Mini-High Temperature HEPA Filter Test Unit

Final Design Report

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Table of Contents

Statement of Disclaimer:

Executive Summary:

There is a need for better HEPA filter materials, especially those able to withstand higher temperatures as experienced in fire conditions.   In order to test these materials our team built a Mini High Temperature Testing Unit (MHTTU) that can rapidly, efficiently, and inexpensively test a large number of new and innovative materials for HEPA filter components. MHTTU test results will be used to down select the most promising materials for HEPA filter components (e.g., media, sealants, gaskets) for full scale testing in the HTTU.   There are already some pieces of equipment that exist in other parts of the country that produce similar effects, but do not fulfil our specific needs of 1300°F air at the low flow rates of 1.25-12 ACFM. Our attempts to source heaters were iterative due to the difficult nature of finding items that fulfilled both extreme specifications.

The design decided upon pre-testing involved using two individually operating heaters, one for each end of flow regime. After initial testing, the immersion heater, originally intended solely for the low range of flows proved better able to handle our complete range than the higher flow heat torch. With the current design, we were only able to reach a temperature of 1116F, but we were able to meet all of our other specifications, including flow rates, warm up time, and differential pressure drop across the test section. We believe that the majority of our heat loss was shed through the un-insulated housing of the heat torch, and recommend removing the heat torch and transfer section from the device. This would lessen the mass of stainless steel to be heated as well as remove a relatively large heat shedding fin from the device.

Introduction

The purpose of this project is to design and build a Mini High Temperature Testing Unit (MHTTU) that can rapidly, efficiently, and inexpensively test a large number of new and innovative materials for HEPA filter components. MHTTU test results will be used to down select the most promising materials for HEPA filter components (e.g., media, sealants, gaskets) for full scale testing in the HTTU.

The past model High Temperature Testing Unit (HTTU) was built to simulate the elevated temperature conditions of a fire for HEPA filters. By testing HEPA filters at high temperatures, new filter material may be designed to reduce the risk of environmental exposure, even under such dangerous conditions. The original HHTU at Cal Poly was built and revised over the course of three senior projects spanning 2011-2013.

The construction of the new device by Team Phoenix builds upon the groundwork laid by previous teams of this type, such as Team Icarus, and continues to further LLNL's mission for increased environmental security by working to more quickly test HEPA filter sample materials.

Figure 1: HEPA filters

Background

Filters are barriers used to protect people from hazardous materials. Unfortunately, the original cellulose material of HEPA filters was susceptible to combustion. In September of 1957, a plutonium fire in a glovebox burned half of the 700 HEPA filters at the Rocky Flats Plant. This resulted in radiation contamination of Building 71. The filters were soon redesigned to glass fiber filter media in stainless steel frames, however another glovebox fire in 1969 destroyed many more filters. This led to water spray nozzles in filter plenums in an attempt to reduce the temperature across the filter media. Unfortunately, in 1980, another fire caused the bonding that held filter media to frame to fail. This was soon followed by full filter blowouts due to clogged filter media via water and particulates. After so many redesigns, it is apparent that better filter material is still required. The search for the best filters is an ongoing iterative process and each design requires testing.

Figure 2: 1969 fire filter damage

Current Standards:

In order to create a device to test HEPA filters at high temperature, we looked into existing test and safety standards. Depending on final design, some relevant standards may include:

- ASME N509 -- Nuclear Power Plant Air-Cleaning Units and Components
- ASME N510 -- Testing of Nuclear Air Treatment Systems
- ASME AG-1 -- Code on Nuclear Air and Gas Treatment
- ASTM F1471-09 -- Standard Test Method for Air Cleaning Performance of a HEPA Filter System
- DOE-STD-1066-97 -- Fire Protection Standard
- DOE-STD-3020 -- HEPA Filter Specifications
- DOE-STD-3022 -- HEPA Filter Test Standard
- DOE-STD-3025 -- HEPA QA Testing Specifications
- MIL-STD 282 -- Provides Filtration Standards for Nuclear Grade Filters
- NFPA72 -- National Electrical Code
- UL 508A -- Industrial Control Equipment Electrical Code
- UL 586 -- Safety Standard for HEPA Filters
- UL 900 -- Safety Standard for Air Filter Units

Existing Technology:

Aside from the previously LLNL sponsored Cal Poly HTTU, we were unable to find any small HEPA filter testing units that operated at the temperatures that LLNL require. Here is a small sampling of what we did find.

NASA Langley HTT (High Temperature Tunnel*)*

- Designed to simulate high-altitude supersonic flight
- Can achieve wind speeds up to Mach 7
- 1,180 – 3,190°F [Mach dependent]

Advanced Thermal Systems CLWT-115

- Operates at up to 1000 CFM, and 185˚F
- Recirculating design for quick heat up time.
- Designed to test PCB heat sinks in high temp. environments

ICET at Mississippi State:

- For certification of HEPA filters after production.
- Flow up to 1000 CFM
- Temperatures of 1000°F

Cal Poly HTTU:

- Flows up to 250 CFM
- Temperatures of 1000°F
- For full verification of fire safety, including flame impingement systems. Verifying material selection.

Figure 3: Existing technology

Previous Cal Poly HTTU Development:

There have been three project teams that have worked on the Cal Poly HTTU sponsored by LLNL. The first, Team Icarus, through manual controls, achieved a temperature of 1000°F at 250 SCFM in about an hour. The following team, CP HEPA, introduced a fully automated control system, increasing the efficiency and speed of the HTTU. Finally the third team, HiTop, worked on direct flame impingement, as well as incorporating a visual system and leak detection.

Team Phoenix plans to design and build a smaller, faster HTTU device to operate at lower flow rates, which were determined to be proportional to full size samples for our smaller test cross sections. While a retrofit of the current HTTU might be possible, the drastic shift in flow rates means that with replacement heat torches capable of handling the flow rates required, the system would be too large and take much longer to warm up. Team Phoenix will be working alongside Marc Goupil from Team CP HEPA who will be working on controls and a GUI for both the old and new HTTU. A future Cal Poly team will design and build a "Universal Test Section" which will house the filter material to be tested.

Figure 4: Previous Cal Poly Development

Objectives:

The scope of this project covers the miniaturization of the previous HTTU developed by team Icarus and further improved by teams CP HEPA and HiTop. In effect, Team Phoenix will be recreating the efforts of team Icarus on a smaller scale with the intent of improving warm-up time, increasing operating temperature, and decreasing power and energy requirements. A Quality Function Deployment analysis table was used to prioritize the specifications and is included in Appendix A. A separate control system team reduces the scope of many specifications concerning the control and user interface of Team Phoenix's device. Another team is developing a test section to interface with the mini-HTTU and is covering the implementation of other test systems such as flame impingement.

Primary Specification Targets

These specifications must be met for the project to be considered successful. A compliance matrix for these specifications is available in Appendix B.

- Target operating temperature of 1300°F supplied to test section test section
- Target flow rates between 1.25 and 12 ACFM at 1300°F
- Maintain flow and temperature with 0.5 to 12 in H_2O pressure drop across test section
- Implement removable test section to accommodate implementation of future Universal Test Section
- Target warm up time of <15mins from room to operating temperature in test section
- Target cool down time of <15mins from operating temperature to <120°F
- Allow for interface with control system for on-the-fly adjustment of flow and temperature settings
- Meet applicable safety codes (OSHA, IEEE, ASME)
- Provide feedback compatible with control system for test section flow rate, temperature, and test section pressure drop
- Include flame arrester and debris capture system on exhaust

Secondary Specification Targets

– These specifications have been deemed not critical for the success of the project, but are important enough to the performance and capability of the Mini-HTTU that they will be pursued if time, budget, and hardware necessary for the fulfillment of primary specifications allow. These are listed in order of priority, though specifications that can be met with minor effort and budget commitment will likely be included:

- Mounting to a movable cart with locking wheels
- Target width of <32” and height of <7’ to allow for transport through standard doorway

As noted on the specification compliance table in Appendix B, two specifications were originally considered to be of a high risk to the project; meaning they have been identified as the largest obstacles to the successful completion of the project.

The first is the target rise time of 15 min. This will be strongly tied to the heat capacity of the apparatus and the amount of heat that can be transferred to the apparatus by the heat source. Therefore, optimizing that performance by way of high powered heaters, good insulation, and well-managed air-flow characteristics is a primary concern.

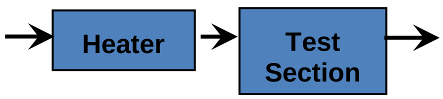
The second is the development of a closed-loop control system for the Mini-HTTU. Developing and tuning the system would be a considerable time constraint, as proper development requires thorough testing of the open-loop control response of the system. This specification was downgraded from a high risk to a medium risk specification upon initial collaboration with Marc Goupil from Team CP HEPA. He is currently tasked with creating a control system capable of interfacing with both HTTUs and will therefore be taking over the bulk of the closed-loop control system development. Team Phoenix will be continually collaborating with him to streamline the integration of the control system with the Mini-HTTU.

Design Development:

For this project, three main configurations were considered. These are briefly listed below, followed by more detailed individual descriptions.

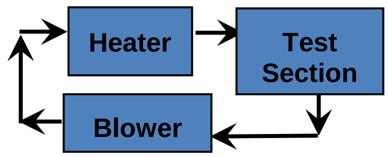
Single Pass

- Cheapest
- Simple
- Least efficient



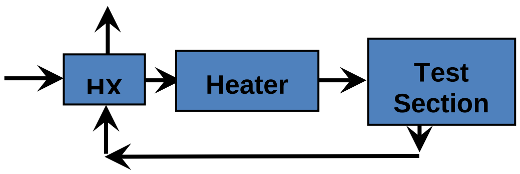
Fully Re-circulating:

- Most efficient
- Quickest
- Conceptually Simple
- Complex to implement
- Difficult to find parts
- Expensive



Single Pass w/ Heat Recovery

- Efficient
- Easy to implement
- Faster than single pass
- Requires in house parts



Once Through:

The first is a once-through design mimicking the layout of the original HTTU. Air would be supplied via compressor or blower through an in-line heating element then pass through the test section. Exhaust from the test section would be vented to the outside environment. This design is the simplest to implement, but has the highest power requirements, as none of the heat energy would be captured and reused. As a result, initial estimates suggest that upwards of 2.5kW of power would be required to adequately heat the incoming air. This makes the design unfeasible to power via standard 120V power circuit, limiting the portability of the design. As enhanced portability is considered secondary to the flow, pressure, and heat requirements of the apparatus, this design is seen as a fall back option if more efficient designs prove unfeasible. Another drawback of the once-through design is that the minimum flow specification for the unit is nearly an order of magnitude less than the minimum safe flow rate prescribed by the less expensive inline heaters. A circulation heater has been sourced that can accomplish the low flows, but the cost is roughly double that of the inline heaters. If the inline heaters are to be used, then a solution for diverting the high temperature flow away from the test section will have to be found and implemented into the control scheme, potentially offsetting any savings from the cheaper heaters and further complicating the unit controls.

Recirculating:

The second design is a fully re-circulating design using a blower in-line with the hot exhaust to re-introduce pre-heated air to the heating element, drastically reducing energy requirements. This design has the benefit of much lower overall energy consumption, as the majority of the heat energy would be contained within the apparatus. Some venting would be required to equalize outside and inside pressures, but this would only take place during warm-up and cool-down cycles. This design is strongly dependent on the availability of high-temperature blowers that are properly sized for these low flow rates and heating elements that are tolerant of high inlet air temperatures. Heating elements that are capable of high inlet temperatures are available, but a high-temperature blower that is small enough to supply the low target flow rates are exceedingly difficult to source. Unless an adequate in-line blower can be found, this design is considered unfeasible.

Once Through with HX:

The third design is a pass-through configuration similar to the first, but with the addition of a heat exchanger to transfer heat from the high temperature exhaust to the cold incoming air. We made a physical model of this option displayed below. The exhaust would be vented to the room as well, but at a much lower temperature. This design combines the simplicity of the once through design with some of the efficiency gains of the re-circulating design. Its advantage over the re-circulating design is the flexibility in air supply, as the supply need not be subjected to the intense heat within the apparatus. This design is also limited by the durability of the heating element, but as stated above, heaters that are tolerant of high inlet temperatures are readily available. The main hardware limitation is the availability of small, affordable air-to-air heat exchangers that are capable of enduring the high temperature of the exhaust and the large temperature difference between the intake and exhaust air. Fortunately, even a simple tube-in-tube heat exchanger section can potentially be fabricated if an adequate commercially available heat exchanger cannot be sourced. The fabrication of the tube-in-tube would increase material costs and the effectiveness of its heat recapturing capability would be relatively unknown prior to testing.

Final Design:

Formal selection of the best design took place via open discussion and analysis with Pugh matrices. However, a great deal of our selection was determined by the availability of heaters, air supplies, and heat exchangers that could meet or exceed the requirements of each design. Pugh matrices used in component and layout selection are included in Appendix C-E.

The design that was decided upon is a variant of the once-through design using two heaters in parallel. Flow would pass through only one heater at a time and only one heater will be operated at a time. Compressed air will be used to provide the airflow. Flow monitoring will be performed upstream of the heaters using a hot wire anemometer. Flow control will be performed by a solenoid controlled proportioning valve. Flow will be directed through either heater using a solenoid actuated diverter valve. An immersion heater will heat low flows up to roughly 4 ACFM, and a standard inline heater will perform heating duty when flows are higher than 4 ACFM. Temperature sensing at the test section will be accomplished via thermocouple, and pressure drop across the test section will be verified using a differential pressure transducer and pressure taps.

