b,Tout33b] = 
Pipe1(Pout32b,Qout32b,Tout32b,0.6,0.75);

% Executing the fittings file after the Cold Pipel file for an expansion in area
[Pout34b,Qout34b,Tout34b] = 
fits(Pout33b,Qout33b,Tout33b,11,0.75,1);

% Executing the fittings file after the Cold Pipel file for a 45 degree elbow
[Pout35b,Qout35b,Tout35b] = 
fits(Pout34b,Qout34b,Tout34b,4,1,1);

% PipetSeparate2
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% Executing the PipeTSeparate2 Hot (User can define the diameter entering the PipeTSeparate2)
%(User can define the diameter entering the PipeTSeparate2)
[Pout37a1,Qout37a1,Tout37a1,Qout37a2,Qout37a2,Tout37a2] = 
PipeTSeparate2(Pout37a,Qout37a,Tout37a,Qh1,Qh2,2);

% Executing the PipeTSeparate2 Cold (User can define the diameter entering the PipeTSeparate2)
%(User can define the diameter entering the PipeTSeparate2)
[Pout34b1,Qout34b1,Tout34b1,Qout34b2,Qout34b2,Tout34b2] = 
PipeTSeparate2(Pout35b,Qout35b,Tout35b,Qc1,Qc2,1);

% Executing the Pipe1 file before mixing valve 1 hot (User can define the diameter and length of the pipe)
[Pout38a1,Qout38a1,Tout38a1] = 
Pipe1(Pout37a1,Qout37a1,Tout37a1,1,2);

% Executing the Pipe1 file before mixing valve 2 hot (User can define the diameter and length of the pipe)
[Pout38a2,Qout38a2,Tout38a2] = 
Pipe1(Pout37a2,Qout37a2,Tout37a2,1,2);

% Executing the fittings file after the Hot Pipel file for a reduction in area
[Pout39a1, Qout39a1, Tout39a1] =
    fittings(Pout38a1, Qout38a1, Tout38a1, 1, 2, 0.5);

% Executing the fittings file after the Hot Pipe2 file for a reduction in area
[Pout39a2, Qout39a2, Tout39a2] =
    fittings(Pout38a2, Qout38a2, Tout38a2, 1, 2, 0.5);

% Executing the Pipel file before mixing valve 1 cold (User can define the diameter and length of the pipe)
[Pout35b1, Qout35b1, Tout35b1] =
    Pipel(Pout34b1, Qout34b1, Tout34b1, 1, 1);

% Executing the Pipel file before mixing valve 2 cold (User can define the diameter and length of the pipe)
[Pout35b2, Qout35b2, Tout35b2] =
    Pipel(Pout34b2, Qout34b2, Tout34b2, 1, 1);

% Executing the fittings file after the Cold Pipel file for a reduction in area
[Pout36bl, Qout36bl, Tout36bl] =
    fittings(Pout35bl, Qout35bl, Tout35bl, 1, 1, 0.5);

% Executing the fittings file after the Cold Pipe2 file for a reduction in area
[Pout36b2, Qout36b2, Tout36b2] =
    fittings(Pout35b2, Qout35b2, Tout35b2, 1, 1, 0.5);

% MIXING VALVE SECTION-----------------------------------------------

else

% Setting desired conditions for the mixing valve 1
percent1 = percent1;

% Executing the mixing valve 1
[Pout1, Qout1, Tout1, percent1] =
    valvemixing(Qi1, Ti1, Pout39a1, Qout39a1, Tout39a1, Pout36b1, Qout36b1, Tout36b1, percent1);

% Setting desired conditions for the mixing valve 2
percent2 = percent2;

% Executing the mixing valve 2
[Pout2, Qout2, Tout2, percent2] =
    valvemixing(Qi2, Ti2, Pout39a2, Qout39a2, Tout39a2, Pout36b2, Qout36b2, Tout36b2, percent2);

% Executing the Pipel file after mixing valve 1 (User can define the diameter and length of the pipe)
[Pout3a, Qout3a, Tout3a] =
    Pipel(Pout1, Qout1, Tout1, 0.3125, 0.5);

% Executing the fittings file after mixing valve 1 for an expansion in area
[Pout4a, Qout4a, Tout4a] =
    fittings(Pout3a, Qout3a, Tout3a, 11, 0.5, 1);
% Executing the flowmeter file after the expansion in area
\[ P_{out5a}, Q_{out5a}, T_{out5a} = \text{flowmeter}(P_{out4a}, Q_{out4a}, T_{out4a}); \]

% Executing the fittings file after mixing valve 1 for a reduction in area
\[ P_{out6a}, Q_{out6a}, T_{out6a} = \text{fittings}(P_{out5a}, Q_{out5a}, T_{out5a}, 1, 1, 0.75); \]

% Executing the Pipel file after mixing valve 1 (User can define the diameter and length of the pipe)
\[ P_{out7a}, Q_{out7a}, T_{out7a} = \text{Pipel}(P_{out6a}, Q_{out6a}, T_{out6a}, 0.375, 0.75); \]

% Executing the fittings file after mixing valve 1 for an expansion in area
\[ P_{out8a}, Q_{out8a}, T_{out8a} = \text{fittings}(P_{out7a}, Q_{out7a}, T_{out7a}, 11, 0.75, 1.25); \]

% Executing the fittings file after mixing valve 1 for a 90 degree turn
\[ P_{out9a}, Q_{out9a}, T_{out9a} = \text{fittings}(P_{out8a}, Q_{out8a}, T_{out8a}, 2, 1.25, 1.25); \]

% Executing the Pipel file after mixing valve 1 (User can define the diameter and length of the pipe)
\[ P_{out10a}, Q_{out10a}, T_{out10a} = \text{Pipel}(P_{out9a}, Q_{out9a}, T_{out9a}, 2, 1.25); \]

% Executing the Pipel file after mixing valve 2 (User can define the diameter and length of the pipe)
\[ P_{out3b}, Q_{out3b}, T_{out3b} = \text{Pipel}(P_{out2}, Q_{out2}, T_{out2}, 0.3125, 0.5); \]

% Executing the fittings file after mixing valve 2 for an expansion in area
\[ P_{out4b}, Q_{out4b}, T_{out4b} = \text{fittings}(P_{out3b}, Q_{out3b}, T_{out3b}, 11, 0.5, 1); \]

% Executing the flowmeter file after the expansion in area
\[ P_{out5b}, Q_{out5b}, T_{out5b} = \text{flowmeter}(P_{out4b}, Q_{out4b}, T_{out4b}); \]

% Executing the fittings file after mixing valve 21 for a reduction in area
\[ P_{out6b}, Q_{out6b}, T_{out6b} = \text{fittings}(P_{out5b}, Q_{out5b}, T_{out5b}, 1, 1, 0.75); \]

% Executing the Pipel file after mixing valve 2 (User can define the diameter and length of the pipe)
\[ P_{out7b}, Q_{out7b}, T_{out7b} = \text{Pipel}(P_{out6b}, Q_{out6b}, T_{out6b}, 0.375, 0.75); \]

% Executing the fittings file after mixing valve 2 for an expansion in area
\[ P_{out8b}, Q_{out8b}, T_{out8b} = \text{fittings}(P_{out7b}, Q_{out7b}, T_{out7b}, 11, 0.75, 1.25); \]

% Executing the fittings file after mixing valve 2 for a 90 degree turn
\[ P_{out9b}, Q_{out9b}, T_{out9b} = \text{fittings}(P_{out8b}, Q_{out8b}, T_{out8b}, 2, 1.25, 1.25); \]

% Executing the Pipel file after mixing valve 2 (User can define the diameter and length of the pipe)
\[ P_{out10b}, Q_{out10b}, T_{out10b} = \text{Pipel}(P_{out9b}, Q_{out9b}, T_{out9b}, 2, 1.25); \]
% Executing the Platen 1 (User can define the initial platen temperature)
%(Assumption: same for both platens)
[Pout11a,Qout11a,Tout11a,Tsout11a] = platen2(Pout10a,Qout10a,Tout10a, Tinitial);

% Executing the Platen 2 (User can define the initial platen temperature)
%(Assumption: same for both platens)
[Pout11b,Qout11b,Tout11b,Tsout11b] = platen2(Pout10b,Qout10b,Tout10b, Tinitial);

% Executing the Pipel file after the Platen 1 (User can define the diameter and length of the pipe)
[Pout12a,Qout12a,Tout12a] = Pipel(Pout11a,Qout11a,Tout11a, 2.66, 1.25);

% Executing the fittings file after the Platen 1 for a Long Radius 90 degree elbow
[Pout13a,Qout13a,Tout13a] = fittings(Pout12a,Qout12a,Tout12a,3,1.25,1.25);

% Executing the fittings file after the Platen 1 for a reduction in area
[Pout14a,Qout14a,Tout14a] = fittings(Pout13a,Qout13a,Tout13a,1,1.25,1);

% Executing the fittings file after the Platen 1 for a 45 degree elbow
[Pout15a,Qout15a,Tout15a] = fittings(Pout14a,Qout14a,Tout14a,4,1,1);

% Executing the Pipel file after the Platen 2 (User can define the diameter and length of the pipe)
[Pout12b,Qout12b,Tout12b] = Pipel(Pout11b,Qout11b,Tout11b, 2.66, 1.25);

% Executing the fittings file after the Platen 2 for a Long Radius 90 degree elbow
[Pout13b,Qout13b,Tout13b] = fittings(Pout12b,Qout12b,Tout12b,3,1.25,1.25);

% Executing the fittings file after the Platen 2 for a reduction in area
[Pout14b,Qout14b,Tout14b] = fittings(Pout13b,Qout13b,Tout13b,1,1.25,1);

% Executing the fittings file after the Platen 2 for a 45 degree elbow
[Pout15b,Qout15b,Tout15b] = fittings(Pout14b,Qout14b,Tout14b,4,1,1);

% Executing the Platen section
%---------------------------------------------------------------
%PIPETCOMBINE1 SECTION

%Executing the PipeTCombine1 bringing the two pipes together after the platens
%(User can define the diameter entering the PipeTCombine1)
    [Pout15,Qout15,Tout15] = PipeTCombine1(Pout15a,Qout15a,Tout15a,
                                          Pout15b,Qout15b,Tout15b, 1);

%Executing the Pipel file after the PipeTCombine1 bringing the two pipes together after the platens
%(User can define the diameter and length of the pipe)
    [Pout16,Qout16,Tout16] = Pipel(Pout15,Qout15,Tout15,0.5,1);

%Executing the fittings file for an expansion in area
    [Pout17,Qout17,Tout17] = fittings(Pout16,Qout16,Tout16,11,1,2);

%Executing the Pipel file after the PipeTCombine1 bringing the two pipes together after the platens
%(User can define the diameter and length of the pipe)
    [Pout18,Qout18,Tout18] = Pipel(Pout17,Qout17,Tout17,5.5,2);

%Executing the fittings file after for a 90 degree elbow
    [Pout19,Qout19,Tout19] = fittings(Pout18,Qout18,Tout18,2,2,2);

%Executing the Pipel file after the PipeTCombine1 bringing the two pipes together after the platens
%(User can define the diameter and length of the pipe)
    [Pout20,Qout20,Tout20] = Pipel(Pout19,Qout19,Tout19,0.5,2);

%Executing the fittings file after for a 90 degree elbow
    [Pout21,Qout21,Tout21] = fittings(Pout20,Qout20,Tout20,2,2,2);

%Y-STRAINER SECTION

%Executing the ystrain file after the pipe
    [Pout22,Qout22,Tout22] = ystrain(Pout21,Qout21,Tout21);

%Executing the fittings file after for a 90 degree elbow
    [Pout23,Qout23,Tout23] = fittings(Pout22,Qout22,Tout22,2,2,2);

%Executing the Pipel file
%(User can define the diameter and length of the pipe)
    [Pout24,Qout24,Tout24] = Pipel(Pout23,Qout23,Tout23,0.7,2);

%PUMP SECTION

%Executing the Pump (User can define the flow rate desired at T=25C)
    [Pout25,Qout25,Tout25,Pdiff] = Pump1(Pout24,Qout24,Tout24);
% Executing the Pipe1 file after the Pump (User can define the diameter and length of the pipe)
\[ \text{[Pout26, Qout26, Tout26]} = \text{Pipe1}(\text{Pout25, Qout25, Tout25, 1.7, 2}); \]

% Executing the fittings file after for a 90 degree elbow
\[ \text{[Pout27, Qout27, Tout27]} = \text{fittings}(\text{Pout26, Qout26, Tout26, 2, 2, 2}); \]

% PIPESEPARATE1 FILE
% Executing the PipeTSeparate1 (User can define the diameter entering the PipeTSeparate1)
\[ \text{[Pout27a, Qout27a, Tout27a, Pout27b, Qout27b, Tout27b]} = \text{PipeTSeparate1}(\text{Pout27, Qout27, Tout27, Qhl, Thl, Qh2, Th2, 2}); \]

% Executing the Hot Pipel file after the PipeTSeparate1 (User can define the diameter and length of the pipe)
\[ \text{[Pout28a, Qout28a, Tout28a]} = \text{Pipe1}(\text{Pout27a, Qout27a, Tout27a, 2, 2}); \]

% Executing the Hot Pipel file after the Hot Pipel file for an expansion in area
\[ \text{[Pout29a, Qout29a, Tout29a]} = \text{fittings}(\text{Pout28a, Qout28a, Tout28a, 11, 2, 2.5}); \]

% Executing the Cold Pipel file after the PipeTSeparate1 (User can define the diameter and length of the pipe)
\[ \text{[Pout28b, Qout28b, Tout28b]} = \text{Pipe1}(\text{Pout27b, Qout27b, Tout27b, 2, 2}); \]

% Executing the fittings file after the Cold Pipel file for a reduction in area
\[ \text{[Pout29b, Qout29b, Tout29b]} = \text{fittings}(\text{Pout28b, Qout28b, Tout28b, 1, 2, 1}); \]