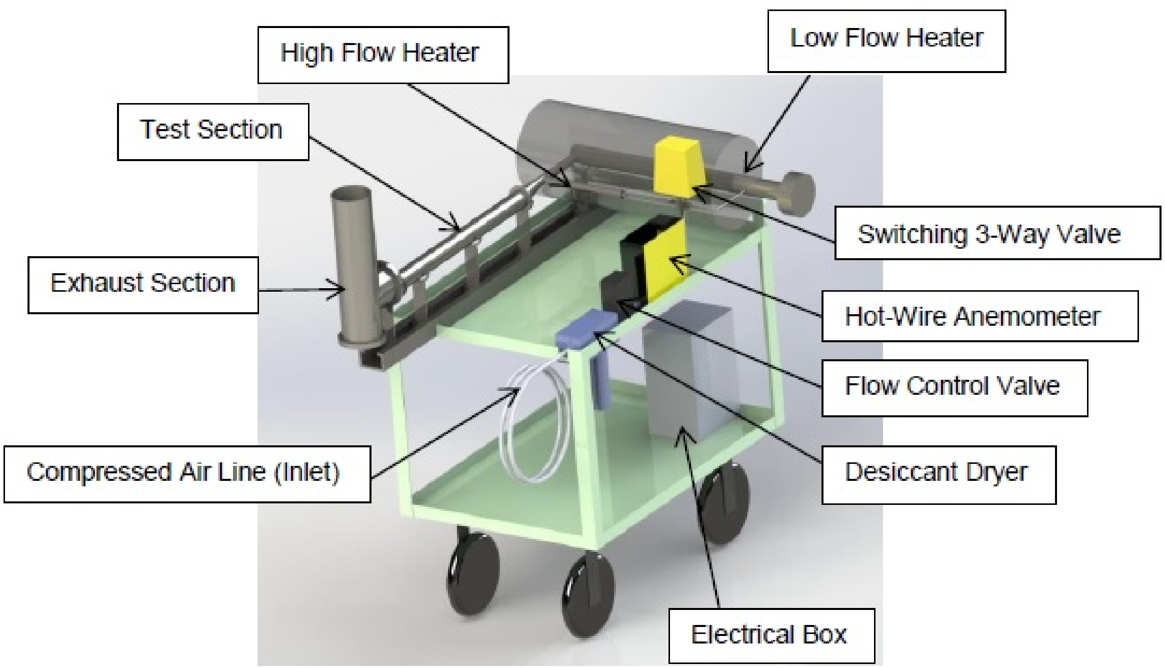


Figure 5: Final Design CAD Model

Heater Selection:

When researching potential heaters for the mini-HTTU, it was found that a common lower limit on flow rate was 1.0 SCFM. The minimum specification for the mini-HTTU called for 1.25ACFM, which translates to roughly 0.4 SCFM. After much searching, it was decided that the best chance Team Phoenix would have of heating the lowest range of flows rested not with inline heaters, but with immersion heaters designed for heating stagnant fluids and gases. With this in mind, analysis of Watlow's line of immersion heaters capable of element temperatures of 1600°F began in earnest. While the manufacturer could provide data for heating performance in stagnant fluids, performance data on using these heaters to heat flows of any speed simply did not exist. Therefore, analysis was required before any recommendation could be made.

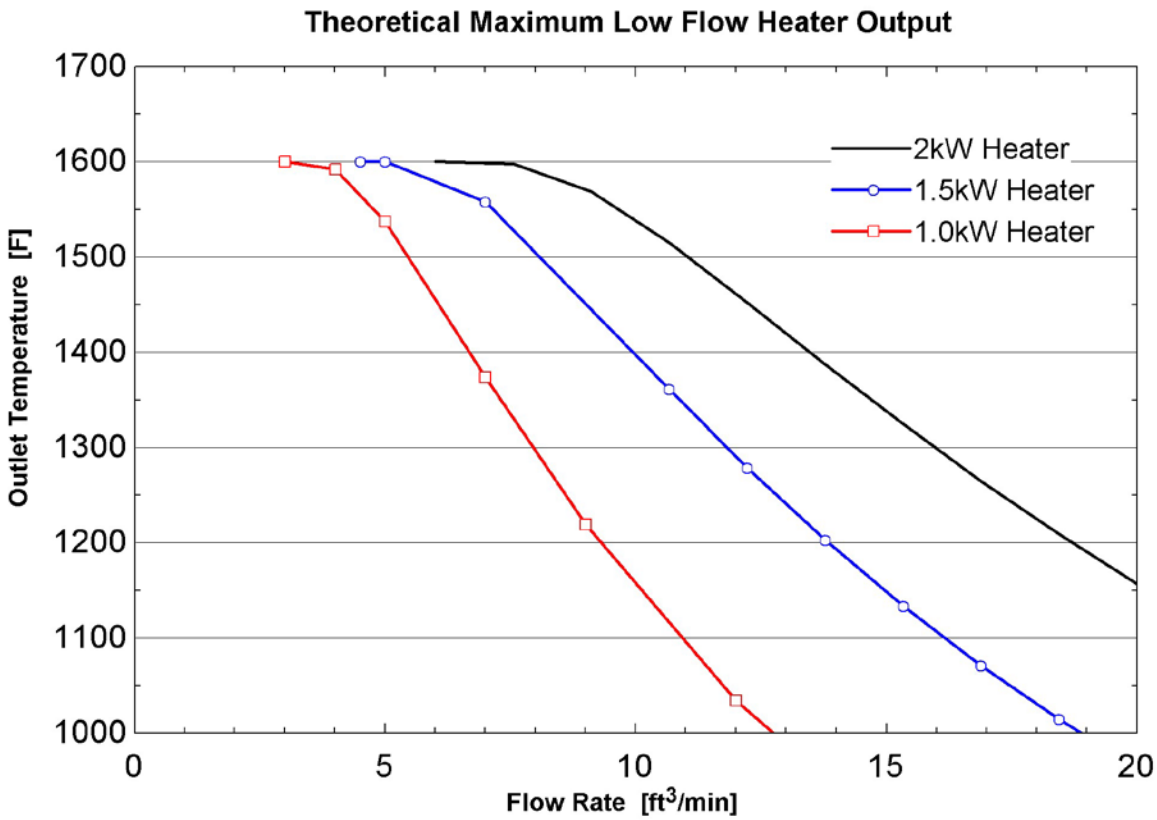


Figure 6: Maximum output- low flow heater

The above chart was generated with numerically solved heat transfer analysis in EES. Raw tabular data and program code is available in Appendix G.

From the above chart, it appears that all three of the examined heaters would be able to adequately heat the process air at low speeds, but would struggle at higher flow rates. This is to be expected, as the heaters were not designed to heat flowing fluids. As this analysis required several assumptions that would reduce the accuracy of the analysis, it was decided that Team Phoenix would use the 2kW heater, as the difference in cost was negligible compared to the overall cost of the project.

For the higher flows, several options exist due to the prevalence of off-the-shelf inline heaters designed to heat flows in that range. The cheaper of our two considered options is a 2kW Hot Air Tool with the heating performance curve found in the chart below.

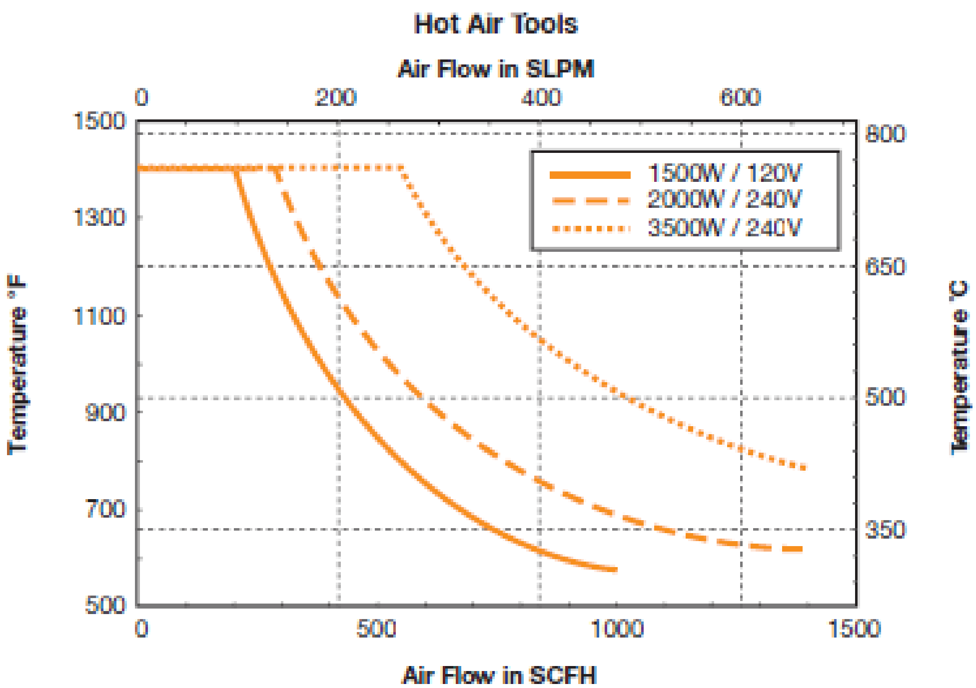


Figure 7: Output- hot air tools heater

If higher flows are desired, Team Phoenix is considering a more expensive 3.6kW dual stage heater with the performance curve below.

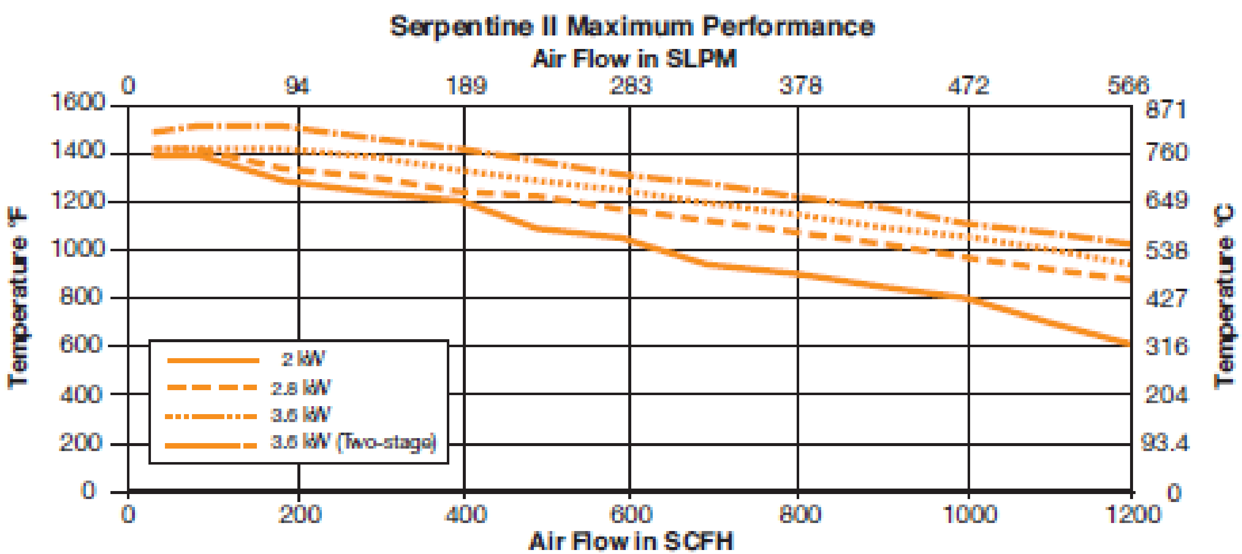


Figure 8: Output- serpentine 2 heater

Insulation and flow duct sizing:

To reduce warm-up time, increase steady state efficiency and decrease surface temperature, utilizing adequate insulation is a primary concern. Since the surface temperature of the stainless steel ducting will likely be very close to the flow temperature of at least 1300°F, insulation rated for extreme temperatures must be utilized. Unfortunately, most readily available insulation capable of surviving the intense heat does not insulate particularly well and is comparatively expensive. With this in mind, a dual layer strategy was decided upon. The extreme temperature insulation would be used as an inner layer to reduce the temperature of the interface between the inner and outer layers of insulation to a level acceptable for use of the cheaper, more effective insulation.

Alumina oxide wrap was decided upon for the inner layer due to its extremely high temperature rating and ease of application. The outer layer will consist of mineral wool wrap due to its fairly high temperature rating and considerably better insulation properties. To keep the insulation well contained, a hardening cast-like wrap will be applied on the outside.

The insulation of the flow path and the size of the flow path become particularly important to the mini-HTTU's operation at the lowest flows. The primary reason for this is that the heat lost through the tubing and insulation is primarily a function of the temperature difference between the flow and the outside air, which remains extremely large regardless of flow rate. The effect of this heat loss is particularly large at the lowest flow rates because there is less total heat energy available in small flows than in large flows. The loss of even a small amount of heat can cause a large drop in the temperature of the flow.

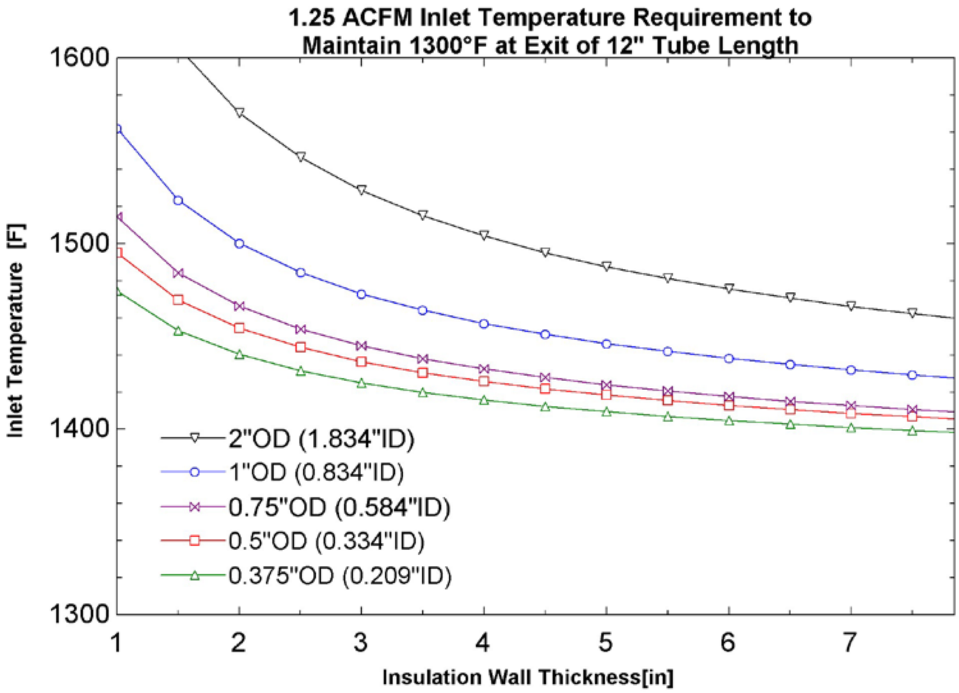


Figure 9: Insulation required for different tube diameters

As shown in the graph, the diameter of the duct also plays a large part in the retention of available heat in the flow. Minimizing the diameter of the duct decreases the amount of time any portion of the air remains in transit to the test section, decreasing the amount of heat and temperature lost by said air. There are limits to how small the duct can reasonably be made, however. Firstly, in order to avoid compressing the flow in the tube, velocity must be kept below roughly 0.3*Ma, or 30% of the speed of sound in the process air.

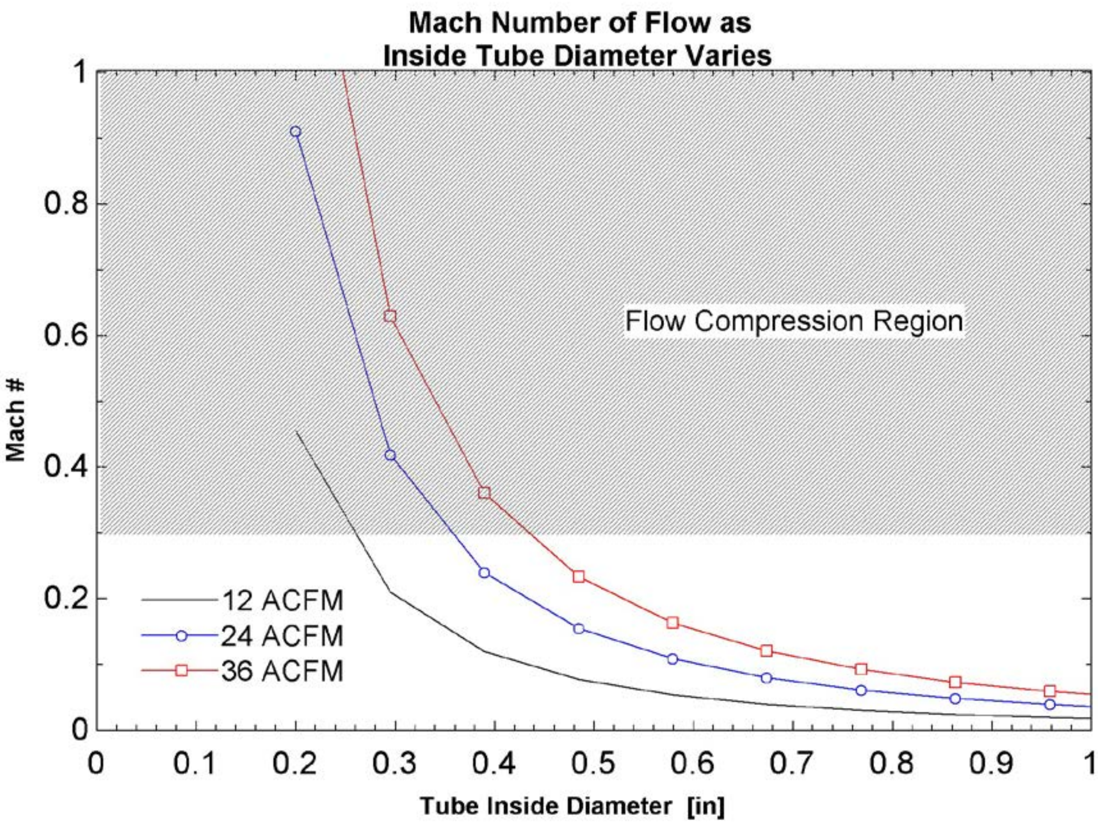


Figure 10: Compressible flow consideration

As shown in the graph, the concern over flow compression only pertains to the upper range of the flow regime, but the limits are still somewhat low.

Another constraint on the feasible size of the tubing is the interface with the test section itself. The (assumed) large range of filter sizes that will need to be accommodated indicates that a larger inlet diameter would prove useful to the test section team for purposes of flow uniformity across the filter face.

Exploration of Ceramic Coating Effectiveness:

It was found that a ceramic inner coating on the steel tubing would prove relatively ineffective compared to the selected outer insulation. Two applications were considered.

First, that a coating on the inside wall of the flow path would reduce the amount of heat lost to the steel. The problem with this idea is that a ceramic coating primarily affects the rate of *radiant* heat transfer to a surface by changing the reflectivity of the surface. In the duct, heat transfer is dominated by *convection*, which is not affected appreciably by surface condition. Once the heat had reached the surface via convection, it was transferred through the tubing walls and insulation primarily via *conduction*. While the ceramic coating would certainly conduct heat much less than the steel it was coating, the coating itself would be extremely thin. As resistance to conduction is directly related to the thickness of the material, any benefit would be extremely small compared to simply adding additional outer insulation, which is much cheaper.

Second, it was thought that taking advantage of the reflection (or absorption) of a ceramic coating could enhance the performance of the low-flow heater. A great deal of radiant heat transfer from the 1600°F heating element to the wall was taking place in the analysis, so a ceramic coating seemed to be in its element in that application. The effect of changing the reflectivity of the tubing surface was analyzed and the below chart was generated.

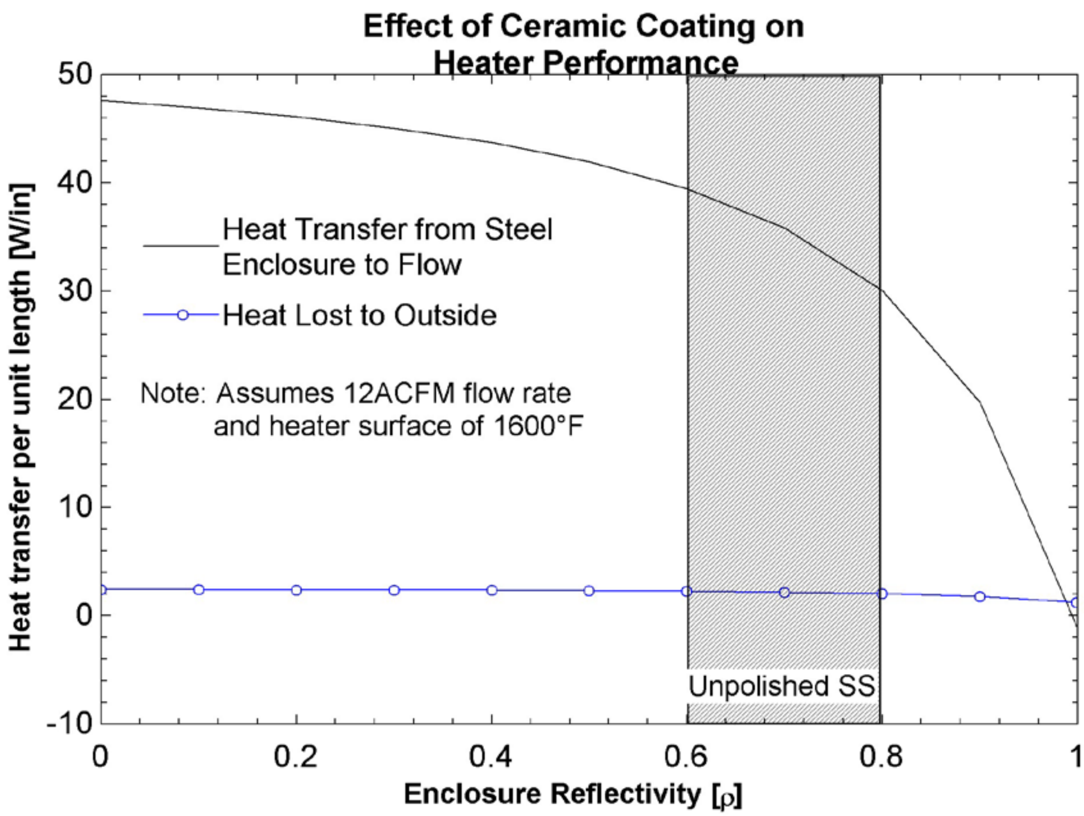


Figure 11: Ceramic coating effects

It was found that by *reducing* reflectivity, heat transfer from the heater assembly to the air improved, and increasing reflectivity greatly reduced its heating performance. Thus, it is apparent that a coating that reduces reflectivity could prove useful, but the effect it would have is only minor and likely not worth the expense of the coating. Should the heater assembly not prove adequate upon testing the option of such a coating will be explored to bring its performance to an acceptable level.

Measurement and Control of Flow Rate:

Accurate measurement and control of the flow rate through the test section is crucial to performing an actual filter test, and so several potential means of accomplishing those goals were considered. A major problem with attempting to measure the flow at the test section is the extremely high temperature of a test. After much debate, it was decided that measuring the *mass* flow rate of the cold inlet flow and using temperature and pressure measurements at the test section to determine density and volumetric flow rate would be the simplest and least expensive means to achieve acceptable accuracy. A hot wire anemometer was selected to directly measure the mass of the air entering the system. Temperature readings would be accomplished via thermocouple, and pressure measurements would be accomplished using a transducer connected to static pressure taps in the test section.

Figure 12: Hot wire anemometer

Figure 13: Control valve

It was determined that the best way to control the air flow through the device would be with an electronically actuated proportioning valve. With electronic control already being implemented for the heaters, it is much more cost effective and simple to stick with all electronic control than to use a pneumatically actuated valve. A Cole-Parmer brand Stepping Motor Proportioning Valve has been selected. This valve allows for flow rate to be adjusted precisely between 0% and 100% of its rated range. A flow coefficient of 0.855 has been selected to allow for a sufficient range of flow rates while maintaining as much resolution as possible. This valve will allow us to reach the original upper flow rate of 12 ACFM with only about 22 PSIA required at the inlet. With only 32 PSIA, we could potentially extend the upper flow rate to 36 ACFM.

In order to direct the flow to one or the other heater, a three-way switching valve is needed. Again, electronic actuation is preferred to avoid further complexity and reduce overall cost. A Swagelok brand valve was donated to the team by LLNL that has an ideal flow coefficient (0.9) for avoiding too much restriction, but came with a pneumatic actuator attached. However, a direct fit electric actuator is available from the manufacturer (Swagelok) to replace the pneumatic one at low cost. This valve will cause less than a 1 PSIA drop at our 12 ACFM upper flow specification, and only about 6 PSIA drop if we extend the upper flow limit to 36 ACFM.

Proofing of Performance Despite Pressure Drop:

The test section that will be used when the mini-HTTU enters service will likely not be completed in time to perform testing on pressure drop resilience for Team Phoenix. Therefore, it is necessary to create a means of generating the specified pressure drop without having a test filter. It was decided that the most economical and accurate means of generating the desired pressure drop was by manufacturing one or more orifice plates and using a differential pressure transducer to measure the pressure drop across the plate. The plate will be mounted between the same flanges used to connect the universal test section to avoid having to modify the unit.

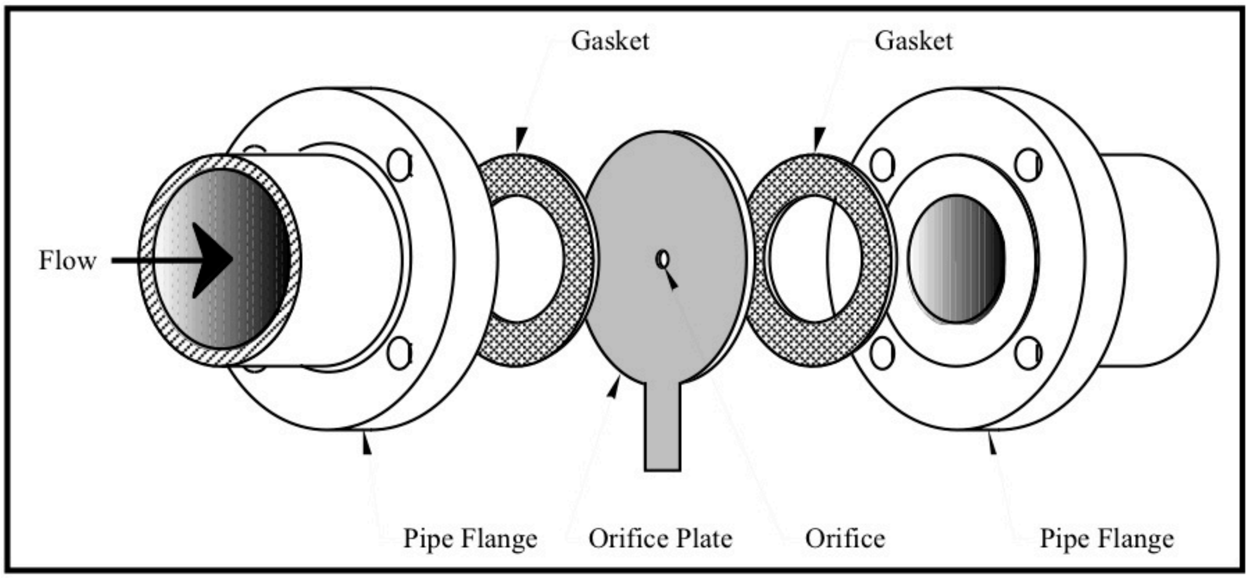


Figure 14: Orifice plate exploded view

Controls:

Controls will be a simple matter from Team Phoenix's side of the MHTTU, as a separate control team is spearheading the development of a universal control system compatible with both the HTTU and MHTTU. Continued collaboration with the control team ensures that compatible components are selected. From a project boundary standpoint, Team Phoenix's responsibility includes the selection and implementation of instruments and the supply of adequate power to said instruments, but not the control of said instruments.

Power Delivery System:

Primary power to the heaters will be supplied via 240V, 1 phase socket. While it was desirable to run the MHTTU solely on 120V power, the amperage draw required would have been dangerously high for most 120V circuits. Power to the control board and sensors will be supplied via 120V wall socket, however. This allows for troubleshooting and testing of the sensor and control system without having access to 240V power. Partitioning the power system in this manner also serves as an additional layer of protection against system damage if a malfunction should occur. For instance, if a heater or relay were to short out and trip the breaker or blow a fuse, the control electronics and sensors would not suffer a power loss or surge. The only interface between the two systems is the relay control lines, which are electronically isolated to 4000V.