% HOT AND COLD HEAT EXCHANGER FILES
% Executing the cold heat exchanger
\[ \text{[Pout30b, Qout30b, Tout30b]} = \text{coldhex_new}(\text{Pout29b, Qout29b, Tout29b}); \]

% Executing the hot heat exchanger
\[ \text{[Pout30a, Qout30a, Tout30a]} = \text{hotwatt}(\text{Pout29a, Qout29a, Tout29a}); \]

% Executing the fittings file after the Hot Pipel file for a reduction in area
\[ \text{[Pout31a, Qout31a, Tout31a]} = \text{fittings}(\text{Pout30a, Qout30a, Tout30a, 1, 2.5, 2}); \]

% Executing the Pipel file hot heat exchanger (User can define the diameter and length of the pipe)
\[ \text{[Pout32a, Qout32a, Tout32a]} = \text{Pipe1}(\text{Pout31a, Qout31a, Tout31a, 0.75, 2}); \]

% Executing the fittings file after the Hot Pipel file for a 90 degree elbow
%Executing the fittings file after the Hot Pipe1 file for a 45 degree elbow
[Pout37a,Qout37a,Tout37a] = fittings(Pout33a,Qout33a,Tout33a,4,2,2);

%Executing the fittings file after the Cold Pipe1 file for a 90 degree elbow
[Pout31b,Qout31b,Tout31b] = fittings(Pout30b,Qout30b,Tout30b,2,1,1);

%Executing the fittings file after the Cold Pipe1 file for a reduction in area
[Pout32b,Qout32b,Tout32b] = fittings(Pout31b,Qout31b,Tout31b,1,1,0.75);

%Executing the Pipe1 file cold heat exchanger (User can define the diameter and length of the pipe)
[Pout33b,Qout33b,Tout33b] = Pipel(Pout32b,Qout32b,Tout32b,0.6,0.75);

%Executing the fittings file after the Cold Pipe1 file for an expansion in area
[Pout34b,Qout34b,Tout34b] = fittings(Pout33b,Qout33b,Tout33b,11,0.75,1);

%Executing the fittings file after the Cold Pipe1 file for a 45 degree elbow
[Pout35b,Qout35b,Tout35b] = fittings(Pout34b,Qout34b,Tout34b,4,1,1);

%PIPETSEPARATE2--------------------------------------------------------
%Executing the PipeTSeparate2 Hot (User can define the diameter entering the PipeTSeparate2)
%User can define the diameter entering the PipeTSeparate2)
[Pout37al,Qout37al,Tout37al,Pout37a2,Qout37a2,Tout37a2] = PipeTSeparate2(Pout37a,Qout37a,Tout37a,Qhl,Qh2,2);

%Executing the PipeTSeparate2 Cold (User can define the diameter entering the PipeTSeparate2)
%User can define the diameter entering the PipeTSeparate2)
[Pout34bl,Qout34bl,Tout34bl,Pout34b2,Qout34b2,Tout34b2] = PipeTSeparate2(Pout35b,Qout35b,Tout35b,Qcl,Qc2,1);

%Executing the Pipe1 file before mixing valve 1 hot (User can define the diameter and length of the pipe)
[Pout38a1,Qout38a1,Tout38a1] = Pipel(Pout37a1,Qout37a1,Tout37a1,1,2);

%Executing the Pipe1 file before mixing valve 2 hot (User can define the diameter and length of the pipe)
%Executing the fittings file after the Hot Pipel file for a reduction in area
[Pout39a1,Qout39a1,Tout39a1] =
fittings(Pout38a1,Qout38a1,Tout38a1,1,2,0.5);

%Executing the fittings file after the Hot Pipe2 file for a reduction in area
[Pout39a2,Qout39a2,Tout39a2] =
fittings(Pout38a2,Qout38a2,Tout38a2,1,2,0.5);

%Executing the Pipel file before mixing valve 1 cold (User can define the diameter and length of the pipe)
[Pout35b1,Qout35b1,Tout35b1] =
Pipel(Pout34b1,Qout34b1,Tout34b1,1,1);

%Executing the Pipel file before mixing valve 2 cold (User can define the diameter and length of the pipe)
[Pout35b2,Qout35b2,Tout35b2] =
Pipel(Pout34b2,Qout34b2,Tout34b2,1,1);

%Executing the fittings file after the Cold Pipel file for a reduction in area
[Pout36bl,Qout36bl,Tout36bl] =
fittings(Pout35bl,Qout35bl,Tout35bl,1,1,0.5);

%Executing the fittings file after the Cold Pipe2 file for a reduction in area
[Pout36b2,Qout36b2,Tout36b2] =
fittings(Pout35b2,Qout35b2,Tout35b2,1,1,0.5);

% vectors for mixing valve output 1
Pout1o(count)=Pout1; Qout1o(count)=Qout1; Tout1o(count)=Tout1;
percent1o(count)=percent1;

% vectors for mixing valve output 1
Pout2o(count)=Pout2; Qout2o(count)=Qout2; Tout2o(count)=Tout2;
percent2o(count)=percent2;

% vectors for platen2 output 1
Pout11ao(count)=Pout11a; Qout11ao(count)=Qout11a;
Tout11ao(count)=Tout11a; Tsout11ao(count)=Tsout11a;

% vectors for platen2 output 2
Pout11bo(count)=Pout11b; Qout11bo(count)=Qout11b;
Tout11bo(count)=Tout11b; Tsout11bo(count)=Tsout11b;

% vectors for other pipeTcombinel output
Pout15o(count)=Pout15; Qout15o(count)=Qout15; Tout15o(count)=Tout15;

% vectors for pump1 output
Pout25o(count)=Pout25; Qout25o(count)=Qout25; Tout25o(count)=Tout25;
Pdiffo(count)=Pdiff;

%vectors for PipeTSeparate1 output
Pout27ao(count)=Pout27a; Qout27ao(count)=Qout27a;
Tout27ao(count)=Tout27a; Pout27bo(count)=Pout27b;
Qout27bo(count)=Qout27b; Tout27bo(count)=Tout27b;

%vectors for coldhex_new output
Pout30bo(count)=Pout30b; Qout30bo(count)=Qout30b;

%vectors for hotwatt output
Pout30ao(count)=Pout30a; Qout30ao(count)=Qout30a;
Tout30ao(count)=Tout30a;

%vectors for PipeTSeparate2 output
Pout37alo(count)=Pout37a1; Tout37alo(count)=Tout37a1;
Pout37a2o(count)=Pout37a2; Qout37a2o(count)=Qout37a2;
Tout37a2o(count)=Tout37a2; Qout37alo(count)=Qout37a1;

%vectors for PipeTSeparate2c output
Pout34blo(count)=Pout34b1; Qout34blo(count)=Qout34b1;
Tout34blo(count)=Tout34b1; Pout34b2o(count)=Pout34b2;
Qout34b2o(count)=Qout34b2; Tout34b2o(count)=Tout34b2;

count=count+1;
end

figure(1)
title('Mixing Valve 1');
set(1,'Name','Mixing Valve 2');
subplot(4,1,1);plot(len,Pout10);title('Mixing Valve Output 1');ylabel('Pressure (Pa)');subplot(4,1,2);plot(len,Qout10);ylabel('Flow rate (m^3/s)');
subplot(4,1,3);plot(len,Tout10);ylabel('Temperature (C)');subplot(4,1,4);plot(len,percent10);ylabel('Valve Position (%)');

figure(2)
title('Mixing Valve 2');
set(2,'Name','Mixing Valve 2');
subplot(4,1,1);plot(len,Pout20);title('Mixing Valve Output 2');ylabel('Pressure (Pa)');subplot(4,1,2);plot(len,Qout20);ylabel('Flow rate (m^3/s)');
subplot(4,1,3);plot(len,Tout20);ylabel('Temperature (C)');subplot(4,1,4);plot(len,percent20);ylabel('Valve Position (%)');

figure(3)
title('Platen Output 1');
set(3,'Name','Platen Output 1');
subplot(4,1,1);plot(len,Pout11ao);title('Platen Output');ylabel('Pressure

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D.2 Paratherm Fluid Properties

This function obtains the properties of Paratherm MR given a certain fluid temperature.

```matlab
function [rho, mu, cp, k] = props(T)
%Sets properties of Paratherm MR at given Temp in deg C for T:
0 <= T <= 250
rho = -0.80441 * T + 823.69;
mu = 0.001 * (1.0945E-12 * T^6 - 9.6662E-10 * T^5 + 3.4202E-07 * T^4 - 6.2338E-05 * T^3 + 6.3028E-03 * T^2 - 3.5758E-01 * T + 1.0649E+01);
cp = 2.713 * T + 2131.8;
k = -8.714e-5 * T + 1.4594;
```
D.3 Calculates the hot and cold flows

This function calculates the hot and cold flow rates given a specified mixed outlet flow.

function \([Qh,Qc]=\text{tempratios}(Tp,Qp,\text{Tc})\)
% Calculates flowrates of hot and cold sides to produce
% desired temperature and flow, accounting for changes in props
% \(Qp=\text{flow rate through platen}\) \(Tp=\text{temp of fluid to platen}\)
% Get properties
[rhoc,muc,cpc,kc]=props(Tc);
[rhoh,muh,cph,kh]=props(Th);
[rhop,mup,cpp,kp]=props(Tp);
% Calculate flowrates
Qh=(Qp*rhop*(cpc*Tc-cpp*Tp))/(rhoh*(cpc*Tc-cph*Th));
Qc=(Qp*rhop-Qh*rhoh)/rhoc;
\text{tempratios}=[Qh,Qc];

D.4 Mixing Valve

This file does not assume a pressure drop across the mixing valve.

function \([\text{Pout},Qout,\text{Tout},\text{percent}]=\text{valvemixing}(Qi,Ti,Ph,Qh,\text{Th},Pc,Qc,\text{Tc},\text{percent})\)
global t
if t==0
    [rhoc,muc,cpc,kc]=props(Tc);
    [rhoh,muh,cph,kh]=props(Th);
    Qout=Qi;
    Tout=Ti;
    [rhoi,mui,cpi,ki]=props(Ti);
    Qout=Qout/6.31667e-5;
    CV=1000;
    deltaP=(rhoi/1000)/((CV/Qout)^2);
    deltaP=deltaP*6894.75729;
    Po=min(Ph,Pc);
    Pout=Po-deltaP;
    Qout=Qout*6.31667e-5;
    percent=((rhoh*Qh)/(rhoi*Qi))*100;
% The valve position established from the initial conditions will be
% used to calculate the pressure output
% for the proceeding time steps
else
    [rhoc,muc,cpc,kc]=props(Tc);
    [rhoh,muh,cph,kh]=props(Th);
    Qout=Qi;
    Tout=Ti;
    [rhoi,mui,cpi,ki]=props(Ti);
    Qout=Qout/6.31667e-5;
    CV=1000;
    deltaP=(rhoi/1000)/((CV/Qout)^2);
    deltaP=deltaP*6894.75729;
    Po=min(Ph,Pc);
    Pout=Po-deltaP;
    Qout=Qout*6.31667e-5;
end

Pout=Po-deltaP;
Qout=Qout*6.31667e-5;
percent=((rhoh*Qh)/(rhoi*Qi))*100;

end

D.5 Straight Pipe

This function calculates the pressure drop across a straight pipe.

function [Po,Qo,To] = Piple(Pin,Qin,Tm,length,diameterin)

global t

%User Defined Parameters
D=diameterin*.0254;
L=(length*12)*.0254;
[rho,mu,cp,k]=props(Tm);

%Flow
V=Qin/((pi*D^2)/4);
mdot=Qin*rho;

%Dimensionless quantities
Re=V*D*rho/mu;
Pr=cp*mu/k;
if Re<2300
    f=64/Re;
    Nu=3.66;
else
    f=(.790*log(Re)-1.64)^-2;
    Nu=((f/8)*(Re-1000)*Pr)/(1+12.7*(f/8)^.5*(Pr^(2/3)-1));
end

%Heat transfer
h=Nu*k/D;

%Find pressure drop
Pdrop=f*(L/D)*V^2*(rho/2);

%Assign block output
Po=Pin-Pdrop;
Qo=Qin;
To=Tm;

D.6 Pipe Fittings

This file is called upon to calculate the pressure drops across a variety of pipe fittings, including 90° elbows, 45° elbows, tees, and ball valves.

function [Po,Qo,To] = fittings(Pin,Qin,Tm,type,diameterin,diameterout)
Area_in = \pi \left( \frac{\text{diameter}_{\text{in}}}{12} \right)^2; \\
Area_out = \pi \left( \frac{\text{diameter}_{\text{out}}}{12} \right)^2; \\
Area_{\text{Ratio}} = \frac{\text{Area}_{\text{out}}}{\text{Area}_{\text{in}}}; \\
switch type \\
case 1 \\
% Pipe is being reduced from diameter_{\text{in}} to diameter_{\text{out}} \\
[K_l] = \text{loss}(Area_{\text{Ratio}}); \\
case 2 \\
% Regular elbow 90 degrees, threaded \\
K_l = 1.5; \\
case 3 \\
% Long radius 90 degrees, threaded \\
K_l = 0.7; \\
case 4 \\
% Regular 45 degrees, threaded \\
K_l = 0.4; \\
case 5 \\
% 180 degree bend, threaded \\
K_l = 1.5; \\
case 6 \\
% Tees line flow, threaded \\
K_l = 0.9; \\
case 7 \\
% Branch flow, threaded \\
K_l = 2.0; \\
case 8 \\
% Ball valve, fully open \\
K_l = 0.05; \\
case 9 \\
% Ball valve, 1/3 closed \\
K_l = 5.5; \\
case 10 \\
% Ball valve, 2/3 closed \\
K_l = 210; \\
case 11 \\
% Pipe is being expanded from diameter_{\text{in}} to diameter_{\text{out}} \\
K_l = \left( 1 - \frac{1}{\text{Area}_{\text{Ratio}}} \right)^2; \\
otherwise \\
error(["Unhandled type = ",num2str(K_l)]); \\
end \\
g = 32.2; \\
Ql = Qin * 264.172 * 60; \\
Q = Ql / (60) * (0.13368); \\
V = Q / min(Area_{\text{in}}, Area_{\text{out}}); \\
HL = K_l * (V^2) / (2 * g); \\
[rho, mu, cp, k] = props(Tm); \\
rhoe = rho * 2.2 * (1/35.31467); \\
Pressuredrop = HL * rhoe * (0.006944444); \\
Pdrop = Pressuredrop * 6894.75729; \\
Po = Pin - Pdrop; \\
To = Tm; \\
Qo = Qin;
D.7 Flow meter