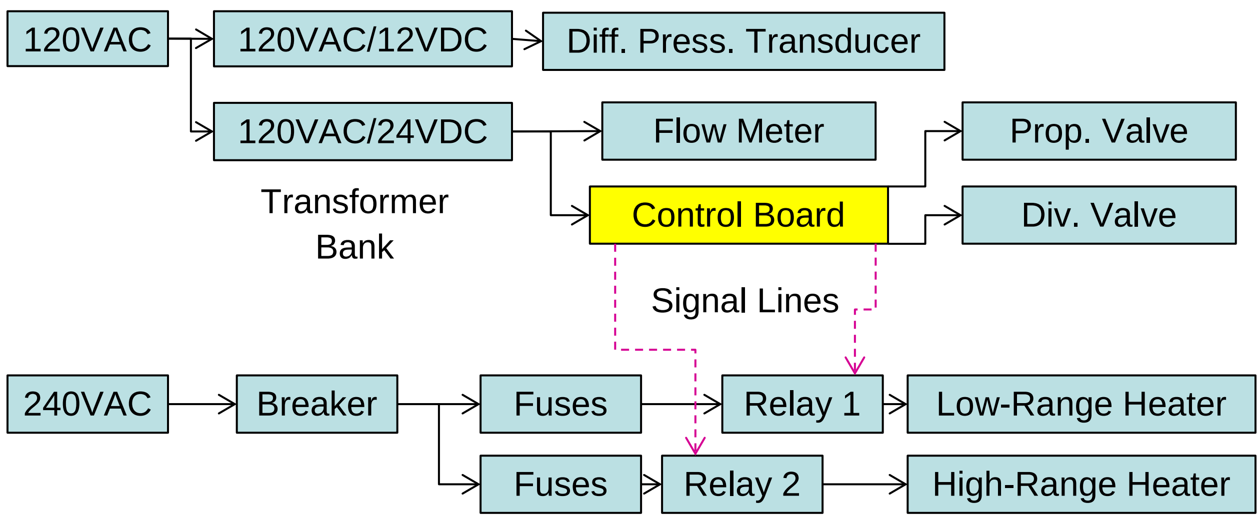


Figure 15: Power diagram

Management Plan:

Key Milestones and Deadlines:

Project Proposal Document – 10/24/2013
Conceptual Design Report – 12/5/2013
Conceptual Design Review – 12/12/2013
Test Plan Developed – 1/16/2014
Long Lead Items Ordered – 2/16/2014
Critical Design Review – 2/13/2014
Project Update Memo – 3/11/2014
Senior Project Expo – 5/29/2014
Final Report – 6/2/2014

Roles and Responsibilities:

Juan Nagengast	- Primary record keeper - Lead in air supply research/control
Mario Trinchero	- Primary Treasurer - Lead in heat source research/control - Fabrication lead
Andrew Wood	- Primary contact with sponsor - Lead in insulation research/implementation - CAD Modeling

Manufacturing:

Fabrication:

The majority of fabrication required involved joining sections of stainless steel tubing to create a high-temperature capable flow-path. The joining of the sections was accomplished using Tungsten Inert Gas welding performed in house at Cal Poly. Critical flow-path welds were done using a flux paste product applied to the inside of the tube sections that was then cleaned out post weld. This provided cleaner, better welds and a smoother flow path to minimize frictional losses.

Figure 16: Welded Assembly of immersion heater housing and transfer section.

Figure 17: "Test Section" to hold orifice plates.

Many of the tube sections needed to have cutting and machining done prior to welding. This was all done in house as well on non-CNC mills, lathes, and other cutting tools. Somewhat extensive mill work was required to fabricate the orifice plate section parts, the low-flow heater housing parts, and a gasket punch for making re-usable gaskets that unfortunately was not able to be used.

Additional fabrication work required the use of an optical-trace plasma cutter for certain round sheet metal parts, often plugs for the ends of tube sections. Several parts with non-critical dimensions, including some of the mounting hardware, were cut using hand held power tools.

Figure 16: Plasma cutting in action

Once the flow path was assembled, the hot sections were insulated using a dual layer wrapping technique with an additional finishing wrap on the surface. The inner layer was an alumina oxide based wrap secured tightly with stainless steel wire, while the outer layer was a mineral wool. Both layers are visible in figure 17, and the outer finished layer is visible on the final assembly in figure 18.

Figure 17: Flow path wrapped in insulation, both layers visible.

Figure 18: Flow path with finishing wrap

Testing:

Design Verification Summary

Table 1: Testing Summary

Item #	Specification	Test Description	Acceptance Criteria	Test Results
0	Low-Flow Heater Performance	Determine flow range capable of heating to 1300°F	~0.36-0.3 SCFM min. 0.36-3.4 SCFM goal.	1.25–12 ACFM
1	Control & Measure Flow	Flow Calibration	±0.1 SCFM	DV
2	Control & Measure Back Pressure	Back Pressure Calibration	±1 in. H20	DV
3	Test Section Flow Rate	Flow test	10.25-12 ACFM range	0.7-19ACFM DV
4	Test Section Air Temperature	Temperature test	1300°F minimum	1116°F DV
5	Test Section Pressure Drop	Pressure test	0.5-12 in. H20 range	29 in.H20 @ 19ACFM DV
7	Time to Operating Temp	Time test	15 minute max	12 minutes DV

*DV: design verification

Tests:

Width Test:

Via inspection, the design does in fact narrowly make its way through a standard doorway, as seen to the right in figure 19. The red bulb in the image is the immersion heater electrical housing, which is the furthest and only overhanging element from the cart structure. The total width of the cart including this overhang is about 33 inches.

Figure 19: Total assembly Fitting through a door.

Flow Calibration Verification:

Utilizing a small rotameter, and the setup shown below in figure 20, we were able to verify the factory calibration of the hot wire anemometer. The rotameter used had a range of 0 to 100 CFH, which with a simple unit conversion comes out to about 75 CFH for our minimum flow of 1.25 CFM, with reasonable resolution.

Figure 20: Flow Meter Test

Pressure Test:

For this test, we swept our flowrate up to our maximum specification of 12 ACFM, or approximately 3.5 SCFM on the cold side. We then measured the pressure differential across the orifice plate using our differential pressure transducer. The results below in figure 21 show that with our orifice plate, increased flow pushed a larger pressure across our orifice. We easily achieved 12 inches of water, verifying our design. The maximum reading the test section recorded was 29 inches of water at 19ACFM, as can be seen below.

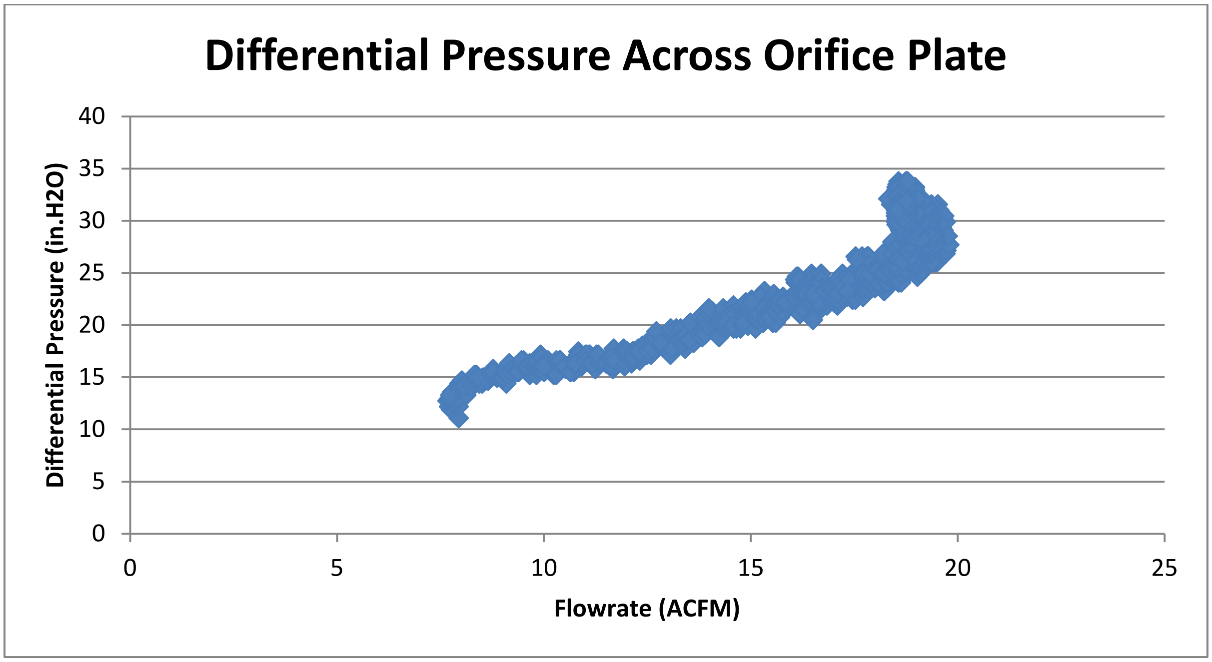


Figure 21: Differential pressure across the orifice plate.

Time to temperature

For this test, we turned on the immersion heater and left it on, recording data of both filter face temperature and filter face pressure. This test occurred at a flow rate of 19ACFM to test the upper limits of our range. From this data, we determined that the filter face temperature is stable after 12 minutes of operation.

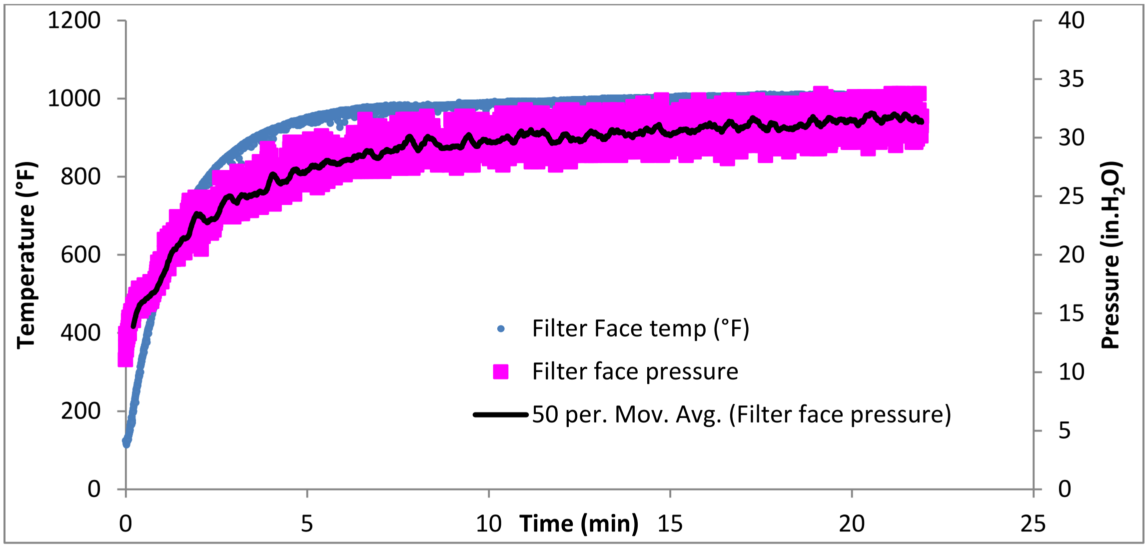


Figure 24: Long run data. Time to filter face temperature with pressure data.

Steady State Temperature vs. Range

We incrementally tested the flow range of each of our heaters. These tests were run with a single heater active per iteration, and using only one increment of input flow at a time. Data was taken from the test section thermocouple beginning when the heater was switched on and terminating once the once the temperature leveled out. We then recorded that temperature as the steady state value at that flow rate range, producing the plot seen below in Figure 25.

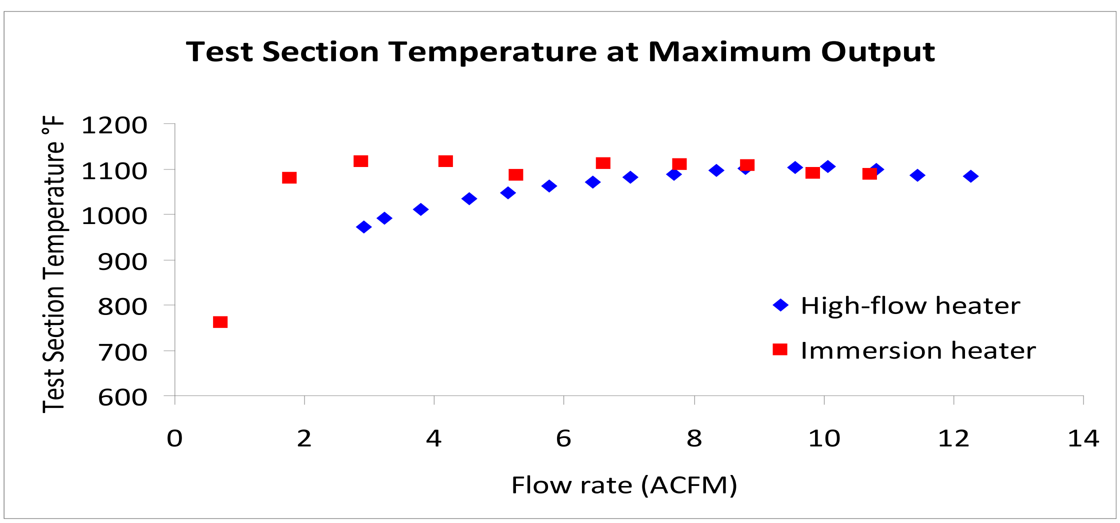


Figure 225: Steady State Test Section Temperature

Communication:

Communication with LLNL took place largely via email, in tandem with scheduled weekly teleconferences to facilitate open discussion. Regular meetings with the Principal Investigator for this project, Dr. Patton, were also be held to provide constant feedback on design decisions. A team email account, phoenix.httu@gmail.com was created to formalize communication with LLNL and manufacturers.

Documentation:

All team members are to keep logbooks for to keep track of concept generation and problem solutions. Physical copies of important documents, spec sheets, and other important information will be kept in a project binder in building 197. Simultaneously, digital documents will be stored between the team Google Drive and Dropbox.

Future Recommendations:

During testing we found that a large quantity of our heat, approximately 300 Watts, was being shed through the un-insulated length of the heat torch. Effectively the surface was acting as a giant fin and heat sink for our device. Testing revealed that our immersion heater alone can heat the MHTTU better than the heat torch. As such, our suggestion for future teams is to cut out the Torch "Fin" Section, and shed that unnecessary heat sink and thermal mass. Additionally, they may wish to wrap the test section in Band heaters in order to more easily heat the metal up, and decrease the thermal capacitance that the immersion heater has to handle. We believe that with both of these recommendations, future teams should easily achieve 1300F.

Works Cited**:**

[1] G. Brown, G. Dong and J. Marino, "High Temperature HEPA Filter Test Unit Final Design Report," Cal Poly Team Icarus, San Luis Obispo, CA, March 2012.

[2] M. Gainer, M. Goupil and A. Woolrich, "HEPA Filter Evaluation Furnace Control Unit Final Report", Cal Poly Team CP HEPA, San Luis Obispo, CA, November, 2012.

[3] B. Frandeen, W. Schill, E. Shewmaker and J. Turgeon, "High Temperature Filter Test Unit Upgrades", Cal Poly Team HiTop, San Luis Obispo, CA, June 2013.