This file calculates the pressure drop across the flow meter. The information is found off flow meter data sheets.

\[
\text{function } [P_0, Q_0, T_0] = \text{flowmeter}(P_{\text{in}}, Q_{\text{in}}, T_{\text{m}}) \\
Q_0 = Q_{\text{in}}; \\
T_0 = T_{\text{m}}; \\
P_0 = P_{\text{in}} - 8 \times 6894.75729; \quad \text{% A little overestimate on the pressure drop across a 1" flowmeter}
\]

D.8 Platen Model

This file is provided by Matthew Dirckx.

\[
\text{function } [P_{\text{out}}, Q_{\text{out}}, T_{\text{out}}, T_{\text{new}}] = \text{platen2}(P_{\text{in}}, Q, T_{\text{m}}, T_{\text{s}}) \\
\text{global } t \\
\text{global } \text{interval} \\
\text{global } \text{finalt} \\
[rho, mu, cp, k] = \text{props}(T_{\text{m}}); \\
D = 0.003175; \\
L = 0.132588; \\
\% Flow 
V = Q / (18 \times \pi / 4 \times D^2); \\
mdot = Q \times \rho; \\
\% Dimensionless quantities 
Re = V \times D \times \rho / \mu; \\
Pr = cp \times \mu / k; \\
\text{if } Re < 2300 
\quad f = 64 / Re; \\
\quad Nu = ((f / 8) \times (Re - 1000) \times Pr) / (1 + 12.7 \times (f / 8)^{0.5} \times (Pr^{2/3} - 1)); 
\text{else} 
\quad f = (0.790 \times \log(Re) - 1.64)^{-2}; \\
\quad Nu = ((f / 8)^2 \times (Re - 1000) \times Pr) / (1 + 12.7 \times (f / 8)^0.5 \times (Pr^{2/3} - 1)); 
\text{end} \\
\% Heat transfer 
h = Nu \times k / D; \\
T_{\text{out}} = (T_{\text{m}} - T_{\text{s}}) \times \exp(-h \times (pi \times D \times L) / (cp \times mdot)) + T_{\text{s}}; \\
[rhoo, muo, cpo, ko] = \text{props}(T_{\text{out}}); \\
Q_{\text{out}} = (Q \times \rho) / rhoo; \\
\% Find pressure drop 
Qi = Q / 18; \\
vi = Qi / ((1/8) \times 2.54)^2; \\
T_{\text{m}}: 
\text{a} = [0.007991664436308; -15.694208783140260; -1.866667973048096; 297.997934215463720; 92.787840163674872; 1309.03754027400; 906.13250733087450; 3178.791014591897200; 5954.364606136258800]; \\
P_{\text{drop}} = (a(1) \times T_{\text{m}}^4) + (a(2) \times vi^4) + (a(3) \times T_{\text{m}}^3) + (a(4) \times vi^3) + (a(5) \times T_{\text{m}}^2) + (a(6) \times vi^2) + (a(7) \times T_{\text{m}}) + (a(8) \times vi) + a(9); 
\]
\[ P_{\text{drop}} = 0.9274400765 \cdot T_m^2 + 1371.8412623064 \cdot v_i^2 + 2223.5061065699 \cdot v_i + 30874.9913112640 \]

\[ P_{\text{drop}} = f \cdot L / D \cdot V^2 \cdot \rho / 2; \]

\[ P_{\text{out}} = P_{\text{in}} - P_{\text{drop}}; \]

\[ \text{ConvA} = L \cdot \pi \cdot D \cdot 18; \]

\[ Q = h \cdot \text{ConvA} \cdot (T_m - T_s); \]

\[ T_m = 1000; \]

\[ dT_s = Q / T_m; \]

\[ T_{\text{new}} = T_s + dT_s \cdot (\text{finalt} - 1) / (\text{interval} - 1); \]

### D.9 Combining Flows

This file calculates the result of two flows combining into one.

function \([P_o, Q_o, T_o] = \text{PipeTCombinel}(P_h, Q_h, T_h, P_c, Q_c, T_c, \text{diameterin})\)

global t

[rhoh, muh, cph, kh] = props(T_h);
[rhoc, muc, cpc, kcl] = props(T_c);

\% User Defined Parameters
Di = diameterin * 0.0254;

\% Assigns the output temperatures (same as the input)
rhoo = ((rhoc * Qc) / (rhoc * Qc + rhoh * Qh)) * rhoc + ((rhoh * Qh) / (rhoc * Qc + rhoh * Qh)) * rhoh;
cpo = ((rhoc * Qc) / (rhoc * Qc + rhoh * Qh)) * cpc + ((rhoh * Qh) / (rhoc * Qc + rhoh * Qh)) * cph;
Qo = (Qh * rhoh + Qc * rhoc) / rhoo;
To = ((rhoc * Qc + cph * Tc + rhoh * Qh * cph * Th) / (rhoh * Qh * cph + rhoc * Qc * cpc));
Po = min(Ph, Pc);

### D.10 Y-Strainer

This file calculates the pressure drop across a 2" Y-strainer.

function \([P_o, Q_o, T_o] = \text{ystrain}(P_i, Q_i, T_m)\)

\[ Q_o = Q_i; \]

\[ T_o = T_m; \]

\[ P_o = P_i - 2 \cdot 6894.75729; \quad \% \text{A little overestimate on the pressure drop across a 2" Y-strainer} \]

### D.11 Positive Displacement Pump
function \[Pi,Qi,Tfi,Pdiff\] = Pumpl\(P, Q, Tf\)\n
%Pump performance curve is a function of the selected Speed, ImpDiameter, and Temperature

%The flow rate is set by the user
Qi=Q;

%The initial pressure out of the
%The temperature of the fluid pump is set to 0, so that the negative of the output pressure of the system is
%the total system pressure required for the particular flow rate set by the user.
if t==0
    Pi=PumpPressure;
else
    Pi=PumpPressure-P;
end
PumpPressure=Pi;

%Fluid into the pump is set as the temperature of the fluid coming into the expansion
%tank (modeled the same as the temperature leaving the platens as there is assumed to be no heat loss after the fluid exits the platens)
Tfi=Tf;
Pdiff=Pi-P;

D.12 Separation of Flows 1

This file calculates the separation of fluid flows after the pump outlet.

function \[Ph,Qh,Tfh,Phc,Qc,Tfc\] = PipeTSeparate\(Pin, Q, Tm, Qh1, Tfh1, Qh2, Tfh2, diameterin\)\n
%User Defined Parameters
Di=diameterin*.0254;

%Assigns the output temperatures (same as the input)
Tfh=Tm;
Tfc=Tm;

[rhoh2,muh2,cph2,kh2]=props(Tfh2);
[rhohl,muhl,cphl,khl]=props(Tfh1);
Qh=((rhoh2*Qh2)+(rhohl*Qhl))/rho;
Qc=Q-Qh;
Ph=Pin;
Pc=Pin;
D.13 Cold Heat Exchanger

This file uses information obtained from Maxchanger, the manufacturer of the cold heat exchanger.

```matlab
function [Pout,Qout,Tout] = coldhex_new(Pin, Qin, Tin)
global t
% Pdrop and Tout from functions fitted to data provided by maxchanger
Pdrop=1.6481E10*Qin^2-2.2281E6*Qin;
[rhoi,mui,cpi,ki]=props(Tin);
[rhoo,muo,cpo,ko]=props(Tout);
Qout=Qin*rhoi/rhoo;
Pout=Pin-Pdrop;
```

D.14 Hot Heat Exchanger

```matlab
function [Pout,Qout,Tout]=hotwatt(Pin,Qin,Tin)

watt=14400;
[rho,mu,cp,k]=props(Tin);
Tout=(watt/(Qin*rho*cp)+Tin);

[rhoi,mui,cpi,ki]=props(Tin);
[rhoo,muo,cpo,ko]=props(Tout);
Qout=Qin*rhoi/rhoo;

% Added as a place holder until the actual pressure behavior of the hot heat exchanger can be established
Pdrop=1.6481E10*Qin^2-2.2281E6*Qin;
Pout=Pin-Pdrop;
Pout=Pin;
```

D.15 Separation of Flows 2

This file separates the fluid flows after the hot and cold heat exchangers.

```matlab
function [P1,Q1,Tf1,P2,Q2,Tf2] = PipeTSeparate2(Pin, Q, Tm, Qin1, Qin2, diameterin)
global t

[rho,mu,cp,k]=props(Tm);

% User Defined Parameters
Di=diameterin*.0254;

% Assigns the output temperatures (same as the input)
Tf1=Tm;
Tf2=Tm;
```
Calculates the flow rate into the two lines going into either the hot or cold valve

\[ Q_1 = Q_{in1}; \]
\[ Q_2 = Q_{in2}; \]

\[ P_1 = P_{in}; \]
\[ P_2 = P_{in}; \]
E Miscellaneous

E.1 Expansion Tank Sizing

- System Volume estimate
  manifolds = (\pi/4) \times 1.5^2 \times 7 \times q;
  platens = (\pi/4) \times 0.125^2 \times 4.625 \times 18 \times 2;
  coldhx = 0.5 \times 24 \times 4 \times 4;
  hothx = (\pi/4) \times 8^2 \times 33 - 36 \times (\pi/4) \times (0.475)^2 \times 33;
  pipe = \pi \times (0.622/2)^2 \times 110.496 + \pi \times (0.824/2)^2 \times 9 + \pi \times (1.049/2)^2 \times 6 + \pi \times (1.38/2)^2 \times 111.84 + \pi \times (2.067/2)^2 \times 148.8;
  valves = 2 \times \pi \times (1/2)^2 \times 8;
  pump = (1/4) / 0.004329;
  system = manifolds + platens + coldhx + hothx + pipe + valves + pump;
  expansion = system \times (807.6 - 680) / (0.75 \times 680 - 0.25 \times 807.6);
  system = expansion + system;
  system = system \times 0.004329;
  thermcoef = (150 - 30) \times 0.0007822;
  exptank = thermcoef \times system \times 2;
E.2 Paratherm System Guide

From Paratherm’s technical data website:

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**Technical Data**

**Recommended Hot Oil System Components**

In designing and constructing a thermal oil system, attention must be paid to the selection of appropriate components. If care is not taken, poor operations, system failure and fire can result.

**Pipe**

Welded and flanged throughout. Specify schedule CS-ASTM-A-106 Grade II seamless carbon steel tubing. We strongly recommend the use of materials and methods to minimize entry of weld spatter and slag into the pipe, and to assure strong and leak-free welds. Pipe should be free of mill scale, welding flux, corrosion and lacquers.

**Flanges/Fittings**

Must be rated for 900°F (482°C) service. For continuous service we recommend 300 ft. forged steel, Schedule 40 butt-weld, Grade B, and American Society for Testing Materials (ASTM A-106).

**Studs/Nuts**

Continuous threaded, alloy steel (ASTM A-193, Grade B) with heavy hex nuts (ASTM A-194, Grade 8).

**Gaskets/Packings**

Flange gaskets: Spiral wound type (Flexelite™, Garlock Pleatseal™, or equivalent).

Valve stem packing: Flange of the burnished graphite foil (Saffol™, Faclon™ or equivalent).

Pump packing: End non-erodible rings of braided carbon yarn (Pulnato™, Garlock™, 491 or equivalent), center rings of teflon-graphite (Tefgroid™, Faclon™ or equivalent).

**Elastomeric O-Rings/Seals**

For service to 400°F (204°C). Fecralasticor: Viton™, Fluoro™ or equivalent.

For higher temperature service, specified for fluoro-elasticor rubber: To 600°F (315°C), Chemetall™ or equivalent.

To 600°F (260°C), Ziltek™ or equivalent.

To 600°F (315°C) Kalrez™ or equivalent.

**Insulation**

2" thick 500°F (260°C) rated cellular glass (Fiberglass Corner Fleece™ or equivalent). Heat loss value not to exceed 30 BTU/hr.

**Valves**

300 ft. cast or forged steel, or nodular (ductile) iron rated for 600°F (315°C) continuous service maximum, with steel or stainless steels in stainless steel ratings (Worthington™ 916-W1 or equivalent, Worthington™ 4446-D or equal ball valves—specify for thermal oil applications). For optimum service, ball valves may be considered (AR7™ or equivalent).

**Pressure Gauges/Thermometers**

Rating to 30 psig, 600°F (316°C). Temperature range of 300°F to 600°F. Thermocouples should be calibrated to provide accurate readings in this range.

**Expansion Joints**

We suggest expansion joints for an expansion growth of 3" per 100 ft. minimum. Both loose and joint expansion devices are acceptable. Either must be high-temperature rated and must be considered part of the piping system.

**Strainers**

While many systems are supplied with 80 mesh mechanical screen (capable of forged or cast steel), we generally recommend 20 mesh.
Recommended Hot Oil System Components

Flow Protection
Most systems utilize a pressure differential switch to provide a method of shutting the system down when fluid flow drops below set limits. Another method used by some manufacturers is to provide flow switches which control flows independently through each branch of the heater.