[4] J. Browne. (2012, Sept. 5). *Wind Tunnel Aids Thermal Management.* [Online]. Available: http://mwrf.com/systems/wind-tunnel-aids-thermal-management

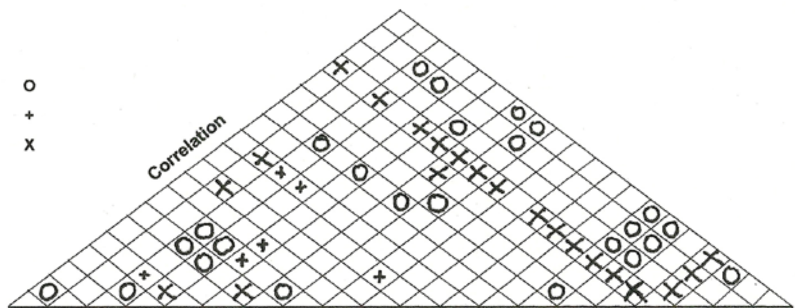
[5] *8 Foot Temperature Tunnel.* [Online]. Available: http://www.aeronautics.nasa.gov/atp/facilities/htt/index.html

Appendix A: Quality Function Deployment Table

Symbiotic Relationship = O

Parasitic Relationship = +

Mutually Detrimental = X



Mini HTTU- Team Phoenix

	Customer Weights (1-10)	Noramlized Weights	Movable Cart with Locking Wheels	Width (in)	Time to Operating Temperature (min)	Time to safe (120°F) from operating temperature (min)	Operating Temperature (°F)	Test Section Pressure Drop (in.H_2O)	Test Section Flow Rate (ACFM)	Flow and Heat Controls	Meet safety codes (OSHA, IEEE, ASME,etc.)	Use sealed removable test section	Include viewing window	Include Flame Impingement System	Include leak detection system	Install and calibrate closed-loop controller	Create graphical user interface for controls & feedback	Include Flame arrester and debris screen on exhaust	Total cost ($)	Include differential pressure meter for test section	Include test section inlet temperature meter	Include flow meter to measure exact flow rate in test section	Current HTTU Score (1-10)	Weighted Score
It has to fit on a workbench or have it's own stand	4	3%	9	9							1												10	0.31
Movable from lab to lab	6	5%	9	9								1											4	0.19
Fast heat up	8	6%			9		3		1	3						3					1	1	1	0.06
Fast cool down	7	5%				9	3		1	3												1	5	0.27
Meets test temperature req.	10	8%			3	3	9			3						1					3		1	0.08
Meets test pressure req.	10	8%						9	3						1	1				3			10	0.78
Meets test flow req.	10	8%					1	3	9	3					1	1						3	10	0.78
Must be adjustable on the fly	7	5%			3	3		1		9	3					3	1			1	1	1	5	0.27
Has to be safe for the operator and observers	10	8%	1			3	1	1	1	9	9	3	3		1	1		9		1	1	1	8	0.62
Has to accommodate a universal test section	9	7%										9											1	0.07
Test section must be viewable during operation	7	5%									3	3	9										8	0.43
Includes Flame Impingement	2	2%												9									10	0.16
Includes leak detection	2	2%													9					1		1	10	0.16
Includes closed-loop control system	3	2%								3	3					9				1	1	1	10	0.23
Includes graphical user interface for controls	1	1%															9						1	0.01
Hot Debris cannot escape test unit	2	2%									3							9					1	0.02
Must fit within budget	6	5%																	9				1	0.05
Feedback for test section pressure drop	8	6%													1		3			9			10	0.62
Feedback for test section temperature	9	7%								1			1				3				9		10	0.70
Feedback for test section flow rate	8	6%								1					1		3					9	10	0.62
Totals	129	100%	0.78	0.70	0.95	1.12	1.20	1.06	1.12	2.20	1.17	1.07	0.79	0.14	0.50	0.87	0.71	0.84	0.42	0.96	1.06	1.06		6.40
Normalized Importance			4.1%	3.7%	5.1%	6.0%	6.4%	5.7%	6.0%	11.7%	6.2%	5.7%	4.2%	0.7%	2.6%	4.6%	3.8%	4.5%	2.2%	5.1%	5.7%	5.7%		
Current HTTU			1	30	180	15	1000	12	250	2	1	1	1	1	1	1	0	0	32k	1	1	1		
Mini-HTTU Targets			1	32	15	15	1300	12	12	2	1	1	0	0	0	0	0	1	20k	1	1	1		

Primary Spec

Secondary Spec

Consideration

Appendix B: Compliance Matrix

#	Specification	Target	Tolerance	Test	Risk	Complication Explanation
1	Movable Cart with Locking Wheels	yes	yes	I	L	
2	Width (in)	32	max	I	M	
3	Time to Operating Temperature (min)	15	max	A,T	H	Potentially difficult to implement in open-loop system. Larger heaters, good insulation, and well-managed flow will be major considerations to pursue this goal. Implementation of closed-loop control will help as well.
4	Time to safe (120°F) from operating temperature (min)	15	max	A,T, I	L	
5	Operating Temperature (°F)	1300	min	A, T	M	
6	Maintain Flow with Test Section Pressure Drop (in.H2O)	0.5-12	min/max	A, T	L	
7	Test Section Flow Rate (ACFM)	0.5-12	min/max	A, T	L	
8	Flow and Heat Controls	yes	yes	I	L	
9	Meet safety codes (OSHA, IEEE, ASME,etc.)	yes	yes	T, I	M	
10	Use sealed removable test section	yes	yes	I, S	L	
11	Include viewing window (pending collaboration w/ test section team)	yes	yes	I	M	
12	Include digital control capability for closed-loop controller	yes	yes	S, A, T	M	A member of CPHEPA, the controls team for the original HTTU, is devising a universal control system for use on the mini-HTTU and the original HTTU. Team Pheonix will be collaborating with him on control integration.
13	Include Flame arrester and debris screen on exhaust	yes	yes	I, T	L	
14	Total cost ($)	$8,000	max	I	M	
15	Include differential pressure readout for test section	yes	yes	I, T	L	
16	Include test section inlet temperature meter	yes	yes	I, T	L	
17	Include flow meter to measure exact flow rate in test section	yes	yes	I, T	L	

Analysis - A
Testing - T
Inspection - I
Similarity to existing design - S

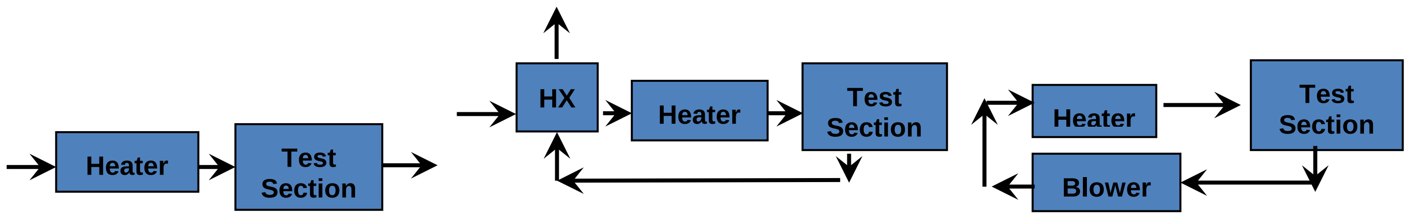
High Risk Obstacle - H
Moderate Risk Obstacle - M
Low Risk Obstacle - L

Appendix C: Component and Layout Pugh Matrices

(Un-weighted. For feature comparison only)

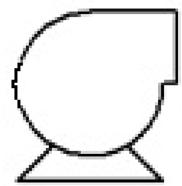
Heater Comparison - HTTU						
Manufacturer	Tutco Farnam	Osram - Sylvania Inline Heaters			Watlow	MHI
Criteria	Heat Torch (Baseline)	Hot Air Tools	Series I,II,III	Serpentine II	Immersion Heater	Inline 4kW heater
Max Temperature	0	1	1	1	1	1
Flow rate @ Max Temperature	0	0	-1	1	1	1
Min Safe Flow Rate	0	0	0	0	1	-1
Max Inlet Temperature	0	-1	-1	0	1	1
Inlet Connection	0	-1	-1	0	1	1
Outlet Connection	0	0	-1	-1	1	1
Working Pressure	0	0	-1	0	1	1
Pressure Drop Through Unit	0	0	-1	0	0	1
Thermocouple Integration	0	1	-1	1	1	1
Control Availability	0	0	0	0	0	0
Cost	0	1	1	-1	0	-1
TOTAL	0	1	-5	1	8	6
Notes	Baseline heater. Cannot safely reach spec. temperature. Does **not** meet minimum flow spec.	Inlet temperature suffers. Volume may be an issue with small, plastic inlet fitting. Does **not** meet minimum flow spec.	Quartz glass outside makes connection a major challenge. Very high temperature capability, but low inlet temperature tolerance. Does **not** meet minimum flow spec.	Outlet connection is awkward, but workable. Higher inlet temperature capability. Does **not** meet minimum flow spec.	Simply a heating element designed to fit inside a channel or tank. Can handle low flows but not designed to heat air streams so effectiveness at heating higher flows is questionable.	Does **not** meet minimum flow specification as we were initially led to believe. Prohibitively expensive.

Appendix D: Pugh Matrix for cycle selection



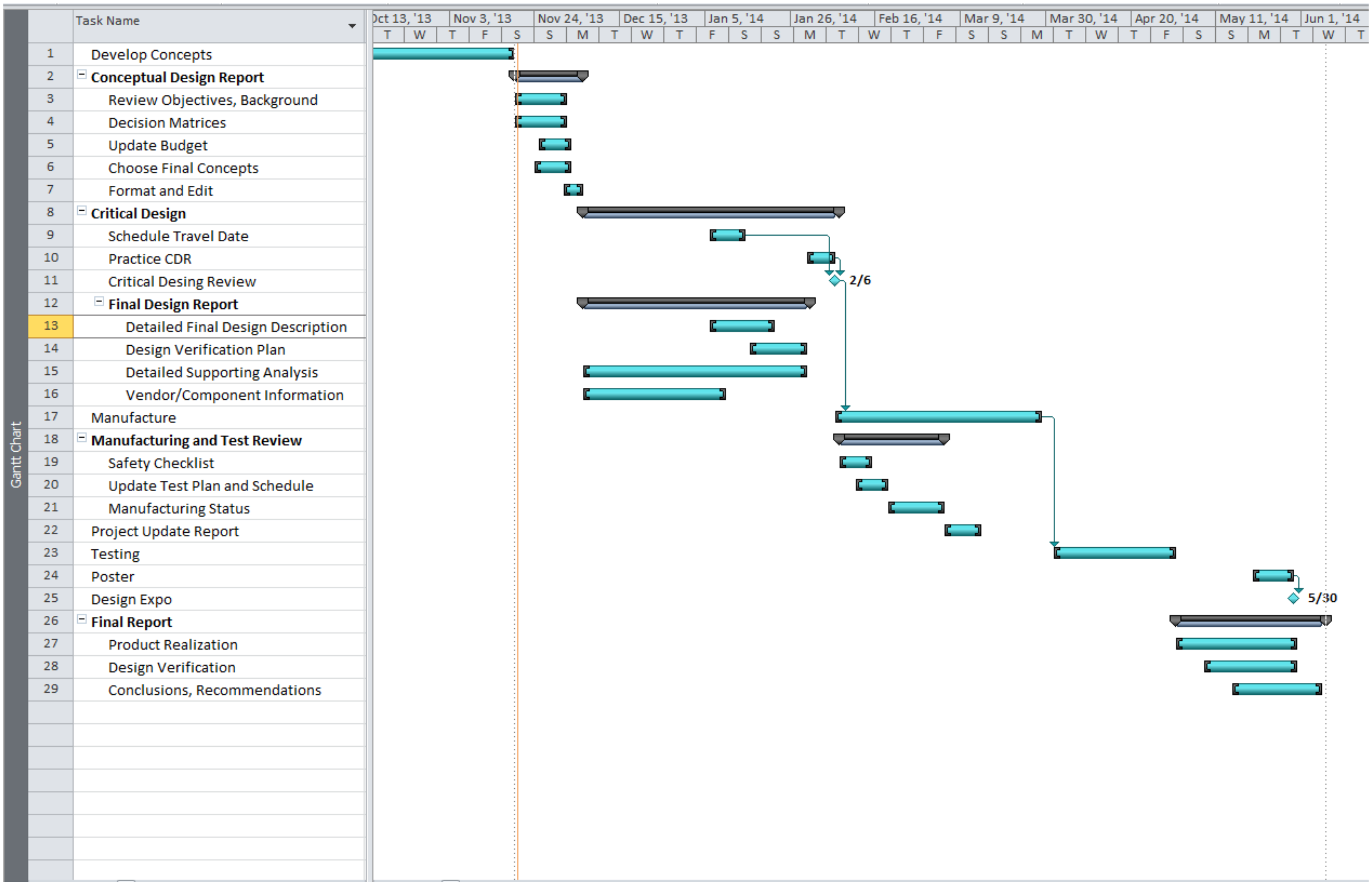
	Once Through (Datum)	Once Through w/ HX	Fully Recirculating
Criteria	Score	Score	Score
Small	0	-	-
Aesthetic	0	0	0
Cost	0	0	-
Ease of Assembly	0	0	-
Long life	0	0	-
Safe	0	0	+
High Temp	0	0	0
Fast	0	+	+
Portable	0	0	0
Power Req.	0	+	+
Total Plus	0	2	3
Total Minus	0	1	4
Net Total	0	1	-1

Appendix E: Pugh Matrix for Air supply



	Vortex Regenerative Blower	Compressed Air Lines	Custom Inline Fan
Performance	+	D	-
Cost	-		-
Portability	+	A	+
Size	-		-
Power Required	-	T	-
Manufaturability	S		-
Σ+	2	U	1
Σ-	3		5
ΣS	1	M	0

Appendix F: Management Plan Gant Chart



Appendix G: Tabular Chart Data

Table G1 – Theoretical Heater output

Heater Output	Vspec	L	ToutF	Wattdensity
	[ft3/min]	[in]	[F]	[W/in2]
Run 1	6	23.06	1600	0.842
Run 2	7.556	23.06	1598	3.49
Run 3	9.111	23.06	1569	5.706
Run 4	10.67	23.06	1515	7.369
Run 5	12.22	23.06	1452	8.66
Run 6	13.78	23.06	1387	9.696
Run 7	15.33	23.06	1324	10.55
Run 8	16.89	23.06	1265	11.26
Run 9	18.44	23.06	1209	11.87
Run 10	20	23.06	1157	12.39
Run 11	4.5	17.06	1600	0.9855
Run 12	5	17.06	1600	2.15
Run 13	7	17.06	1558	6.123
Run 14	10.67	17.06	1361	10.07
Run 15	12.22	17.06	1278	11.11
Run 16	13.78	17.06	1202	11.94
Run 17	15.33	17.06	1133	12.61
Run 18	16.89	17.06	1071	13.18
Run 19	18.44	17.06	1015	13.65
Run 20	20	17.06	963.4	14.06
Run 21	3	11.44	1600	0.9245
Run 22	4	11.44	1592	4.284
Run 23	5	11.44	1537	6.794
Run 24	7	11.44	1373	9.893
Run 25	9	11.44	1219	11.76
Run 26	12	11.44	1034	13.49
Run 27	15.33	11.44	881.1	14.66
Run 28	16.89	11.44	824.1	15.05
Run 29	18.44	11.44	774	15.38
Run 30	20	11.44	729.8	15.66