Some systems are equipped with flowmeters in addition to the pressure differential switches. While this is an acceptable 'belt and suspenders' technique, if the heat transfer fluid deteriorates, flowmeters can provide false readings.

These false readings can result from significant changes in the fluid's physical characteristics that occur with thermal degradation and normal aging.

Notes:
- Contractors must apply all national and local codes for thermal applications.
- Thermal heater room must be provided with a 2-hour fire rated enclosure.
- Full pump capacity must be maintained at all times when heater is in operation.

Questions? We'd like to hear from you. Call toll-free, 888-222-3611, or fax or e-mail us, or visit our website, www.paratherm.com.

For 3/4 to 3" pipe, and 94" perforations for 4" diameter pipe and above.

NOTE: Once the construction debris is sufficiently removed from the system, some heater manufacturers recommend the use of flushes to ensure no restriction in flow.
E.3 Multitherm System Guide

From Multitherm’s system design website:
http://www.multitherm.com/system-design.html

Thermal Fluid System Design

Piping:
Welded installations are recommended:

- Up through 1 1/2" - ASTM 106 Grade B Schedule 40 seamless carbon steel pipe.
- 2” through 24” - ASTM A 53 Type S Grade B Schedule 40 seamless carbon steel pipe.
- Mill scale and protective coatings should be removed prior to installation.
- Use of backing rings at pipe to pipe welds is recommended (Robvon or equal).

Threaded installations:

- Up through 1" - ASTM A 106 Grade B Schedule 80 seamless carbon steel pipe.
- 1” to 2” - ASTM A 106 Grade B Schedule 40 seamless carbon steel pipe.
- Greater than 2” - ASTM A 53 Type S Grade B Schedule 40 seamless carbon steel pipe
- Back weld all connections or use thread sealant (Felpro HPS, Copalite, X-PANDO or equal).

Flanges:
300 lb. forged steel; welded neck: 1/16” raised face, Schedule 40 bore, ASTM A 181. Use of backing rings at pipe-to-flange welds in recommended.

Gaskets:
Spiral wound graphite filled (Grafoil, Flexitallic or equal) or expended/filled PTFE (Goretex, Gylon or equal).

Studs:
Alloy steel continuous threaded, ASTM A 193, Grade B7 or higher.

Nuts:
Heavy hex nuts, ASTM A 194, Grade 2H or higher.

Insulation:
Calcium silicate or fiberglass rated to 850°F is acceptable where potential for leaks is minimal. Closed cell foamed glass (Pittsburgh Corning or Equal) is recommended within several feet of flanges, valves, pipe taps or any potential leak point.

Note: Flanges should be left uninsulated to facilitate the detection of leaks. If flanges must be insulated after startup, closed cell formed glass is recommended.

Valves:
Cast or forged carbon steel; socket weld or flanged (300 lb.). Graphite or expanded/filled PTFE valve stem packing or bellows seal recommended.

Isolation Valves: Ball valves recommended (Orbit or equal)

Control Valves: Globe valves recommended
Note: Install valve stems pointing downwards to allow leaking fluid to drain away from insulation.

**Pumps:**

**Positive Displacement:** Alloy steel; gear-within-a-gear (Viking or equal) or sliding vane (Blackmer or equal).

**Centrifugal:** Ductile or cast iron wetted parts (Sihi, Dean brothers, Goulds, ITT, MP Pumps, or equal)

**Mechanical Seals:** Bellow type; carbon vs silicon/tungsten carbide seal faces recommended for low particulate loading; tungsten carbide vs. silicon carbide seal faces recommended for high particulate loading (BW/IP, A W Chesteron, John Crane, Durametallic, or equal)

**Canned Motor:** (Crane Chempump, Sundyne or equal)

**Magnetic Drive:** (Caster, Dickow, Kontro or equal).
## E.4 HME System Bill of Materials

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Cost</th>
<th>#</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roper 3711 Positive Displacement Pump &amp; Motor (3 phase: 230-460V)</td>
<td>$2,784.00</td>
<td>1</td>
<td>$2,784.00</td>
</tr>
<tr>
<td>Hitachi L100-040HFU Motor Starter</td>
<td>$400.00</td>
<td>1</td>
<td>$400.00</td>
</tr>
<tr>
<td>Paxton 2830 3-way mixing valve 1/2&quot; stainless steel body with linear trim</td>
<td>$858.00</td>
<td>2</td>
<td>$1,716.00</td>
</tr>
<tr>
<td>Paxton DL49 Actuator (49 sq. in.)</td>
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<td>76E Moore 760 Electro-Pneumatic</td>
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<td>Kinney-Tuthill KVO-5 Rotary Vane Pump (1 phase: 115 V)</td>
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<td>Electric circulation heater</td>
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<td>Chromalox SCR Power Controller with Process and High Limit Controller</td>
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<td>5 Gallons of Paratherm MR</td>
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<td>Copper</td>
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<td>Brazing</td>
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Welding of Expansion Tank fittings