Table G2 – Insulation and heat loss analysis data

Pipe heat loss data

	Vflow	tinsulation, total	tinner	OD pipe	Tr4		q		Tinlet,F	RaD,out	C	n
	[ft3/min]	[in]	[in]	[in]	[R]	[F]	[Btu/h]	{[W]}	[F]			
Run 1	0.5	1	0.4193	2	759.8	299.8	280.9	{82.31}	2752	5.13E+06	0.48	0.25
Run 2	0.5	1.5	0.4955	2	686.9	226.9	204.6	{59.95}	2369	8.72E+06	0.48	0.25
Run 3	0.5	2	0.5656	2	650.5	190.5	168.4	{49.34}	2185	1.30E+07	0.125	0.333
Run 4	0.5	2.5	0.6291	2	627.8	167.8	146.7	{43.01}	2074	1.80E+07	0.125	0.333
Run 5	0.5	3	0.6873	2	612.9	152.9	132.1	{38.71}	1999	2.36E+07	0.125	0.333
Run 6	0.5	3.5	0.741	2	602.3	142.3	121.4	{35.58}	1944	3.00E+07	0.125	0.333
Run 7	0.5	4	0.791	2	594.4	134.4	113.2	{33.18}	1901	3.72E+07	0.125	0.333
Run 8	0.5	4.5	0.8377	2	588.3	128.3	106.7	{31.28}	1867	4.50E+07	0.125	0.333
Run 9	0.5	5	0.8817	2	583.4	123.4	101.4	{29.72}	1840	5.37E+07	0.125	0.333
Run 10	0.5	5.5	0.9233	2	579.4	119.4	96.94	{28.41}	1816	6.30E+07	0.125	0.333
Run 11	0.5	6	0.9628	2	576.1	116.1	93.16	{27.3}	1797	7.32E+07	0.125	0.333
Run 12	0.5	6.5	1	2	573.3	113.3	89.89	{26.34}	1780	8.41E+07	0.125	0.333
Run 13	0.5	7	1.036	2	570.9	110.9	87.03	{25.5}	1765	9.57E+07	0.125	0.333
Run 14	0.5	7.5	1.071	2	568.8	108.8	84.5	{24.76}	1751	1.08E+08	0.125	0.333
Run 15	0.5	8	1.104	2	567	107	82.25	{24.1}	1739	1.21E+08	0.125	0.333
Run 16	1.25	1	0.01776	2	675.9	215.9	157.5	{46.17}	1638	4.31E+06	0.48	0.25
Run 17	1.25	1.5	0.08346	2	642.5	182.5	132.1	{38.72}	1584	7.21E+06	0.48	0.25
Run 18	1.25	2	0.1403	2	622.8	162.8	116.6	{34.18}	1551	1.09E+07	0.125	0.333
Run 19	1.25	2.5	0.1901	2	608.2	148.2	106.2	{31.13}	1529	1.51E+07	0.125	0.333
Run 20	1.25	3	0.2351	2	598	138	98.55	{28.88}	1513	2.00E+07	0.125	0.333
Run 21	1.25	3.5	0.2764	2	590.5	130.5	92.63	{27.15}	1500	2.56E+07	0.125	0.333
Run 22	1.25	4	0.3145	2	584.7	124.7	87.89	{25.76}	1490	3.18E+07	0.125	0.333
Run 23	1.25	4.5	0.3501	2	580.1	120.1	83.99	{24.61}	1481	3.88E+07	0.125	0.333
Run 24	1.25	5	0.3835	2	576.4	116.4	80.71	{23.65}	1474	4.64E+07	0.125	0.333
Run 25	1.25	5.5	0.415	2	573.3	113.3	77.91	{22.83}	1468	5.47E+07	0.125	0.333
Run 26	1.25	6	0.4448	2	570.7	110.7	75.48	{22.12}	1463	6.37E+07	0.125	0.333
Run 27	1.25	6.5	0.4732	2	568.5	108.5	73.35	{21.5}	1459	7.35E+07	0.125	0.333
Run 28	1.25	7	0.5003	2	566.6	106.6	71.45	{20.94}	1455	8.39E+07	0.125	0.333
Run 29	1.25	7.5	0.5262	2	564.9	104.9	69.76	{20.45}	1451	9.50E+07	0.125	0.333

Run 30	1.25	8	0.5511	2	563.4	103.4	68.24	{20}	1448	1.07E+08	0.125	0.333
Run 31	12	1	1.18E-34	2	652.8	192.8	125.7	{36.83}	1328	3.91E+06	0.48	0.25
Run 32	12	1.5	6.25E-66	2	627.7	167.7	109.3	{32.03}	1325	6.54E+06	0.48	0.25
Run 33	12	2	6.58E-33	2	612.2	152.2	98.67	{28.92}	1322	9.90E+06	0.48	0.25
Run 34	12	2.5	3.69E-34	2	600.6	140.6	91.19	{26.73}	1321	1.38E+07	0.125	0.333
Run 35	12	3	0.0245	2	592	132	85.55	{25.07}	1319	1.84E+07	0.125	0.333
Run 36	12	3.5	0.05943	2	585.6	125.6	81.11	{23.77}	1318	2.36E+07	0.125	0.333
Run 37	12	4	0.0917	2	580.6	120.6	77.49	{22.71}	1318	2.94E+07	0.125	0.333
Run 38	12	4.5	0.1218	2	576.6	116.6	74.47	{21.82}	1317	3.59E+07	0.125	0.333
Run 39	12	5	0.1499	2	573.3	113.3	71.9	{21.07}	1316	4.30E+07	0.125	0.333
Run 40	12	5.5	0.1765	2	570.6	110.6	69.69	{20.42}	1316	5.08E+07	0.125	0.333
Run 41	12	6	0.2017	2	568.2	108.2	67.75	{19.86}	1315	5.93E+07	0.125	0.333
Run 42	36	1	0.1553	2	698.1	238.1	189.1	{55.41}	1314	4.61E+06	0.48	0.25
Run 43	36	1.5	0.2289	2	655.8	195.8	153.3	{44.92}	1312	7.74E+06	0.48	0.25
Run 44	36	2	0.2926	2	631.6	171.6	132.7	{38.9}	1310	1.16E+07	0.125	0.333
Run 45	36	2.5	0.3487	2	614.7	154.7	119.3	{34.97}	1309	1.61E+07	0.125	0.333
Run 46	36	3	0.3994	2	603.1	143.1	109.7	{32.15}	1308	2.13E+07	0.125	0.333
Run 47	36	3.5	0.4459	2	594.6	134.6	102.4	{30}	1308	2.72E+07	0.125	0.333
Run 48	36	4	0.4889	2	588.1	128.1	96.59	{28.31}	1307	3.38E+07	0.125	0.333
Run 49	36	4.5	0.5291	2	583	123	91.88	{26.93}	1307	4.10E+07	0.125	0.333
Run 50	36	5	0.5668	2	578.9	118.9	87.96	{25.78}	1307	4.90E+07	0.125	0.333
Run 51	36	5.5	0.6023	2	575.5	115.5	84.64	{24.8}	1306	5.78E+07	0.125	0.333
Run 52	36	6	0.636	2	572.6	112.6	81.77	{23.96}	1306	6.72E+07	0.125	0.333
Run 53	0.5	1	0.3966	1	716.4	{256.7}	173.9	{50.98}	2213	2.03E+06	0.48	0.25
Run 54	0.5	1.5	0.4968	1	661.9	{202.2}	138	{40.44}	2029	4.07E+06	0.48	0.25
Run 55	0.5	2	0.5837	1	634	{174.4}	119	{34.86}	1931	6.84E+06	0.48	0.25
Run 56	0.5	2.5	0.6613	1	617.3	{157.6}	106.9	{31.33}	1868	1.04E+07	0.125	0.333
Run 57	0.5	3	0.7307	1	604.4	{144.7}	98.55	{28.88}	1825	1.45E+07	0.125	0.333
Run 58	0.5	3.5	0.7946	1	595.2	{135.5}	92.29	{27.05}	1792	1.92E+07	0.125	0.333
Run 59	0.5	4	0.854	1	588.3	{128.6}	87.38	{25.61}	1766	2.47E+07	0.125	0.333
Run 60	0.5	4.5	0.9098	1	582.9	{123.3}	83.4	{24.44}	1746	3.08E+07	0.125	0.333
Run 61	0.5	5	0.9624	1	578.7	{119}	80.09	{23.47}	1728	3.76E+07	0.125	0.333
Run 62	0.5	5.5	1.012	1	575.2	{115.5}	77.29	{22.65}	1713	4.51E+07	0.125	0.333
Run 63	0.5	6	1.06	1	572.3	{112.6}	74.88	{21.94}	1701	5.33E+07	0.125	0.333
Run 64	0.5	6.5	1.105	1	569.8	{110.2}	72.77	{21.33}	1690	6.22E+07	0.125	0.333

Run 65	0.5	7	1.149	1	567.7	{108.1}	70.91	{20.78}	1680	7.18E+07	0.125	0.333
Run 66	0.5	7.5	1.191	1	565.9	{106.3}	69.25	{20.3}	1671	8.21E+07	0.125	0.333
Run 67	0.5	8	1.231	1	564.3	{104.7}	67.76	{19.86}	1663	9.32E+07	0.125	0.333
Run 68	12	1	0.2557	1	684.1	{224.4}	136.2	{39.93}	1331	1.87E+06	0.48	0.25
Run 69	12	1.5	0.3431	1	644	{184.3}	113.7	{33.33}	1326	3.72E+06	0.48	0.25
Run 70	12	2	0.4183	1	622.1	{162.4}	100.7	{29.52}	1323	6.26E+06	0.48	0.25
Run 71	12	2.5	0.485	1	608.2	{148.5}	92.07	{26.98}	1321	9.51E+06	0.48	0.25
Run 72	12	3	0.545	1	597.8	{138.2}	85.87	{25.17}	1319	1.34E+07	0.125	0.333
Run 73	12	3.5	0.6	1	589.9	{130.3}	81.13	{23.78}	1318	1.78E+07	0.125	0.333
Run 74	12	4	0.651	1	583.9	{124.3}	77.35	{22.67}	1318	2.29E+07	0.125	0.333
Run 75	12	4.5	0.6989	1	579.3	{119.6}	74.24	{21.76}	1317	2.86E+07	0.125	0.333
Run 76	12	5	0.744	1	575.5	{115.8}	71.64	{20.99}	1316	3.50E+07	0.125	0.333
Run 77	12	5.5	0.7868	1	572.4	{112.7}	69.4	{20.34}	1316	4.20E+07	0.125	0.333
Run 78	12	6	0.8276	1	569.8	{110.1}	67.47	{19.77}	1315	4.98E+07	0.125	0.333
Run 79	36	1	0.2917	1	691.5	{231.8}	144.8	{42.43}	1311	1.91E+06	0.48	0.25
Run 80	36	1.5	0.3834	1	648.3	{188.7}	119.6	{35.05}	1309	3.82E+06	0.48	0.25
Run 81	36	2	0.4624	1	625.1	{165.4}	105.3	{30.86}	1308	6.41E+06	0.48	0.25
Run 82	36	2.5	0.5324	1	610.5	{150.8}	95.87	{28.1}	1307	9.74E+06	0.48	0.25
Run 83	36	3	0.5954	1	599.6	{139.9}	89.17	{26.13}	1307	1.37E+07	0.125	0.333
Run 84	36	3.5	0.653	1	591.3	{131.6}	84.07	{24.64}	1306	1.82E+07	0.125	0.333
Run 85	36	4	0.7066	1	585.1	{125.4}	80.01	{23.45}	1306	2.34E+07	0.125	0.333
Run 86	36	4.5	0.7568	1	580.2	{120.6}	76.69	{22.48}	1306	2.92E+07	0.125	0.333
Run 87	36	5	0.8041	1	576.4	{116.7}	73.91	{21.66}	1306	3.57E+07	0.125	0.333
Run 88	36	5.5	0.849	1	573.2	{113.5}	71.54	{20.97}	1305	4.29E+07	0.125	0.333
Run 89	36	6	0.8918	1	570.5	{110.8}	69.48	{20.36}	1305	5.07E+07	0.125	0.333
Run 90	1.25	1	0.1879	1	671.3	{211.7}	121.8	{35.69}	1562	1.79E+06	0.48	0.25
Run 91	1.25	1.5	0.2676	1	636.3	{176.6}	103.6	{30.35}	1523	3.55E+06	0.48	0.25
Run 92	1.25	2	0.3363	1	616.7	{157}	92.71	{27.17}	1500	5.98E+06	0.48	0.25
Run 93	1.25	2.5	0.3972	1	604.1	{144.4}	85.36	{25.02}	1484	9.09E+06	0.48	0.25
Run 94	1.25	3	0.452	1	594.8	{135.1}	80	{23.45}	1473	1.28E+07	0.125	0.333
Run 95	1.25	3.5	0.5021	1	587.4	{127.7}	75.89	{22.24}	1464	1.71E+07	0.125	0.333
Run 96	1.25	4	0.5487	1	581.8	{122.2}	72.58	{21.27}	1457	2.20E+07	0.125	0.333
Run 97	1.25	4.5	0.5923	1	577.4	{117.8}	69.85	{20.47}	1451	2.75E+07	0.125	0.333
Run 98	1.25	5	0.6335	1	573.9	{114.2}	67.54	{19.79}	1446	3.37E+07	0.125	0.333
Run 99	1.25	5.5	0.6726	1	571	{111.3}	65.55	{19.21}	1442	4.05E+07	0.125	0.333