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<td>Electrical work done by facilities to wire the PD Pump and Hot Heat Exchanger</td>
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<td>Anvil for the Instron</td>
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<tr>
<td>1 KN Load Cell for the Instron</td>
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<td>2&quot; Carbon Steel Y-strainer</td>
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<tr>
<td>2&quot; Cast Iron (30-100 psi) Pressure Relief Valve</td>
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<tr>
<td>Loctite PST 567 (250 ml) Manufacturer #56765</td>
<td>3</td>
<td>$157.65</td>
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<tr>
<td>Compressed Air Regulator With Pressure Gauge 1/2&quot; Pipe Size, 5 To 60 PSI Range</td>
<td>1</td>
<td>$51.57</td>
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<td>Carbon Steel Hose With Galvanized Steel Braid W/Steel Male X Fem Fittings, 24&quot; L, 1/2&quot; ID, 300 PSI</td>
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<td>Extra-Flex PTFE Hose With SS Wire Braid Znc-Ptd Rigid Male Fittings, 36&quot; L, 1-1/4&quot; ID, 1000 PSI</td>
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<td>Carbon Steel Hose With Galvanized Steel Braid W/Steel Male X Fem Fittings, 12&quot; L, 1/2&quot; ID, 300 PSI</td>
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<td>Black Welded Steel Pipe - Schedule 40 2&quot; Pipe X 24&quot; L, Threaded Ends, 1-1/16&quot; Thread Length</td>
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<td>Black Malleable Iron Pipe Fitting - 150 PSI 2&quot; x 1/2&quot; Pipe Size, Reducing Coupling</td>
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<td>Black Malleable Iron Pipe Fitting - 150 PSI 1&quot; Pipe Size, Lateral</td>
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<td>Black Malleable Iron Pipe Fitting - 150 PSI 2&quot; Pipe Size, Lateral</td>
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<tr>
<td>Black Malleable Iron Pipe Fitting - 150 PSI 3/4&quot; X 1/4&quot; X 3/4&quot; Pipe Size, Reducing Tee</td>
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<td>Black Malleable Iron Pipe Fitting - 150 PSI 2&quot; x 1/2&quot; x 2&quot; Pipe Size, Reducing Tee</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 2-1/2&quot; L, Threaded Ends, 1-1/16&quot; L Thread</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 1/2&quot; Pipe X 1-1/2&quot; L, Threaded Ends, 25/32&quot; L Thread</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 3/4&quot; Pipe X 1-1/2&quot; L, Threaded Ends, 25/32&quot; L Thread</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 1&quot; Pipe X 2&quot; Length, Threaded Ends, 1&quot; Thread Length</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 4&quot; Length, Threaded Ends, 1-1/16&quot; L Thread</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 6&quot; Length, Threaded Ends, 1-1/16&quot; L Thread</td>
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<td>Description</td>
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<tr>
<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 1&quot; X 3/4&quot; Pipe Size, Female Reducing Coupling</td>
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<td>$6.34</td>
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<tr>
<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 1&quot; X 1/2&quot; Pipe Size, Female Reducing Coupling</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 1-1/4&quot; X 1&quot; Pipe Size, Female Reducing Coupling</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 2&quot; X 1&quot; Pipe Size, Female Reducing Coupling</td>
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<tr>
<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 2&quot; X 1/2&quot; Pipe Size, Female Reducing Coupling</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 1-1/4&quot; X 1&quot; Pipe Size, Male X Female, 90 Degree Elbow</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 2&quot; X 1/2&quot; Pipe Size, Male X Female, 90 Degree Elbow</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 2&quot; Pipe Size, Tee</td>
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<td>Grainger Ball Valve Carbon Steel, 2&quot; NPT Female</td>
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<td>Grainger Ball Valve Carbon Steel, 1/2&quot; NPT Female</td>
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<td>Grainger Ball Valve Carbon Steel, 1&quot; NPT Female</td>
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<td>General Purpose Stl Compression Tube Fitting Male Straight Adapter for 5/8&quot; Tube, 1/2&quot; NPTF</td>
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<td>Smooth-Flow Reducing Pipe Nipple-Schedule 80 1&quot; X 1/2&quot; Pipe Size X 3-1/2&quot; Length</td>
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<td>Smooth-Flow Reducing Pipe Nipple-Schedule 80 1-1/4&quot; X 3/4&quot; Pipe Size X 4&quot; Length</td>
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<td>316 Stainless Steel Full-Port Ball Valve Lockable Lever Handle, 3/4&quot; NPT Female</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 1-1/4&quot; Pipe X 2&quot; Length, Threaded Ends, 1&quot; L Thread</td>
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<td>316 Stainless Steel Full-Port Ball Valve Lockable Lever Handle, 1&quot; NPT Female</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 8&quot; Length, Threaded Ends, 1-1/16&quot; L Thread</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 12&quot; Length, Threaded Ends, 1-1/16&quot; L Thrd</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 5&quot; Length, Threaded Ends, 1-1/16&quot; L Thrd</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 1&quot; Pipe X 5&quot; Length, Threaded Ends, 1&quot; Length Thread</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 1/2&quot; Pipe X 5&quot; Length, Threaded Ends, 25/32&quot; L Thrd</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 1/2&quot; Pipe Size, 1-1/8 OD, Half Coupling</td>
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<td>Standard Wall Black Welded Steel Pipe 1/2&quot; Pipe X 24&quot; L, Thrd Ends, 25/32&quot; L Thrd, Sch 40</td>
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<td>PVC/Fiber-Reinforced Vibration Damping Pad 19.7&quot; X 39.4&quot; X 1/4&quot; Thick, 174 PSI Maximum Load</td>
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<tr>
<td>60&quot; of 1/4&quot; Stainless Steel Hose with Stainless Steel Wire Braid for Vacuum Pump Connection</td>
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<td>Bk Forged Stl Threaded Pipe Fitting-3000 PSI 3/8&quot; X 1/4&quot; Pipe Size, Hex Bushing</td>
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<tr>
<td>Brass Single-Barbed Tube Fitting Barbed X NPT Male for 3/32&quot; Tube ID, 1/4&quot; NPT</td>
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<tr>
<td>Tin-Plated Steel Pail With Cover 3 Gal Cap, 9&quot; Top Dia, 13-3/4&quot; HT</td>
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<td>Low Pressure Blk Malleable Thrd Pipe Fitting 1/2&quot; X 1/4&quot; Pipe, Reducing Cplg, 1-1/4&quot; L, 150 PSI</td>
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<tr>
<td>Loctite 7649 Structural Adhesives Container (Primer)</td>
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<td>Low-Pressure Brass Threaded Pipe Fitting 1&quot; X 3/4&quot; Female Pipe Sz, Reducing Cplg, 1-15/32&quot; L</td>
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<td>All-Flow EPDM Rubber Multipurpose Hose With Brass Male X Female, 10', 3/4&quot; ID, 200 PSI (Same as 5304K97)</td>
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<td>All-Flow EPDM Rubber Multipurpose Hose With Brass Male X Female, 15', 1/4&quot; ID, 200 PSI</td>
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<td>Low-Pressure Brass Threaded Pipe Fitting 1/4&quot; Pipe Size, Tee</td>
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<tr>
<td>Med Pressure Extruded Brass Hex Nipple 1/4&quot; Pipe Size, 1-3/8&quot; Length</td>
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<td>Master-Flow Oil-Resistant Multipurpose Hose W/Brass Male X Male Fittings, 5', 1/2&quot; ID, 250 PSI</td>
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<td>Standard Wall Blk Steel Threaded Pipe Nipple 1/2&quot; Pipe X 5&quot; L, Thrded Ends, 25/32&quot; L Thrd, Sch 40</td>
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<tr>
<td>Alloy Steel Flat Head Socket Cap Screw 1/4&quot;-20 Thread, 3&quot; Length, Packs of 5</td>
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<td>Filter With Zinc Body and Bowl Manual Drain, 1/4&quot; Pipe, 45 Scfm Max</td>
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<tr>
<td>Precision Thrd Hi-Pressure Brass Pipe Fitting 1/2&quot; X3/8&quot; NPT, Fem X Male Adapter, 3600PSI, 1-11/16&quot; L</td>
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<td>Med Pressure Extruded Brass Hex Nipple 1/2&quot; Pipe Size, 1-13/16&quot; Length</td>
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<td>Med Pressure Extruded Brass Hex Nipple 1/4&quot; Pipe Size, 1-3/8&quot; Length</td>
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<td>Blk Forged Stl Threaded Pipe Fitting-3000 PSI 1/2&quot; Pipe Size, Cap</td>
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<tr>
<td>Loctite 5900 Silicone Flange Sealant 10.1-Ounce Cartridge, Black</td>
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<tr>
<td>Permex No. 2 Form-A-Gasket Sealant 11-Ounce Tube, Black</td>
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<tr>
<td>Loctite 7649 Structural Adhesives Container (Primer)</td>
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<tr>
<td>Loctite 294- Action Bearing Company</td>
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<td>D.L. Thurrott Roper Pump parts for the Pressure Relief Valve</td>
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<tr>
<td>PCI-6208 8/8 analog voltage/current output</td>
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<td>Interface Cable and Termination Board</td>
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**Total** $250
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<tr>
<td>TC-(K)-NPT-G-36-DUAL 1/8&quot; NPT Thermocouple from Omega.com</td>
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<td>OMEGA Sensors for the Platens HKMTSS-032G-6</td>
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<td>Light Switch Rocker, 20 Amps @ 277 Vac, SPST-No, Ivory (Same as 7030K52)</td>
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<td>Thin-Wall Rigid Metal Conduit (EMT) Fitting Insulated Set Screw Connector, Steel, 3/4&quot; Trade Sz</td>
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<td>SOLDER-TYPE COMPUTER CONNECTOR, STANDARD DB25 MALE 1</td>
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<td>SHIELDED STANDARD COMPUTER CABLE, MULTICONDUCTOR FOIL SHIELD, 25 CONDUCTOR, 0.37&quot; OD 25</td>
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<tr>
<td>RadioShack Electronic Component Purchases</td>
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<tr>
<td>Cable Mount Adhesive Mount Strap, 1.25&quot; Max Bundle Diameter</td>
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<td>Indoor Steel Enclosure W/Knockouts (NEMA 1) 4&quot; Height X 4&quot; Width X 4&quot; Depth</td>
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<td>Stranded Single-Conductor Wire UL 1015, 24 AWG, 600 Vac, Blue</td>
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<td>Thermocouple wire FF-K-20S-TWSH-25</td>
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<td>Thermocouple Connectors (SMP-K-M)</td>
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<td>Unistrut: 11 x 10' Green painted Carbon Steel Struts from Newman Associates</td>
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<tr>
<td>Steel Single Strut Channel Slotted, 1-5/8&quot; X 1-5/8&quot;, Green-Painted, 10' Length (Same as 3310T3)</td>
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<td>$25.67</td>
<td>$128.35</td>
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<tr>
<td>Corner Brace for Strut Channel Green-Painted Steel</td>
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<tr>
<td>Bracket for Strut Channel 5-Hole Connecting Plate, Green-Painted Steel</td>
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<td>$5.56</td>
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<tr>
<td>Grade 5 Zinc-Plated Steel Hex Head Cap Screw 1/2&quot;-13 Thread, 1-1/4&quot; Long, Fully Threaded, Packs of 50</td>
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<td>Grade 5 Zinc-Plated Steel Hex Nut 1/2&quot;-13 Screw Size, 3/4&quot; Width, 7/16&quot; Height, Packs of 100</td>
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<td>Zinc-Plated SAE High Strength Flat Washer 1/2&quot; Screw, 17/32&quot; ID, 1-1/16&quot; OD, .097&quot;-.121&quot; Thk, Packs of 25</td>
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<td>Strut Channel Nut W/Spring, Galv, for 1-5/8 X 1-5/8 Strut, 1/2&quot;-13 Thrd, Packs of 5</td>
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<td>Bracket for Strut Channel 90 Degree Angle, 4-Hole, Green-Painted Steel</td>
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<td>Newman Associates UNISTRUT Fitting P1031GR</td>
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<td>Top-Mount Clamping Hanger for 3-1/2&quot; OD, for 3&quot; Pipe Size, 500 Pound WLL</td>
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<td>Strut-Mount Clamp Zinc-Plated Steel, for 1-5/16&quot; OD, 1&quot; Pipe</td>
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<tr>
<td>Flexible Hanger Strap Galvanized Steel W/O Holes, 1&quot; W, .036&quot; Thk, 10'Coil</td>
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<td>Strut-Mount Clamp Zinc-Plated Steel, for 4-1/2&quot; OD, 4&quot; Pipe</td>
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<tr>
<td>Top-Mount Clamping Hanger for 2-3/8&quot; OD, for 2&quot; Pipe Size, 275 Pound WLL</td>
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<td>Top-Mount Clamping Hanger for 1-11/16&quot; OD, for 1-1/4&quot; Pipe Size, 275 Pound WLL</td>
<td>$0.42</td>
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<td>Strut-Mount Clamp Zinc-Plated Steel, 1/2&quot; Tube OD</td>
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<td>Strut-Mount Clamp Zinc-Plated Steel, for 1-1/4&quot; Conduit, 600 lb WLL</td>
<td>$1.38</td>
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<td>Bracket for Strut Channel 90 Degree Angle, 2-Hole, Green-Painted Steel</td>
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<tr>
<td>Metric Blue Coated Socket Head Cap Screw M10 Thread, 35mm Length, 1.50mm Pitch, Packs of 25 (Same as 91303A900)</td>
<td>$8.70</td>
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<td>Metric Black-Oxide Stl Extra-Thk Flat Washer M10 Screw Size, 10.5mm ID, 23mm OD, 4.8-5.4 mm Thk, Packs of 5</td>
<td>$6.15</td>
<td>2</td>
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<td>Corner Brace for Strut Channel Green-Painted Steel</td>
<td>$6.34</td>
<td>8</td>
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<tr>
<td>Bracket for Strut Channel 5-Hole Connecting Plate, Green-Painted Steel</td>
<td>$5.56</td>
<td>4</td>
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<tr>
<td>PETG Sheet 1/8&quot; Thick, 48&quot; X 96&quot;</td>
<td>$64.69</td>
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<td>Surface Hinge W/Holes Zinc Pltd Fnsh, Removable Pin, 3' Leaf H, 2-1/2' Open W</td>
<td>$4.17</td>
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<td>$8.34</td>
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<td>Extruded Alum Pull Handle W/Threaded Holes Oval-Grip, Plain Finish, 3&quot; Center To Center</td>
<td>$3.06</td>
<td>2</td>
<td>$6.12</td>
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<tr>
<td>ECONOMICAL PVC-COA TED FIBERGLASS DUCT HOSE, 10&quot; ID, 10-11/32&quot; OD 10 FT</td>
<td>$70.20</td>
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<tr>
<td>DRIE Mask</td>
<td>$950.00</td>
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<td>TO BE PURCHASED: Closed Cell Foam Glass w/ ASG Wrap for Carbon Steel Pipe in Hot Oil Application (Minimum 1.5&quot; thick, Recommend: 2.0&quot;). fiberglass insulation for hose areas because foamglas is rigid.</td>
<td>$150.00</td>
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<tr>
<td>Hand-Held Zinc-Plated Steel Plunger Drum Pump 16 Ounce/Stroke Flow Rate</td>
<td>$18.22</td>
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<tr>
<td>Brass Single-Barbed Tube Fitting Barbed X NPT Male for 1/8&quot; Tube ID, 1/4&quot; NPT</td>
<td>$7.18</td>
<td>1</td>
<td>$7.18</td>
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<tr>
<td>Brass Single-Barbed Tube Fitting Barbed X NPT Male for 3/32&quot; Tube ID, 1/4&quot; NPT</td>
<td>$7.18</td>
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<td>Teflon Pipe Thread Tape 3/4&quot; Width: 520&quot; Length</td>
<td>$1.84</td>
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<tr>
<td>5-Gallon Steel Pail with Lug Cover</td>
<td>$0.00</td>
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<td>Class ABC Dry Chemical Fire Extinguisher 3-A:40-B:C UL Rating, 5 lb Capacity, Wall Bracket</td>
<td>$30.38</td>
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<td>Light Duty Machinists' Vise 5-1/2&quot; Jaw Width, 5&quot; Max Opening, 3-3/16&quot; D Throat</td>
<td>$59.43</td>
<td>1</td>
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<tr>
<td>5 Gallons Of Mineral Spirits (Paint Thinner)</td>
<td>$34.18</td>
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<tr>
<td>Solid-Carbide 2-Flute Twist Drill Bit Letter Size &quot; H&quot;, 3-1/2&quot; L O'al, 2-1/8&quot; Flute L</td>
<td>$22.93</td>
<td>2</td>
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<tr>
<td>Neoprene Gloves Size 9, 22 Mils Thk, 12-1/2&quot; Length, Black, Flocked (Same as 5278T15)</td>
<td>$2.90</td>
<td>2</td>
<td>$5.80</td>
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<tr>
<td>Color-Coded Hygienic Scrub Brush Twisted Wire Hndl, 1-1/2&quot; L Brush, 15&quot; L O'al, Blue (Same as 63935T18)</td>
<td>$3.39</td>
<td>1</td>
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<tr>
<td>All-Purpose Cleaning and Finishing Brush Polypropylene Bristle, Plastic Handle, 5/8&quot; Bristle</td>
<td>$3.39</td>
<td>2</td>
<td>$6.78</td>
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<tr>
<td>Tube Fitting Brush Plumbing, 1/2&quot; ID Tube/Fitting Size</td>
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<td>Tube Fitting Brush Plumbing, 1&quot; ID Tube/Fitting Size</td>
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<tr>
<td>Tube Fitting Brush Plumbing, 2&quot; ID Tube/Fitting Size</td>
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<td>Single-Spiral Wire Bristle Brush 302 SS, 1/2&quot; Dia, 3&quot; Brush L, 27&quot; Overall L</td>
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<td>Single-Spiral Wire Bristle Brush 302 SS, 1&quot; Dia, 3&quot; Brush L, 27&quot; Overall L</td>
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<td>Single-Spiral Wire Bristle Brush 302 SS, 1-1/2&quot; Dia, 3&quot; Brush L, 27&quot; Overall Length</td>
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<td>Disposable Respirator Mask R95 Filter, for Nuisance Organic Vapors</td>
<td>2</td>
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<tr>
<td>Face Shield Clear, 8&quot; H X 12&quot; W Acetate Window, Pinlock Headgear</td>
<td>1</td>
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<tr>
<td>Color-Coded Flexible PVC Conduit (ENT) 1/2&quot; Trade Size, 0.6&quot; ID, 0.84&quot; OD, Blue</td>
<td>1</td>
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<tr>
<td>Shank-Mounted Miniature Carbon Steel Brush Cup Type, 5/8&quot; Dia, .003&quot; Wire, 1/4&quot; Wire Length</td>
<td>1</td>
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<td>$2.51</td>
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<tr>
<td>Military Grade Teflon® Thread Sealant Tape Premium, 43'L X 3/4&quot; W, .003&quot; Thk, 1.2 G/CC Gravity</td>
<td>1</td>
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<td>Graduated Glass Bottle 1 oz, 1-15/16&quot; Dia Base, 2-13/16&quot; Overall Height</td>
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<td>Graduated Glass Bottle 2 oz, 1-11/16&quot; Diameter Base, 3-5/16&quot; Overall Height</td>
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<tr>
<td>Graduated Glass Bottle 4 oz, 2&quot; Diameter Base, 4&quot; Overall Height</td>
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<tr>
<td>Graduated Glass Bottle 8 oz, 2-1/2&quot; Diameter Base, 5&quot; Overall Height</td>
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<td>Graduated Glass Bottle 16 oz, 3-3/16&quot; Diameter Base, 6&quot; Overall Height</td>
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<td>Graduated Glass Bottle 32 oz, 3&quot; Square, 8&quot; Overall Height</td>
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<td>Disposable Respirator Mask R95 Filter, for Nuisance Organic Vapors</td>
<td>4</td>
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<td>Tin-Plated Steel Container Friction-Top Lid, Without Bail Handle, 32 Ounce</td>
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<td>Light Duty Box Fan 20&quot; Blade Diameter</td>
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<td>Shank Mounted Abrasive Filament Cup Brush 2&quot; Diameter, 80 Grit, 3/4&quot; Bristle Length</td>
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<td>Miniature Abrasive Filament Brush Cup Type, 9/16&quot; Diameter, 3/8&quot; Bristle Length</td>
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<td>Miniature Abrasive Filament Brush Wheel Type, 1-1/4&quot; Diameter, 3/8&quot; Bristle Length</td>
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<td>Double-Spiral Double-Stem Power Brush Stainless Steel, 1/4&quot; Brush Dia, 0.005&quot; Bristle Sz</td>
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<td>Metal Handle Wire Scratch Brush .014&quot; Steel Bristles, 5/8&quot; X 1-3/8&quot;, 3/4&quot; L Bristle</td>
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<td>36&quot; LG, 5' CAPACITY ALUMINUM PIPEWRENCHES</td>
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<td>Three-Outlet Indoor/Outdoor Extension Cord NEMA 5-15, SJTW-Round, 14/3 AWG, 10'L, Orange</td>
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<td>Low-Density Polyethylene Funnel 1-1/2 Gal Capacity, 6&quot; Top OD, 10-1/2&quot; O'All Height</td>
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<td>Citrus Orange Soap With Scrubbing Grit 1 Gallon Pump Dispenser</td>
<td>1</td>
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<td>Purchase Made by Matt: The small mirror, clips to secure plastic tubing, etc.</td>
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<td>Grainger Ball Valve Carbon Steel, 1/2&quot; NPT Female</td>
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<td>Grainger Ball Valve Carbon Steel, 3/4&quot; NPT Female</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 2&quot; Pipe X 2-1/2&quot; L, Threaded Ends, 1-1/16&quot; L Thread</td>
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<td>Black Welded Steel Pipe Nipple-Schedule 40 1&quot; Pipe X 2&quot; Length, Threaded Ends, 1&quot; Thread Length</td>
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<td>Grainger Ball Valve Carbon Steel, 1&quot; NPT Female</td>
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<td>Industrial-Shape Hose Coupling Push-To-Connect Socket, 1/2&quot; NPTF Male, 3/8&quot; Cplg Sz</td>
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<td>Carbon Steel Hose With Galvanized Steel Braid W/Stl Male X Fem Fittings, 18&quot; L, 2&quot; ID, 300 PSI (Same as 56155K68)</td>
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<tr>
<td>Black Welded Steel Pipe Nipple-Schedule 40 1/2&quot; Pipe X 1-1/2&quot; L, Threaded Ends, 25/32&quot; L Thread</td>
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<tr>
<td>Carbon Steel Hose With Galvanized Steel Braid W/Steel Male X Fem Fittings, 18&quot; L, 1/2&quot; ID, 300 PSI (Same as 56155K83)</td>
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<td>Low Pressure Blk Malleable Thrd Pipe Fitting 1/2&quot; X 1/4&quot; Pipe, Reducing Cplg, 1-1/4&quot; L, 150 PSI</td>
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<td>Extra-Flex PTFE Hose With SS Wire Braid Znc-Pltd Rigid Male Fittings, 24&quot; L, 1-1/4&quot; ID, 1000PSI (Same as 54685K204)</td>
<td>1</td>
<td>$119.79</td>
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<tr>
<td>Steel, 1/8&quot; Pipe, Square Head Plug, 150 PSI</td>
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<td>$0.07</td>
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<td>Brass Single-Barbed Tube Fitting Barbed X NPT Male for 1/8&quot; Tube ID, 1/4&quot; NPT</td>
<td>1</td>
<td>$7.18</td>
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<td>D.L. Thurrott Roper Pump parts for the Pressure Relief Valve</td>
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<td>$15.00</td>
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<tr>
<td>POLYESTER BAG AIR FILTER, 90-95% EFFICIENCY, 5 POCKET, 24&quot; X 20&quot; X 22&quot;</td>
<td>1</td>
<td>$33.42</td>
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<tr>
<td>New High Speed Lower Accuracy PCI Board for Analog Input with Cable</td>
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## FTS Bill of Materials

### Functional Testing System - Bill of Materials

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<tr>
<th>Part Description</th>
<th>Vendor</th>
<th>Qty</th>
<th>Cost</th>
<th>Total Cost</th>
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<tr>
<td>1. 2 PHH 22/0000 Syringe Pump Infusion Only 2 Syringe Rack High Pressure</td>
<td>Harvard Apparatus</td>
<td>1</td>
<td>$2,850.00</td>
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<tr>
<td>2. Three-Channel Camcorder, 7 in. LCD</td>
<td>Harvard Apparatus</td>
<td>1</td>
<td>$10,080.00</td>
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<tr>
<td>3. BALANCE, X 0.001G</td>
<td>Case Partner</td>
<td>1</td>
<td>$465.00</td>
<td>$465.00</td>
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<tr>
<td>4. 10S KIT + CABLE FOR MASS SCALE</td>
<td>Case Partner</td>
<td>1</td>
<td>$32.00</td>
<td>$32.00</td>
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<tr>
<td>5. Nico-Acquise Dental Test Game with Data Output capabilities</td>
<td>Case Partner</td>
<td>1</td>
<td>$425.00</td>
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<tr>
<td>6. Hi-Force Steel Junior-Pattem C-Clamp</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$105.00</td>
<td>$105.00</td>
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<td>7. Disposable Purse/Tube w/ Male and Female Luer Lab 25</td>
<td>Harvard Apparatus</td>
<td>1</td>
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<td>8. 200 x 1400 Plastic syringes</td>
<td>Harvard Apparatus</td>
<td>1</td>
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<td>9. USB to RS232 M/Comms</td>
<td>Best Buy</td>
<td>1</td>
<td>$83.99</td>
<td>$83.99</td>
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<tr>
<td>10. Self-Aligning Brass Compression Tube Fitting Nut for Clear Cast Acrylic Sheet .985&quot; Thick, 12&quot; X 12&quot;</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$8.16</td>
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<td>11. Low-Pressure Brass Threaded Pipe Fitting 1/4&quot; Male X 1/8&quot; NPT</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$2.32</td>
<td>$2.32</td>
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<tr>
<td>12. Glass-Filled Nylon Instant Tube Fitting Male Straight Adapter for 1/8&quot; Tube OD, 1/8&quot; NPT</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$2.32</td>
<td>$2.32</td>
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<tr>
<td>13. Die-Cast Acrylic Sheet 1/8&quot; Thick, 12&quot; X 12&quot;</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$15.78</td>
<td>$15.78</td>
</tr>
<tr>
<td>14. Polyurethane Strip .020&quot; Thickness, 12&quot; Width</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$17.00</td>
<td>$17.00</td>
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<tr>
<td>15. Weather-Resistant EPDM Rubber Sheet 1/32&quot; Thick. 12&quot; X 12&quot;</td>
<td>McMaster-Carr</td>
<td>1</td>
<td>$24.28</td>
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<tr>
<td>16. Low-Pressure Brass Threaded Pipe Fitting 1/4&quot; Male X 1/8&quot; Fem Pipe Sz</td>
<td>McMaster-Carr</td>
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<tr>
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**Total Part Number:** 1

**Total Cost:** $13,230.00
### Summary of Functional HME Parts

#### MODEL FIT SERIES OF PARTS

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<tr>
<th>SERIES #</th>
<th>RUN #</th>
<th>TEMPERATURE (°C)</th>
<th>TEMPERATURE (°C)</th>
<th>FORCE</th>
<th>Aspect Ratio</th>
<th>FORCE RATE (N/min)</th>
<th>TIME STAMP</th>
<th>DATE</th>
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</thead>
<tbody>
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#### HME CHARACTERIZATION SECOND SERIES OF PARTS

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<th>Aspect Ratio</th>
<th>FORCE RATE (N/min)</th>
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</thead>
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## HME Characterization First Series of Parts

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<th>DE-EMBOSSING TEMPERATURE-C</th>
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</table>

### Notes:

2. During de-embossing in 25-21, the part reservoir cracked. The part was changed slightly for this and all subsequent parts.
3. Black side of part (75 mm²) faced the wafer flat.
4. Experiments carried out on microchannel (nominal): 800 micron width, 33.75 micron deep, 8000 micron long, with 2000 micron reservoirs.
5. The force rate was 1000 N/min.
### Summary of Functional Test Runs

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>FILENAME</th>
<th>OBJECTIVE</th>
<th>RELEVANT PARAMETERS</th>
<th>NOTES</th>
<th>NOTES2</th>
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<tbody>
<tr>
<td>1</td>
<td>FLOWTEST1</td>
<td>Set Q(pump) and Observe P(drop) and flowrate change along syringe (to find region of syringe in which to operate). Also, determine suitable pressures at which to test and get a handle of pressure accuracy/change and pump accuracy/change.</td>
<td>10 Distilled</td>
<td>130</td>
<td>- Syringe (140ml-10ml). Direct fluid path (no FTP). D=38.4mm.</td>
</tr>
<tr>
<td>2</td>
<td>FLOWTEST2</td>
<td>Set Q(pump) and Observe P(drop) and flowrate change along syringe (to find region of syringe in which to operate). Also, determine suitable pressures at which to test and get a handle of pressure accuracy/change and pump accuracy/change.</td>
<td>10 Distilled</td>
<td>130</td>
<td>- Syringe (140ml-10ml). Direct fluid path (no FTP). D=37.693 mm.</td>
</tr>
<tr>
<td>3</td>
<td>FLOWTEST3</td>
<td>Repeat FLOWTEST2 with Dyed H2O as opposed to Distilled H2O to observe the difference in P(drop) which is linearly dependent to viscosity. No significant change in P(drop).</td>
<td>80 Distilled</td>
<td>130</td>
<td>- Syringe (140ml-10ml). Direct fluid path (no FTP). D=37.693 mm.</td>
</tr>
<tr>
<td>4</td>
<td>FLOWTEST4</td>
<td>Tested original 18-1 part to determine change in pressure with flowrate. Determined that the pressure drop for a given flowrate was much less than before. More precise testing now.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>5</td>
<td>FLOWTEST5</td>
<td>Tested original 18-1 part to determine change in pressure with change in applied force. Determined that a change in force of (+/- 3%) was evident before drop off in fluid pressure or with fluid pressure. Can get more precise given use of spring.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>6</td>
<td>FLOWTEST6</td>
<td>Tested 25-4 part to determine change in pressure with change in applied force. Determined that a change in force of (+/- 3%) was evident before drop off in fluid pressure or with fluid pressure. Can get more precise given use of spring. Operate each spring at 15mm.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
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<td>7</td>
<td>FLOWTEST7</td>
<td>Tested 25-4 first registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Go 0.5 ml/min to 112.5ml. Go 1.5 ml/min to 110ml. Go 4.5 ml/min to 85ml. Go 1.5 ml/min to 72.5ml.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
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<td>FLOWTEST25-4-1</td>
<td>Tested 25-4 second registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Go 0.5 ml/min to 112.5ml. Go 1.5 ml/min to 110ml. Go 4.5 ml/min to 85ml. Go 1.5 ml/min to 72.5ml.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
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<td>9</td>
<td>FLOWTEST25-4-2</td>
<td>Tested 25-4 third registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Go 0.5 ml/min to 112.5ml. Go 1.5 ml/min to 110ml. Go 4.5 ml/min to 85ml. Go 1.5 ml/min to 72.5ml.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>10</td>
<td>FLOWTEST25-4-3</td>
<td>Tested 25-4 fourth registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Get to 35 psi. Run at 4.5 ml/min from 110ml to 90ml. Get to 11 psi. Run at 1.5 ml/min from 8.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>11</td>
<td>FLOWTEST25-4-4</td>
<td>Tested 25-4 fourth registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Get to 35 psi. Run at 4.5 ml/min from 110ml to 90ml. Get to 11 psi. Run at 1.5 ml/min from 8.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>12</td>
<td>FLOWTEST25-4-5</td>
<td>Tested 25-4 fifth registration. (0.5 ml/min, 1.5 ml/min and 4.5 ml/min) were chosen because of the range of pressures they correlated with. Start at 115ml. Get to 35 psi. Run at 4.5 ml/min from 110ml to 90ml. Get to 11 psi. Run at 1.5 ml/min from 8.</td>
<td>Varied Dyed</td>
<td>130</td>
<td>- Syringe (105ml-45ml). New-Latest FTP 4. D=37.693 mm.</td>
</tr>
<tr>
<td>Test Code</td>
<td>Description</td>
<td>Pressure Drop (psi)</td>
<td>Method</td>
<td></td>
<td></td>
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<tr>
<td>-----------</td>
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<td></td>
</tr>
<tr>
<td>Test 25-6</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-10</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-28</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-36</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-26</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-31</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-11</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-27</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-32</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-12</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-33</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-13</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-34</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-14</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-35</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-15</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-36</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-26</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-31</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-12</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-33</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-14</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-35</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-16</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-37</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-17</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-38</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-18</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-39</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-19</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-40</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-20</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test 25-41</td>
<td>Tested 1 reg</td>
<td>0.25-0.05 mm/min</td>
<td>1.5 mm/min and 4.5 mm/min</td>
<td>Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15mm.</td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Methodology</td>
<td>Pressure Settings</td>
<td>Comments</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>26 FLOWTEST26-5-1</td>
<td>Tested 26-5 one registration. (0.06 ml/min, 0.12 ml/min and 0.18 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=6.8 psi and ran 0.06 ml/min. Then went to P=13 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 FLOWTEST26-6-1</td>
<td>Tested 26-6 one registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=6.46 psi and ran 1.0 ml/min. Then went to P=74.27 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 FLOWTEST27-1-1</td>
<td>Tested 27-1-1 one registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=14.6 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 FLOWTEST27-2-1</td>
<td>Tested 27-2-1 one registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 FLOWTEST27-3-1</td>
<td>Tested 27-3-1 one registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 FLOWTEST27-4-1</td>
<td>Tested 27-4-1 one registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31 FLOWTEST27-5-1</td>
<td>Tested 27-5-1 first registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32 FLOWTEST27-5-2</td>
<td>Tested 27-5-1 second registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33 FLOWTEST27-5-3</td>
<td>Tested 27-5-1 third registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34 FLOWTEST27-5-4</td>
<td>Tested 27-5-1 fourth registration. (1.0 ml/min, 0.50 ml/min and 0.25 ml/min) were chosen because of the range of pressures they correlated with Method. Ran each condition out for at least 3-5 minutes. Started P=15 psi and ran 0.50 ml/min. Then went to P=7.5 psi.</td>
<td>Syringe (105 ml-45 ml).</td>
<td>- Syringe (105 ml-45 ml). New-Latest FTP 4. D=37.933 mm. Add 0.22-0.26 psi to model pressure drop when comparing due to Pheight. 3 pieces of scotch tape against top support platform. Operated each spring at 15 mm.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
%USER INPUTS%---------------------------------------------------------------
mu=0.01004; %g/cm*sec%
rho=0.998; %g/cm3%
q=0.0167*1.5; %cm3/sec (0.0167*X = X ml/min)%

%SECTION1%
d1=0.15875; %cm%
l1=85.02; %cm%

%EXPANSION 1%
d2=0.6858; %cm%
l2=1.5;
k1=(1-(d1/d2))^2;

%EXPANSION 2%
d3=0.8; %cm%
l3=0.8; %cm%
k2=(1-(d2/d3))^2;

%CONTRACTION 1%
d4=0.39; %cm%
l4=1; %cm%
k3=0.25;

%90 degree turn 1%
d4=0.39; %cm%
k4=1.1;

%CONTRACTION 2%
d5=0.30; %cm%
l5=1.4;
k5=0.25;

%CONTRACTION NEW 1%
dnew=0.20; %cm%
knew=0.13;

%90 degree turn 2%
d6=0.20; %cm%
k6=1.1;
l6=0.1; %cm%

%USER INPUTS%---------------------------------------------------------------
%%IF WIDTH IS LESS THAN DEPTH AND DEPTH/HEIGHT<5- THEN REVERSE WIDTH AND DEPTH MEASUREMENTS FOR THIS PROGRAM%%

%width=0.0065; %cm%
%depth=0.0036; %cm%

17=0.8; %cm%
x=(width*depth)/(3.14*d6^2/(4));
k7=1.0417*x^3-1.5446*x^2+0.003*x+0.5007;
%Curve fit for sudden Contraction R=0.9999%

%%EXPANSION 3%%
d8=0.20; %cm%
18=0.1; %cm%
y=(width*depth)/(3.14*d8^2/(4));
k8=(l-y)^2;