Run 100	1.25	6	0.7097	1	568.6	{108.9}	63.83	{18.71}	1438	4.79E+07	0.125	0.333
Run 101	1.25	6.5	0.7453	1	566.5	{106.8}	62.3	{18.26}	1435	5.61E+07	0.125	0.333
Run 102	1.25	7	0.7794	1	564.7	{105}	60.94	{17.86}	1432	6.48E+07	0.125	0.333
Run 103	1.25	7.5	0.8122	1	563.1	{103.5}	59.72	{17.5}	1429	7.43E+07	0.125	0.333
Run 104	1.25	8	0.8438	1	561.8	{102.1}	58.62	{17.18}	1427	8.44E+07	0.125	0.333
Run 105	0.5	1	0.2543	0.75	690	{230.3}	134	{39.27}	2009	1.47E+06	0.48	0.25
Run 106	0.5	1.5	0.3073	0.75	644.5	{184.8}	109	{31.95}	1879	3.08E+06	0.48	0.25
Run 107	0.5	2	0.3516	0.75	621	{161.4}	95.44	{27.97}	1809	5.32E+06	0.48	0.25
Run 108	0.5	2.5	0.3899	0.75	606.6	{147}	86.68	{25.4}	1763	8.23E+06	0.48	0.25
Run 109	0.5	3	0.4239	0.75	596.6	{136.9}	80.49	{23.59}	1730	1.18E+07	0.125	0.333
Run 110	0.5	3.5	0.4542	0.75	588.6	{128.9}	75.85	{22.23}	1706	1.58E+07	0.125	0.333
Run 111	0.5	4	0.482	0.75	582.6	{122.9}	72.18	{21.15}	1687	2.05E+07	0.125	0.333
Run 112	0.5	4.5	0.5077	0.75	577.9	{118.2}	69.18	{20.28}	1671	2.58E+07	0.125	0.333
Run 113	0.5	5	0.5316	0.75	574.2	{114.5}	66.68	{19.54}	1658	3.16E+07	0.125	0.333
Run 114	0.5	5.5	0.5541	0.75	571.1	{111.5}	64.55	{18.92}	1646	3.82E+07	0.125	0.333
Run 115	0.5	6	0.5752	0.75	568.6	{108.9}	62.7	{18.38}	1636	4.53E+07	0.125	0.333
Run 116	0.5	6.5	0.5953	0.75	566.4	{106.8}	61.09	{17.9}	1628	5.31E+07	0.125	0.333
Run 117	0.5	7	0.6144	0.75	564.6	{104.9}	59.65	{17.48}	1620	6.15E+07	0.125	0.333
Run 118	0.5	7.5	0.6326	0.75	563	{103.3}	58.37	{17.11}	1614	7.05E+07	0.125	0.333
Run 119	0.5	8	0.65	0.75	561.6	{101.9}	57.22	{16.77}	1607	8.02E+07	0.125	0.333
Run 120	12	1	0.1557	0.75	669.9	{210.2}	112.6	{32.99}	1326	1.37E+06	0.48	0.25
Run 121	12	1.5	0.2022	0.75	633.1	{173.4}	94.71	{27.76}	1321	2.87E+06	0.48	0.25
Run 122	12	2	0.2407	0.75	613.3	{153.6}	84.42	{24.74}	1319	4.97E+06	0.48	0.25
Run 123	12	2.5	0.2739	0.75	600.9	{141.2}	77.57	{22.73}	1318	7.70E+06	0.48	0.25
Run 124	12	3	0.3033	0.75	592.2	{132.6}	72.61	{21.28}	1316	1.11E+07	0.125	0.333
Run 125	12	3.5	0.3295	0.75	585.1	{125.4}	68.84	{20.18}	1316	1.49E+07	0.125	0.333
Run 126	12	4	0.3534	0.75	579.7	{120}	65.83	{19.29}	1315	1.93E+07	0.125	0.333
Run 127	12	4.5	0.3755	0.75	575.4	{115.7}	63.35	{18.57}	1314	2.43E+07	0.125	0.333
Run 128	12	5	0.3961	0.75	572	{112.3}	61.26	{17.95}	1314	2.99E+07	0.125	0.333
Run 129	12	5.5	0.4154	0.75	569.2	{109.6}	59.46	{17.43}	1313	3.61E+07	0.125	0.333
Run 130	12	6	0.4337	0.75	566.9	{107.2}	57.9	{16.97}	1313	4.29E+07	0.125	0.333
Run 131	36	1	0.1767	0.75	673.9	{214.3}	116.8	{34.24}	1309	1.39E+06	0.48	0.25
Run 132	36	1.5	0.2252	0.75	635.5	{175.8}	97.7	{28.63}	1307	2.91E+06	0.48	0.25
Run 133	36	2	0.2653	0.75	615	{155.3}	86.79	{25.44}	1307	5.05E+06	0.48	0.25
Run 134	36	2.5	0.2999	0.75	602.1	{142.5}	79.56	{23.32}	1306	7.82E+06	0.48	0.25

Run 135	36	3	0.3304	0.75	593.2	{133.5}	74.35	{21.79}	1306	1.12E+07	0.125	0.333
Run 136	36	3.5	0.3576	0.75	585.9	{126.2}	70.41	{20.63}	1305	1.51E+07	0.125	0.333
Run 137	36	4	0.3825	0.75	580.3	{120.6}	67.26	{19.71}	1305	1.96E+07	0.125	0.333
Run 138	36	4.5	0.4056	0.75	576	{116.3}	64.67	{18.95}	1305	2.47E+07	0.125	0.333
Run 139	36	5	0.427	0.75	572.5	{112.8}	62.49	{18.31}	1305	3.03E+07	0.125	0.333
Run 140	36	5.5	0.4471	0.75	569.7	{110}	60.62	{17.77}	1305	3.66E+07	0.125	0.333
Run 141	36	6	0.466	0.75	567.3	{107.6}	59	{17.29}	1304	4.35E+07	0.125	0.333
Run 142	1.25	1	0.08586	0.75	657.3	{197.6}	99.42	{29.14}	1515	1.30E+06	0.48	0.25
Run 143	1.25	1.5	0.1264	0.75	625.4	{165.8}	85.3	{25}	1484	2.71E+06	0.48	0.25
Run 144	1.25	2	0.1599	0.75	607.9	{148.2}	76.89	{22.53}	1466	4.70E+06	0.48	0.25
Run 145	1.25	2.5	0.1888	0.75	596.7	{137.1}	71.19	{20.86}	1454	7.30E+06	0.48	0.25
Run 146	1.25	3	0.2145	0.75	589.1	{129.4}	66.99	{19.63}	1445	1.06E+07	0.125	0.333
Run 147	1.25	3.5	0.2372	0.75	582.5	{122.8}	63.78	{18.69}	1438	1.42E+07	0.125	0.333
Run 148	1.25	4	0.2581	0.75	577.5	{117.8}	61.19	{17.93}	1433	1.84E+07	0.125	0.333
Run 149	1.25	4.5	0.2773	0.75	573.6	{113.9}	59.04	{17.3}	1428	2.32E+07	0.125	0.333
Run 150	1.25	5	0.2952	0.75	570.4	{110.7}	57.23	{16.77}	1424	2.86E+07	0.125	0.333
Run 151	1.25	5.5	0.312	0.75	567.8	{108.1}	55.66	{16.31}	1421	3.46E+07	0.125	0.333
Run 152	1.25	6	0.3279	0.75	565.6	{105.9}	54.29	{15.91}	1418	4.11E+07	0.125	0.333
Run 153	1.25	6.5	0.3429	0.75	563.7	{104.1}	53.08	{15.56}	1415	4.82E+07	0.125	0.333
Run 154	1.25	7	0.3571	0.75	562.1	{102.5}	52.01	{15.24}	1413	5.60E+07	0.125	0.333
Run 155	1.25	7.5	0.3707	0.75	560.7	{101.1}	51.04	{14.96}	1411	6.43E+07	0.125	0.333
Run 156	1.25	8	0.3837	0.75	559.5	{99.85}	50.16	{14.7}	1409	7.32E+07	0.125	0.333
Run 157	0.5	1	0.3009	0.5	680.3	{220.6}	115	{33.72}	1911	1.07E+06	0.48	0.25
Run 158	0.5	1.5	0.3761	0.5	638.4	{178.7}	96.22	{28.2}	1813	2.41E+06	0.48	0.25
Run 159	0.5	2	0.438	0.5	616.7	{157}	85.68	{25.11}	1758	4.36E+06	0.48	0.25
Run 160	0.5	2.5	0.4923	0.5	603.3	{143.6}	78.75	{23.08}	1721	6.94E+06	0.48	0.25
Run 161	0.5	3	0.5413	0.5	594.5	{134.8}	73.75	{21.62}	1695	1.02E+07	0.125	0.333
Run 162	0.5	3.5	0.5853	0.5	586.8	{127.1}	70	{20.51}	1675	1.39E+07	0.125	0.333
Run 163	0.5	4	0.6261	0.5	581.1	{121.4}	67	{19.63}	1659	1.83E+07	0.125	0.333
Run 164	0.5	4.5	0.6641	0.5	576.7	{117}	64.53	{18.91}	1646	2.32E+07	0.125	0.333
Run 165	0.5	5	0.6999	0.5	573.1	{113.4}	62.45	{18.3}	1635	2.87E+07	0.125	0.333
Run 166	0.5	5.5	0.7338	0.5	570.2	{110.5}	60.67	{17.78}	1626	3.48E+07	0.125	0.333
Run 167	0.5	6	0.766	0.5	567.7	{108.1}	59.13	{17.33}	1618	4.16E+07	0.125	0.333
Run 168	0.5	6.5	0.7968	0.5	565.7	{106}	57.76	{16.93}	1610	4.89E+07	0.125	0.333
Run 169	0.5	7	0.8262	0.5	563.9	{104.3}	56.55	{16.57}	1604	5.70E+07	0.125	0.333

Run 170	0.5	7.5	0.8545	0.5	562.4	{102.7}	55.46	{16.25}	1598	6.56E+07	0.125	0.333
Run 171	0.5	8	0.8817	0.5	561	{101.4}	54.48	{15.97}	1593	7.49E+07	0.125	0.333
Run 172	12	1	0.2329	0.5	667.7	{208}	102.6	{30.08}	1323	1.02E+06	0.48	0.25
Run 173	12	1.5	0.3087	0.5	631.1	{171.4}	87.58	{25.67}	1320	2.30E+06	0.48	0.25
Run 174	12	2	0.3661	0.5	611.7	{152}	78.85	{23.11}	1318	4.16E+06	0.48	0.25
Run 175	12	2.5	0.4152	0.5	599.5	{139.8}	72.99	{21.39}	1317	6.62E+06	0.48	0.25
Run 176	12	3	0.4594	0.5	591.2	{131.5}	68.72	{20.14}	1316	9.73E+06	0.48	0.25
Run 177	12	3.5	0.4993	0.5	584.5	{124.8}	65.45	{19.18}	1315	1.34E+07	0.125	0.333
Run 178	12	4	0.5361	0.5	579.1	{119.4}	62.84	{18.42}	1314	1.75E+07	0.125	0.333
Run 179	12	4.5	0.5704	0.5	575	{115.3}	60.67	{17.78}	1314	2.23E+07	0.125	0.333
Run 180	12	5	0.6028	0.5	571.6	{111.9}	58.84	{17.25}	1313	2.76E+07	0.125	0.333
Run 181	12	5.5	0.6333	0.5	568.9	{109.2}	57.27	{16.78}	1313	3.35E+07	0.125	0.333
Run 182	12	6	0.6624	0.5	566.6	{106.9}	55.89	{16.38}	1313	4.00E+07	0.125	0.333
Run 183	36	1	0.243	0.5	669.4	{209.7}	104.3	{30.57}	1308	1.03E+06	0.48	0.25
Run 184	36	1.5	0.3188	0.5	632.1	{172.5}	88.79	{26.02}	1307	2.32E+06	0.48	0.25
Run 185	36	2	0.3767	0.5	612.4	{152.7}	79.82	{23.39}	1306	4.19E+06	0.48	0.25
Run 186	36	2.5	0.4266	0.5	600.1	{140.4}	73.83	{21.64}	1306	6.67E+06	0.48	0.25
Run 187	36	3	0.4715	0.5	591.6	{131.9}	69.46	{20.36}	1305	9.80E+06	0.48	0.25
Run 188	36	3.5	0.5121	0.5	584.8	{125.1}	66.12	{19.38}	1305	1.35E+07	0.125	0.333
Run 189	36	4	0.5496	0.5	579.4	{119.7}	63.45	{18.6}	1305	1.76E+07	0.125	0.333
Run 190	36	4.5	0.5845	0.5	575.2	{115.5}	61.25	{17.95}	1305	2.24E+07	0.125	0.333
Run 191	36	5	0.6174	0.5	571.8	{112.2}	59.38	{17.4}	1304	2.78E+07	0.125	0.333
Run 192	36	5.5	0.6485	0.5	569.1	{109.4}	57.78	{16.93}	1304	3.37E+07	0.125	0.333
Run 193	36	6	0.6781	0.5	566.8	{107.1}	56.38	{16.52}	1304	4.03E+07	0.125	0.333
Run 194	1.25	1	0.1462	0.5	654.9	{195.2}	90.27	{26.46}	1495	962915	0.48	0.25
Run 195	1.25	1.5	0.2219	0.5	623.2	{163.6}	78.45	{22.99}	1470	2.17E+06	0.48	0.25
Run 196	1.25	2	0.2791	0.5	606.1	{146.4}	71.39	{20.92}	1454	3.92E+06	0.48	0.25
Run 197	1.25	2.5	0.3252	0.5	595.2	{135.5}	66.57	{19.51}	1444	6.26E+06	0.48	0.25
Run 198	1.25	3	0.3638	0.5	587.7	{128}	63.01	{18.47}	1436	9.20E+06	0.48	0.25
Run 199	1.25	3.5	0.3985	0.5	581.7	{122}	60.25	{17.66}	1430	1.27E+07	0.125	0.333
Run 200	1.25	4	0.4303	0.5	576.8	{117.1}	58.03	{17.01}	1426	1.66E+07	0.125	0.333
Run 201	1.25	4.5	0.46	0.5	572.9	{113.3}	56.19	{16.47}	1422	2.12E+07	0.125	0.333
Run 202	1.25	5	0.488	0.5	569.8	{110.2}	54.62	{16.01}	1418	2.63E+07	0.125	0.333
Run 203	1.25	5.5	0.5144	0.5	567.3	{107.6}	53.26	{15.61}	1415	3.19E+07	0.125	0.333
Run 204	1.25	6	0.5396	0.5	565.2	{105.5}	52.07	{15.26}	1413	3.82E+07	0.125	0.333