%%90 degree turn 3%%
d9=0.20; %cm%
k9=1.1;

%%EXPANSION NEW 18%%
dnew2=0.30; %cm%
knew2=(1-(d9/dnew2))^2;
lnew2=1.4; %cm%

%%EXPANSION 4%%
d10=0.39; %cm%
k10=(1-(dnew2/d10))^2;

%%90 degree turn 4%%
d11=0.39; %cm%
k11=1.1;
l11=1.0; %cm%

%%EXPANSION 5%%
d12=0.80; %cm%
k12=(1-(d11/d12))^2;
l12=0.8; %cm%

%%CONTRACTION 4%%
d13=0.6858; %cm%
l13=1.5; %cm%
k13=0.05;

%%CONTRACTION 5%%
d14=0.15875; %cm%
l14=45.72; %cm%
k14=0.45;

%%VELOCITY CALCULATIONS-----------------------------%%
v1=q/(3.14*(d1^2)/4); %cm/sec%
v2=q/(3.14*(d2^2)/4); %cm/sec%
v3=q/(3.14*(d3^2)/4); %cm/sec%
v4=q/(3.14*(d4^2)/4); %cm/sec%
v5=q/(3.14*(d5^2)/4); %cm/sec%
v6=q/(3.14*(d6^2)/4); %cm/sec%
v7=q/(width*depth); %cm/sec%
v8=q/(3.14*(d8^2)/4); %cm/sec%

vnew2=q/(3.14*(dnew^2)/4); %cm/sec%
v11=q/(3.14*(d11^2)/4); %cm/sec%
v12=q/(3.14*(d12^2)/4); %cm/sec%
v13=q/(3.14*(d13^2)/4); %cm/sec%
v14=q/(3.14*(d14^2)/4); %cm/sec%

%%RESONANCE TIME CALCULATIONS----------------------------------------%%
T1=ll/vl; %seconds%
T2=12/v2; %seconds%
T3=13/v3; %seconds%
T4=14/v4; %seconds%
T5=15/v5; %seconds%
T6=16/v6; %seconds%
T7=17/v7; %seconds%
T8=18/v8; %seconds%
Tnew2=1new2/vnew2; %seconds%
T11=111/v11; %seconds%
T12=112/v12; %seconds%
T13=113/v13; %seconds%
T14=114/v14; %seconds%

%%REYNOLDS NUMBER CALCULATIONS---------------------------------------%%
Re1=(rho*vl*dl)/(mu); %dimensionless%
Re2=(rho*v2*d2)/(mu); %dimensionless%
Re3=(rho*v3*d3)/(mu); %dimensionless%
Re4=(rho*v4*d4)/(mu); %dimensionless%
Re5=(rho*v5*d5)/(mu); %dimensionless%
Re6=(rho*v6*d6)/(mu); %dimensionless%
Re7=(rho*v7*(2*width*depth/(width+depth)))/(mu); %dimensionless%
Re8=(rho*v8*d8)/(mu); %dimensionless%
Renew2=(rho*vnew2*dnew2)/(mu); %dimensionless%
Re11=(rho*v11*d11)/(mu); %dimensionless%
Re12=(rho*v12*d12)/(mu); %dimensionless%
Re13=(rho*v13*d13)/(mu); %dimensionless%
Re14=(rho*v14*d14)/(mu); %dimensionless%

%%RESISTANCE AND PRESSURE DROP CALCULATIONS IN STRAIGHT SECTIONS------%%
R1=(8*mu*ll)/(3.14*(d1/2)^4); %g/sec*cm4%
R2=(8*mu*12)/(3.14*(d2/2)^4); %g/sec*cm4%
R3=(8*mu*13)/(3.14*(d3/2)^4); %g/sec*cm4%
R4=(8*mu*14)/(3.14*(d4/2)^4); %g/sec*cm4%
R5=(8*mu*15)/(3.14*(d5/2)^4); %g/sec*cm4%
R6=(8*mu*16)/(3.14*(d6/2)^4); %g/sec*cm4%

%%ALTERNATE PRESSURE DROP CALCULATIONS CAN BE PLACED HERE FOR W AND H%%
%%CHANGING%%
if (width/depth) < 5 | (depth/width) < 5
    HYPERBOLIC=0;
    for n=1:100
        HYPERBOLIC=HYPERBOLIC+1/n^5)*tanh(n*3.14*width/depth);
    end
    R7=((12*mu*17)/(width*depth^3))*(1-(1-(1/(depth/width)*192/(3.14^5))*HYPERBOLIC)^(-1));

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%g/sec*cm4% %Width-Depth%
end
if (width/depth) > 5 | (width/depth) == 5
R7=(12*mu*17)/(width*depth^3); %g/sec*cm4%
%Width>>Depth%
end
if (depth/width) > 5 | (depth/width) == 5
R7=(12*mu*17)/(width^3*depth); %g/sec*cm4%
%Depth>>Width%
end
R8=(8*mu*18)/(3.14*(d8/2)^4); %g/sec*cm4%
Rnew2=(8*mu*lnew2)/(3.14*(dnew2/2)^4); %g/sec*cm4%
R11=(8*mu*111)/(3.14*(d11/2)^4); %g/sec*cm4%
R12=(8*mu*112)/(3.14*(d12/2)^4); %g/sec*cm4%
R13=(8*mu*113)/(3.14*(d13/2)^4); %g/sec*cm4%
R14=(8*mu*114)/(3.14*(d14/2)^4); %g/sec*cm4%
P1=R1*q/1333.33*(0.0194); %psi%
P2=R2*q/1333.33*(0.0194); %psi%
P3=R3*q/1333.33*(0.0194); %psi%
P4=R4*q/1333.33*(0.0194); %psi%
P5=R5*q/1333.33*(0.0194); %psi%
P6=R6*q/1333.33*(0.0194); %psi%
P7=R7*q/1333.33*(0.0194); %psi%
P8=R8*q/1333.33*(0.0194); %psi%
Pnew2=Rnew2*q/1333.33*(0.0194); %psi%
P11=R11*q/1333.33*(0.0194); %psi%
P12=R12*q/1333.33*(0.0194); %psi%
P13=R13*q/1333.33*(0.0194); %psi%
P14=R14*q/1333.33*(0.0194); %psi%

%%PRESSURE DROP CALCULATIONS IN MINOR LOSSES--------------------------%%
MP1=0.5*k1*v1^2*rho/1333.33*(0.0194); %psi%
MP2=0.5*k2*v2^2*rho/1333.33*(0.0194); %psi%
MP3=0.5*k3*v4^2*rho/1333.33*(0.0194); %psi%
MP4=0.5*k4*v4^2*rho/1333.33*(0.0194); %psi%
MP5=0.5*k5*v5^2*rho/1333.33*(0.0194); %psi%
MPNEW=0.5*knew*v6^2*rho/1333.33*(0.0194); %psi%
MP6=0.5*k6*v5^2*rho/1333.33*(0.0194); %psi%
MP7=0.5*k7*v7^2*rho/1333.33*(0.0194); %psi%
MP8=0.5*k8*v7^2*rho/1333.33*(0.0194); %psi%
MP9=0.5*k9*v8^2*rho/1333.33*(0.0194); %psi%
MPNEW2=0.5*knew2*v8^2*rho/1333.33*(0.0194); %psi%
MP10=0.5*k10*v11^2*rho/1333.33*(0.0194); %psi%
MP11=0.5*k11*v11^2*rho/1333.33*(0.0194); %psi%
MP12=0.5*k12*v11^2*rho/1333.33*(0.0194); %psi%
MP13=0.5*k13*v13^2*rho/1333.33*(0.0194); %psi%
MP14=0.5*k14*v14^2*rho/1333.33*(0.0194); %psi%

%%SUMMARY INFORMATION AND OUTPUT--------------------------------------%%
PTOTAL1=P1+P2+P3+P4+P5+P6+P7+P8+Pnew2+P11+P12+P13+P14; %psi%
PTOTAL2=MP1+MP2+MP3+MP4+MP5+MP6+MP7+MP8+MP9+MP10+MP11+MP12+MP13+MP14+MPNEW+MPNEW2; %psi%

%%OPTION OF ADDING PHEIGHT CONTRIBUTION TERM WHERE NECESSARY%%
PHEIGHT=0.24; %psi%

PTOTAL=PHEIGHT+PTOTAL1+PTOTAL2 %psi%

1.2 FTP Version 5 Fluid Model

%%USER INPUTS%%------------------------------------------------------%%
mu=0.01004; %g/cm*sec%
rho=0.998; %g/cm3%
qu=0.0167*4.5; %cm3/sec (0.0167*X = X ml/min)%
%%-------------------------------------------------------------------

%%SECTION1%%
dl=0.15875; %cm%
l1=85.02; %cm%

%%EXPANSION 1%%
d2=0.6858; %cm%
l2=1.5;
k1=(1-(d1/d2))^2;

%%EXPANSION 2%%
d3=0.8; %cm%
l3=0.8; %cm%
k2=(1-(d2/d3))^2;

%%CONTRACTION 1%%
d4=0.39; %cm%
l4=1; %cm%
k3=0.25;

%%90 degree turn 1%%
d4=0.39; %cm%
k4=1.1;

%%CONTRACTION 2%%
d5=0.10; %cm%
l5=1.4; %cm%
k5=0.40;

%%EXPANSION NEW%%
dnew=0.14; %cm%
knew=(1-(d5/dnew))^2;
lnew=0.0254;%cm%

%%EXPANSION NEW%%
dnew2= 0.20; %cm%
knew2=(1-(dnew/dnew2))^2;

%%90 degree turn 2%%
d6=0.20; %cm%
k6=1.1;
l6=0.1; %cm%
%%USER INPUTS%%----------------------------------------------%%

%CONTRACTION 3%
width=0.0200; %cm%
depth=0.0100; %cm%

%IF WIDTH IS LESS THAN DEPTH AND DEPTH/HEIGHT<5-THEN REVERSE WIDTH AND
%DEPTH MEASUREMENTS FOR THIS PROGRAM%

%width=0.0065; %cm%
%depth=0.0036; %cm%


-------------------------------------------------------------------

17=0.8; %cm%
x=(width*depth)/(3.14*d6^2/(4));
k7=1.0417*x^3-1.5446*x^2+0.003*x+0.5007; %Curve fit for sudden
Contraction R=0.9999%

%EXPANSION 3%
d8=0.20; %cm%
18=0.1; %cm%
y=(width*depth)/(3.14*d8^2/(4));
k8=(1-y)^2;

%90 degree turn 3%
d8=0.20; %cm%
k9=1.1;

%CONTRACTION NEW%
dnew3=0.14;%cm%
knew3=0.1;
lnew3=0.0254; %cm%

%CONTRACTION NEW2%
dnew4=0.10;%cm%
knew4=0.1;
lnew4=1.4; %cm%

%EXPANSION 4%
d10=0.39; %cm%
k10=(1-(dnew4/d10))^2;

%90 degree turn 4%
d11=0.39; %cm%
k11=1.1;
l11=1.0; %cm%

%EXPANSION 5%
d12=0.80; %cm%
k12=(1-(d11/d12))^2;
l12=0.8; %cm%

%CONTRACTION 4%
d13=0.6858; %cm%
l13=1.5; %cm%
k13=0 .05;

%CONTRACTION 5%
d14=0.15875; %cm%
l14=45.72; %cm%

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k14=0.45;

%%VELOCITY CALCULATIONS---------------------------------------------------
vl=q/(3.14*(dl^2)/4); %cm/sec%
v2=q/(3.14*(d2^2)/4); %cm/sec%
v3=q/(3.14*(d3^2)/4); %cm/sec%
v4=q/(3.14*(d4^2)/4); %cm/sec%
v5=q/(3.14*(d5^2)/4); %cm/sec%
vnew=q/(3.14*(dnew^2)/4); %cm/sec%
v6=q/(3.14*(d6^2)/4); %cm/sec%
v7=q/(width*depth); %cm/sec%
v8=q/(3.14*(d8^2)/4); %cm/sec%
v9=q/(3.14*(d9^2)/4); %cm/sec%
v10=q/(3.14*(d10^2)/4); %cm/sec%
v11=q/(3.14*(d11^2)/4); %cm/sec%
v12=q/(3.14*(d12^2)/4); %cm/sec%
v13=q/(3.14*(d13^2)/4); %cm/sec%
v14=q/(3.14*(d14^2)/4); %cm/sec%

%%RESONANCE TIME CALCULATIONS---------------------------------------
T1=11/vl; %seconds%
T2=12/v2; %seconds%
T3=13/v3; %seconds%
T4=14/v4; %seconds%
T5=15/v5; %seconds%
TNEW=lnew/vnew; %seconds%
T6=16/v6; %seconds%
T7=17/v7; %seconds%
T8=18/v8; %seconds%
TNEW3=lnew3/vnew3; %seconds%
TNEW4=lnew4/vnew4; %seconds%
T11=11/v11; %seconds%
T12=12/v12; %seconds%
T13=13/v13; %seconds%
T14=14/v14; %seconds%

%%REYNOLDS NUMBER CALCULATIONS---------------------------------------------
Re1=(rho*v1*dl)/(mu); %dimensionless%
Re2=(rho*v2*d2)/(mu); %dimensionless%
Re3=(rho*v3*d3)/(mu); %dimensionless%
Re4=(rho*v4*d4)/(mu); %dimensionless%
Re5=(rho*v5*d5)/(mu); %dimensionless%
Renew=(rho*vnew*dnew)/(mu); %dimensionless%
Re6=(rho*v6*d6)/(mu); %dimensionless%
Re7=(rho*v7*(2*width*depth/((width+depth))))/(mu); %dimensionless%
Re8=(rho*v8*d8)/(mu); %dimensionless%
Renew3=(rho*vnew3*dnew3)/(mu); %dimensionless%
Renew4=(rho*vnew4*dnew4)/(mu); %dimensionless%
Re11=(rho*v11*d11)/(mu); %dimensionless%
Re12=(rho*v12*d12)/(mu); %dimensionless%
Re13=(rho*v13*d13)/(mu); %dimensionless%
Re14=(rho*v14*d14)/(mu); %dimensionless%

%%RESISTANCE AND PRESSURE DROP CALCULATIONS IN STRAIGHT SECTIONS---------
R1=(8*mu*l1)/(3.14*(d1/2)^4); %g/sec*cm4
R2=(8*mu*l2)/(3.14*(d2/2)^4); %g/sec*cm4
R3=(8*mu*l3)/(3.14*(d3/2)^4); %g/sec*cm4
R4 = (8*mu*14)/(3.14*(d4/2)^4); %g/sec*cm4%
R5 = (8*mu*15)/(3.14*(d5/2)^4); %g/sec*cm4%
RNEW = (8*mu*lnew)/(3.14*(dnew/2)^4); %g/sec*cm4%
R6 = (8*mu*16)/(3.14*(d6/2)^4); %g/sec*cm4%

%%ALTERNATE PRESSURE DROP CALCULATIONS CAN BE PLACED HERE FOR W AND H%%
%%CHANGING%%
if (width/depth) < 5 | (depth/width) < 5
  HYPERBOLIC = 0;
  for n=1:100
    HYPERBOLIC = HYPERBOLIC + (1/n^5)*tanh(n*3.14*width/depth);
  end
  R7 = ((12*mu*17)/(width*depth^3))*(1-((depth/width)*(192/(3.14^5))*HYPERBOLIC)^(-1));
  %g/sec*cm4% %Width-Depth%
end
if (width/depth) > 5 | (width/depth) == 5
  R7 = (12*mu*17)/(width*depth^3); %g/sec*cm4% %Width>>Depth%
end
if (depth/width) > 5 | (depth/width) == 5
  R7 = (12*mu*17)/(width^3*depth); %g/sec*cm4% %Depth>>Width%
end

R8 = (8*mu*18)/(3.14*(d8/2)^4); %g/sec*cm4%
RNEW3 = (8*mu*lnew3)/(3.14*(dnew3/2)^4); %g/sec*cm4%
RNEW4 = (8*mu*lnew4)/(3.14*(dnew4/2)^4); %g/sec*cm4%
R11 = (8*mu*l11)/(3.14*(dll/2)^4); %g/sec*cm4%
R12 = (8*mu*l12)/(3.14*(d12/2)^4); %g/sec*cm4%
R13 = (8*mu*l13)/(3.14*(d13/2)^4); %g/sec*cm4%
R14 = (8*mu*l14)/(3.14*(d14/2)^4); %g/sec*cm4%

P1 = R1*q/1333.33*(0.0194); %psi%
P2 = R2*q/1333.33*(0.0194); %psi%
P3 = R3*q/1333.33*(0.0194); %psi%
P4 = R4*q/1333.33*(0.0194); %psi%
P5 = R5*q/1333.33*(0.0194); %psi%
PNEW = RNEW*q/1333.33*(0.0194); %psi%
P6 = R6*q/1333.33*(0.0194); %psi%
P7 = R7*q/1333.33*(0.0194); %psi%
P8 = R8*q/1333.33*(0.0194); %psi%
PNEW3 = RNEW3*q/1333.33*(0.0194); %psi%
PNEW4 = RNEW4*q/1333.33*(0.0194); %psi%
P11 = R11*q/1333.33*(0.0194); %psi%
P12 = R12*q/1333.33*(0.0194); %psi%
P13 = R13*q/1333.33*(0.0194); %psi%
P14 = R14*q/1333.33*(0.0194); %psi%

%%PRESURE DROP CALCULATIONS IN MINOR LOSSES---------------------------%%
MP1 = 0.5*k1*v1^2*rho/1333.33*(0.0194); %psi%
MP2 = 0.5*k2*v2^2*rho/1333.33*(0.0194); %psi%
MP3 = 0.5*k3*v4^2*rho/1333.33*(0.0194); %psi%
MP4 = 0.5*k4*v4^2*rho/1333.33*(0.0194); %psi%
MP5 = 0.5*k5*v5^2*rho/1333.33*(0.0194); %psi%
MPNEW = 0.5*knew*v5^2*rho/1333.33*(0.0194); %psi%
MPNEW2=0.5*knew2*vnew^2*rho/1333.33*(0.0194); \%psi\%
MP6=0.5*k6*v6^2*rho/1333.33*(0.0194); \%psi\%
MP7=0.5*k7*v7^2*rho/1333.33*(0.0194); \%psi\%
MP8=0.5*k8*v8^2*rho/1333.33*(0.0194); \%psi\%
MPNEW3=0.5*knew3*vnew^3*rho/1333.33*(0.0194); \%psi\%
MPNEW4=0.5*knew4*vnew^4*rho/1333.33*(0.0194); \%psi\%
MP9=0.5*k9*v9^2*rho/1333.33*(0.0194); \%psi\%
MP10=0.5*k10*v11^2*rho/1333.33*(0.0194); \%psi\%
MP11=0.5*k11*v11^2*rho/1333.33*(0.0194); \%psi\%
MP12=0.5*k12*v11^2*rho/1333.33*(0.0194); \%psi\%
MP13=0.5*k13*v13^2*rho/1333.33*(0.0194); \%psi\%
MP14=0.5*k14*v14^2*rho/1333.33*(0.0194); \%psi\%

%%%SUMMARY INFORMATION AND OUTPUT-------------------------------------%%

PTOTAL1=P1+P2+P3+P4+P5+PNEW+P6+P7+P8+PNEW3+PNEW4+P11+P12+P13+P14; \%psi\%
PTOTAL2=MP1+MP2+MP3+MP4+MP5+MP6+MP7+MP8+MP9+MP10+MP11+MP12+MP13+MP14+MP
NEW+MPNEW2+MPNEW3+MPNEW4; \%psi\%

%%%OPTION OF ADDING PHEIGHT CONTRIBUTION TERM WHERE NECESSARY%%% 
PHEIGHT=0.24; \%psi\%

PTOTAL=PHEIGHT+PTOTAL1+PTOTAL2 \%psi\%
The steps below outline the procedures used to load and test hot micro-embossed (HME) Poly(methyl methacrylate)-PMMA parts in the FTS. The procedures can be completed by one person. Personal protective equipment including lab coat and goggles should be worn during testing. The deformed spring could come loose and the pressurized fluid could spray/leak creating potential for injury. Each step must be carried out precisely to ensure repeatable test conditions. Transparent tape is preferred over translucent tape to help in imaging during alignment. To unload a part from the functional testing platform (FTP), simply reverse the basic instructions below.

**J.1 Part Loading and FTP Preparation**

1. Make sure the FTP is connected to the fluid circuit near the tee junction at the base of the pressure sensor with the brass fitting end of tubing from the FTP. Zero pressure sensor before connecting any tubing to it.

2. Place the top support platform (1" thick acrylic piece) on the bench top with the fluid I/O side facing up.

3. Take the TPX® (polymethylpentene) gasket layer and align it to the I/O on the top support platform. Align the holes and insert the 1000 \( \mu m \) drill bit into the I/O in the top support platform. If the bit can be inserted and removed without displacing the gasket layer, a proper fluid connection has been made. Make sure the shiny or polished side of the gasket layer faces up. Carefully tape the gasket layer to the top support.
platform on the edges. Tape the gasket layer down while the drill bit is
inserted in one of the two holes to minimize the chance of movement.

4. Take the test part with a piece of tape attached to the side without
features and place it on top of the gasket layer with the features facing
down. Align the test part reservoir to the gasket layer and fluid I/O
opening as closely as possible by eye using the coaxial light at different
angles. Tape the test part down quickly, without allowing it to move.

5. Place the entire assembly under the microscope and use the microscope
light and the coaxial light to obtain an image as seen below. Make sure
the reservoir diameter encircles the fluid I/O and gasket hole diameters
and the gasket hole diameter encircles the fluid I/O diameter. This will
ensure repeatable testing conditions.
6. If the conditions in Step 5 are not met, remove the assembly from the microscope, undo Steps 1-5 and then repeat Steps 1-5 until the conditions in Step 5 are met.

7. Remove the assembly from the microscope.

8. Before placing the assembly back on the bench top, place four fasteners with washers on the bench top and place the assembly down (part facing up) on the four fasteners so they are inserted in the four holes on the corners of the assembly.

9. Place a 30 mm diameter (1mm thick) PMMA blank on top of the test part and tape it down as well.
10. Finally, place the bottom support platform with the silicone gasket layer facing down on top of the assembly, aligning the four holes in the corners with the four fasteners protruding from the assembly.

11. Take four nuts and lightly tighten the four fasteners by hand.

12. Flip the assembly over and over so the fastener heads are pointing up.

13. Tape two 30 mm diameter (1mm thick) PMMA blanks on the top side of the top support platform and bottom side of the bottom support platform. These blanks will serve to protect the acrylic platforms from damage from contact with the c-clamps and springs.

14. Carefully clamp down on the FTP with two c-clamps with springs inserted to calibrate the force. Clamp down until each springs length is ~15 mm (~33 lbs/spring). Note this force requirement may be different for parts with different cross-sectional areas. However, it is important to use the same clamping force for a comparison of parts to assess HME process variation or process window characterization. Therefore, the minimum force used should be the minimum force required to seal all parts in a given series. See the two images below of the final FTP assembly.
J.2 Running Tests and Recording Data

1. Turn power on to the syringe pump, mass scale, pressure sensor, humidity/temp sensor, and the PC running LabView. When turning on power to the pressure sensor, hold the ZERO/TARE button while holding down the power button for a few seconds. A message: NO
AUTO OFF should be displayed before the pressure reading is shown. This ensures the pressure sensor does not automatically turn off every 20 minutes.

2. Place an empty beaker on the mass scale and cover the mass scale with the enclosure. Tare the mass scale. Insert the humidity/temp probe into the humidity enclosure.

3. Open the LabView program for FTS control and data acquisition.
   Open file: C:\FUNCTIONAL TESTING SYSTEM>MASTERFILE9.

4. When prompted to select which VI to open select the first option: HA Series 2000 Controller.vi

5. Remove the syringe from the syringe pump by unscrewing the Luer-Lock. Refill the syringe with the dyed water (~120 ml). Hold the syringe with the tip facing up over a sink and press the syringe to remove as much as air from the syringe as possible.

6. Load the syringe in the syringe pump, connect to the Luer-Lock tubing, and move the stop block up to the end of the syringe plunger.

7. Place the syringe pump at an angle by placing a something under the left side to angle down the tip of the syringe. This forces air to the back of the syringe and minimizes air in the system.

8. Place the free end of the FTP tubing in the hole at the top of the enclosure over the mass scale (feeds into the beaker). Secure against the mass scale lid to ensure it cannot move and do not allow the tubing to touch the beaker on the mass scale.
9. Turn on the syringe pump at an arbitrary rate based on the micro-channel geometry and run fluid through the assembly. Do not allow the pressure to exceed ~35 psi. The objective of this step is to remove air from the system as quickly as possible. Change the orientation of the FTP and pressure sensor (shake/tilt them to force out all air bubbles). Place the FTP back on the bench top at an angle with the outlet higher than the inlet.

10. Once all the air has been removed from the system, stop the flow rate and observe for leakage at a high pressure (20-40 psi) by cinching off the outlet tubing to the mass scale and observing the pressure reading. If the pressure holds relatively steady, there is sufficient sealing. If not, repeat the entire testing over starting from Appendix J.1 until this condition is met. Re-tare the mass scale. Always monitor the FTP for signs of leakage.

11. Run the LabView program by pressing the LabView start button at the left of the screen. A prompt will ask where to place the data file created from the file. Indicate an appropriate filename and file location.

12. At the program user interface (screen shot shown below) immediately make sure Pump no.=0 and set the COM port to COM 1. Then click connect. The picture of the pump (previously grayscale) should turn colored. This indicates pump communication has been established. Data from the mass scale and pressure sensor started recording.
immediately after a file name and location was entered. For problems with the program, such as non-response, no data acquisition, etc., see the Master Notes prompt on the LabView interface.

13. Do not adjust the syringe diameter unless the syringe has been changed and a new diameter has been verified.

14. Adjust the infusion rate, infusion units, and stop volume in LabView or on the pump itself. Note down all command flowrates used.

15. Run tests by altering the command flow rate (multiple times if desired) and allowing the pressure to reach steady state (no observable
movement up or down for 30 seconds). Note, sometimes the tests do not reach a steady state value but oscillate between two bounded values. This is more typical at higher pressures. In this case, the average of the oscillating range can be considered the steady state value.

16. When tests have been completed, stop the pump on either the pump itself or on in the LabView program. Then press the large STOP button on the LabView program to stop mass scale and pressure sensor data acquisition. Then press the stop button on the syringe pump program and then the disconnect button to terminate communication with the syringe pump. Finally, press Exit to terminate the program.

17. Open the file created by LabView in Excel. Specify tab spacing to separate data columns. The columns of data are as follows: (1) time; (2) hour; (3) minute; (4) msec counter; (5) mass (g); (6) pressure (value or PSI symbol); and (7) pressure (value or PSI symbol). Process, analyze and save data in excel format.

18. Note down minimum and maximum values of temperature and %RH. Turn off power to the syringe pump, mass scale, pressure sensor, humidity/temp sensor and logoff from the PC.

19. To repeat testing, empty fluid from the beaker on the mass scale into the dyed fluid container and repeat steps 1-18. See the equipment manuals for further details on operations and additional advanced features.
References


4 Zengerie, Roland. Stefan Haeberle. “Presentation-Microfluidics: Introduction to Microfluidics”. Freiburg, Germany. The Institute of Microsystem Technology (IMTEK) at the University of Freiburg. Slides 1-35.


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