Run 205	1.25	6.5	0.5636	0.5	563.3	{103.7}	51.02	{14.95}	1411	4.50E+07	0.125	0.333
Run 206	1.25	7	0.5866	0.5	561.8	{102.1}	50.07	{14.68}	1409	5.24E+07	0.125	0.333
Run 207	1.25	7.5	0.6087	0.5	560.4	{100.8}	49.22	{14.43}	1407	6.04E+07	0.125	0.333
Run 208	1.25	8	0.6299	0.5	559.2	{99.56}	48.45	{14.2}	1405	6.90E+07	0.125	0.333
Run 209	0.5	1	0.249	0.375	668.7	{209}	99.73	{29.23}	1831	877179	0.48	0.25
Run 210	0.5	1.5	0.3269	0.375	630.7	{171.1}	84.83	{24.86}	1753	2.06E+06	0.48	0.25
Run 211	0.5	2	0.3852	0.375	611	{151.3}	76.33	{22.37}	1708	3.80E+06	0.48	0.25
Run 212	0.5	2.5	0.4323	0.375	598.8	{139.1}	70.67	{20.71}	1679	6.13E+06	0.48	0.25
Run 213	0.5	3	0.4739	0.375	590.4	{130.8}	66.57	{19.51}	1657	9.08E+06	0.48	0.25
Run 214	0.5	3.5	0.5117	0.375	584	{124.3}	63.42	{18.59}	1640	1.26E+07	0.125	0.333
Run 215	0.5	4	0.5463	0.375	578.6	{119}	60.92	{17.85}	1627	1.66E+07	0.125	0.333
Run 216	0.5	4.5	0.5786	0.375	574.5	{114.8}	58.85	{17.25}	1616	2.12E+07	0.125	0.333
Run 217	0.5	5	0.609	0.375	571.2	{111.5}	57.1	{16.74}	1607	2.63E+07	0.125	0.333
Run 218	0.5	5.5	0.6377	0.375	568.5	{108.8}	55.6	{16.29}	1599	3.20E+07	0.125	0.333
Run 219	0.5	6	0.665	0.375	566.2	{106.5}	54.28	{15.91}	1592	3.83E+07	0.125	0.333
Run 220	0.5	6.5	0.691	0.375	564.3	{104.6}	53.13	{15.57}	1586	4.53E+07	0.125	0.333
Run 221	0.5	7	0.7159	0.375	562.6	{102.9}	52.09	{15.27}	1580	5.28E+07	0.125	0.333
Run 222	0.5	7.5	0.7399	0.375	561.2	{101.5}	51.16	{14.99}	1575	6.09E+07	0.125	0.333
Run 223	0.5	8	0.7629	0.375	559.9	{100.2}	50.32	{14.75}	1571	6.96E+07	0.125	0.333
Run 224	12	1	0.191	0.375	660	{200.3}	91.57	{26.84}	1321	845424	0.48	0.25
Run 225	12	1.5	0.2698	0.375	625.6	{165.9}	78.97	{23.14}	1318	1.98E+06	0.48	0.25
Run 226	12	2	0.3287	0.375	607.4	{147.7}	71.61	{20.99}	1316	3.66E+06	0.48	0.25
Run 227	12	2.5	0.3758	0.375	596	{136.4}	66.64	{19.53}	1315	5.91E+06	0.48	0.25
Run 228	12	3	0.4151	0.375	588.2	{128.6}	63	{18.46}	1314	8.76E+06	0.48	0.25
Run 229	12	3.5	0.4497	0.375	582.2	{122.5}	60.19	{17.64}	1314	1.22E+07	0.125	0.333
Run 230	12	4	0.4814	0.375	577.2	{117.5}	57.94	{16.98}	1313	1.61E+07	0.125	0.333
Run 231	12	4.5	0.511	0.375	573.2	{113.6}	56.08	{16.43}	1313	2.05E+07	0.125	0.333
Run 232	12	5	0.5388	0.375	570.1	{110.4}	54.49	{15.97}	1312	2.55E+07	0.125	0.333
Run 233	12	5.5	0.5652	0.375	567.5	{107.8}	53.13	{15.57}	1312	3.11E+07	0.125	0.333
Run 234	12	6	0.5901	0.375	565.3	{105.6}	51.93	{15.22}	1312	3.72E+07	0.125	0.333
Run 235	36	1	0.1959	0.375	660.6	{201}	92.2	{27.02}	1307	848020	0.48	0.25
Run 236	36	1.5	0.2747	0.375	626	{166.3}	79.45	{23.28}	1306	1.99E+06	0.48	0.25
Run 237	36	2	0.3336	0.375	607.7	{148}	72	{21.1}	1305	3.67E+06	0.48	0.25
Run 238	36	2.5	0.3807	0.375	596.3	{136.6}	66.98	{19.63}	1305	5.93E+06	0.48	0.25
Run 239	36	3	0.42	0.375	588.4	{128.7}	63.3	{18.55}	1305	8.79E+06	0.48	0.25

Run 240	36	3.5	0.4549	0.375	582.4	{122.7}	60.46	{17.72}	1305	1.22E+07	0.125	0.333
Run 241	36	4	0.4869	0.375	577.3	{117.6}	58.19	{17.05}	1304	1.61E+07	0.125	0.333
Run 242	36	4.5	0.5168	0.375	573.3	{113.7}	56.31	{16.5}	1304	2.06E+07	0.125	0.333
Run 243	36	5	0.5448	0.375	570.2	{110.5}	54.72	{16.04}	1304	2.56E+07	0.125	0.333
Run 244	36	5.5	0.5714	0.375	567.6	{107.9}	53.34	{15.63}	1304	3.11E+07	0.125	0.333
Run 245	36	6	0.5966	0.375	565.4	{105.7}	52.13	{15.28}	1304	3.73E+07	0.125	0.333
Run 246	1.25	1	0.09542	0.375	648.1	{188.5}	80.7	{23.65}	1474	797692	0.48	0.25
Run 247	1.25	1.5	0.1741	0.375	618.3	{158.6}	70.79	{20.75}	1453	1.87E+06	0.48	0.25
Run 248	1.25	2	0.233	0.375	602.1	{142.5}	64.83	{19}	1440	3.44E+06	0.48	0.25
Run 249	1.25	2.5	0.28	0.375	592	{132.3}	60.75	{17.8}	1432	5.57E+06	0.48	0.25
Run 250	1.25	3	0.3193	0.375	584.9	{125.2}	57.71	{16.91}	1425	8.28E+06	0.48	0.25
Run 251	1.25	3.5	0.3529	0.375	579.6	{119.9}	55.34	{16.22}	1420	1.16E+07	0.125	0.333
Run 252	1.25	4	0.382	0.375	574.9	{115.3}	53.44	{15.66}	1416	1.52E+07	0.125	0.333
Run 253	1.25	4.5	0.408	0.375	571.3	{111.6}	51.85	{15.2}	1412	1.95E+07	0.125	0.333
Run 254	1.25	5	0.4317	0.375	568.4	{108.7}	50.5	{14.8}	1409	2.42E+07	0.125	0.333
Run 255	1.25	5.5	0.4541	0.375	566	{106.3}	49.32	{14.46}	1407	2.95E+07	0.125	0.333
Run 256	1.25	6	0.4754	0.375	563.9	{104.3}	48.29	{14.15}	1405	3.54E+07	0.125	0.333
Run 257	1.25	6.5	0.4957	0.375	562.2	{102.5}	47.38	{13.89}	1403	4.19E+07	0.125	0.333
Run 258	1.25	7	0.5152	0.375	560.7	{101.1}	46.56	{13.64}	1401	4.89E+07	0.125	0.333
Run 259	1.25	7.5	0.5339	0.375	559.4	{99.78}	45.82	{13.43}	1399	5.64E+07	0.125	0.333
Run 260	1.25	8	0.5519	0.375	558.3	{98.65}	45.14	{13.23}	1398	6.46E+07	0.125	0.333

Table G3 – Effect of Pipe Diameter on Flow Speed

Mach Numbers

	Vflow [ft3/min]	IDpipe [in]	Ma
Run 1	12	0.2	0.4554
Run 2	12	0.2947	0.2097
Run 3	12	0.3895	0.1201
Run 4	12	0.4842	0.07768
Run 5	12	0.5789	0.05434
Run 6	12	0.6737	0.04013
Run 7	12	0.7684	0.03084

Run 8	12	0.8632	0.02445
Run 9	12	0.9579	0.01985
Run 10	12	1.053	0.01644
Run 11	12	1.147	0.01384
Run 12	12	1.242	0.01181
Run 13	12	1.337	0.01019
Run 14	12	1.432	0.008887
Run 15	12	1.526	0.007818
Run 16	12	1.621	0.006931
Run 17	12	1.716	0.006187
Run 18	12	1.811	0.005556
Run 19	12	1.905	0.005017
Run 20	12	2	0.004553
Run 21	24	0.2	0.9112
Run 22	24	0.2947	0.4195
Run 23	24	0.3895	0.2403
Run 24	24	0.4842	0.1554
Run 25	24	0.5789	0.1087
Run 26	24	0.6737	0.0803
Run 27	24	0.7684	0.06172
Run 28	24	0.8632	0.04892
Run 29	24	0.9579	0.03972
Run 30	24	1.053	0.03289
Run 31	24	1.147	0.02768
Run 32	24	1.242	0.02362
Run 33	24	1.337	0.02039
Run 34	24	1.432	0.01778
Run 35	24	1.526	0.01564
Run 36	24	1.621	0.01387
Run 37	24	1.716	0.01238
Run 38	24	1.811	0.01112
Run 39	24	1.905	0.01004
Run 40	24	2	0.009111
Run 41	36	0.2	1.367
Run 42	36	0.2947	0.6294
Run 43	36	0.3895	0.3605

Run 44	36	0.4842	0.2332
Run 45	36	0.5789	0.1631
Run 46	36	0.6737	0.1205
Run 47	36	0.7684	0.0926
Run 48	36	0.8632	0.07339
Run 49	36	0.9579	0.05959
Run 50	36	1.053	0.04934
Run 51	36	1.147	0.04153
Run 52	36	1.242	0.03544
Run 53	36	1.337	0.03059
Run 54	36	1.432	0.02668
Run 55	36	1.526	0.02347
Run 56	36	1.621	0.02081
Run 57	36	1.716	0.01857
Run 58	36	1.811	0.01668
Run 59	36	1.905	0.01506
Run 60	36	2	0.01367

Table G4 – Reflective Coating Effect Analysis Data

Effect of Changing Reflectivity

	εss	reflectivityss	L [in]	q'wall2air [W/in]	q'W [W/in]
Run	0.001	0.999	59.32	-0.965	1.268
Run	0.1	0.9	34.91	19.71	1.814
Run	0.2	0.8	28.95	30.05	2.06
Run	0.3	0.7	26.43	35.83	2.191
Run	0.4	0.6	25.06	39.45	2.272
Run	0.5	0.5	24.21	41.92	2.326
Run	0.6	0.4	23.63	43.7	2.364
Run	0.7	0.3	23.21	45.04	2.393
Run	0.8	0.2	22.89	46.1	2.415
Run	0.9	0.1	22.64	46.94	2.433
Run	1	0	22.44	47.63	2.448

Appendix H: Final Line Item Budget

Vendor	Order/Reciept#	Item#	Description	QTY	Total
McMaster-Carr	0128MTRINCHERO	3871K912	Thermocouple	1	$ 55.45
McMaster-Carr	0128MTRINCHERO	45545K45	Insulation Wrap	1	$ 17.28
McMaster-Carr	0128MTRINCHERO	87575K89	Insulation Strip	1	$ 53.74
McMaster-Carr	0128MTRINCHERO	9328K42	Mineral Wool Insulation	1	$ 10.94
McMaster-Carr	0128MTRINCHERO	9328K22	Mesh-Faced mineral wool	1	$ 23.11
McMaster-Carr	0128MTRINCHERO	5081K23	2" Female clamp fitting	2	$ 24.56
McMaster-Carr	0128MTRINCHERO	5081K83	2" male clamp fitting	2	$ 28.14
McMaster-Carr	0128MTRINCHERO	5081K63	2" clamp fitting clamp	2	$ 68.04
McMaster-Carr	0128MTRINCHERO	4464K475	1" SS NPT half-coupler	1	$ 5.87
McMaster-Carr	0128MTRINCHERO	4464K476	1-1/4" SS NPT half-coupler	1	$ 9.18
McMaster-Carr	0128MTRINCHERO	52245K521	1/4" tube to 1/4" NPT adapter	1	$ 15.01
McMaster-Carr	0128MTRINCHERO	4464K471	1/4" SS NPT half-coupler	1	$ 2.28
McMaster-Carr	0128MTRINCHERO	3572T13	Bulk Gasket Material	1	$ 26.62
McMaster-Carr	0128MTRINCHERO	5182K92	3/16" tube fitting	1	$ 12.14
McMaster-Carr	0128MTRINCHERO	89895K727	1/4"OD 0.084"ID SS Tube	1	$ 10.27
McMaster-Carr	0128MTRINCHERO	89895K724	1/4"OD 0.18"ID SS Tube	1	$ 11.25
McMaster-Carr	0128MTRINCHERO	TAX		1	$ 28.04
McMaster-Carr	0128MTRINCHERO	Shipping		1	$ 19.36
MSC	34141195	75767806	Eccentric SS reducer	1	$ 76.51
MSC	34141195	75766964	Tee fitting	1	$ 47.27
MSC	34141195	75767806	Eccentric SS reducer	1	$ (76.51)
MSC	34141195	75766964	Tee fitting	1	$ (47.27)
MSC	34141195	TAX		1	$ 10.41
MSC	34141195	Shipping		1	$ 10.98
Jobco, Inc.	1247	68463	2kW Hot Air Heater	1	$ 455.00
Jobco, Inc.	1247	Shipping		1	$ 15.90
Omega	389577	FMA1743-AIR	Mass Flow Meter	1	$ 940.00
Omega	389577	PX142-002D5V	Diff. Press. Transducer	1	$ 119.00
Omega	389577	CX136-3	Connector	1	$ 2.50
Omega	389577	SL-PS-S4024	24VDC power supply	1	$ 73.00
Omega	389577	SL-PS-S2012	12VDC Power Supply	1	$ 62.00
Omega	389577	DRTB-RAIL-3575-1	1m DIN rail	1	$ 4.00
Omega	389577	DRTB-RAIL-SBKT-1-6PK	DIN rail standoff brackets	1	$ 5.00
Omega	389577	SSR330DC25	Solid state relay	2	$ 54.00

Omega	389577	FHS-7	Relay Heat Sink	2	$ 60.00
Omega	389577	TAX		1	$ 28.46
Omega	389577	Shipping		1	$ 12.05
McMaster-Carr	0224MTRINCHERO	9364K56	2-3/8" ID insulation	1	$ 29.40
McMaster-Carr	0224MTRINCHERO	9364K59	4-1/2" ID insulation	1	$ 40.07
McMaster-Carr	0224MTRINCHERO	TAX		1	$ 5.22
McMaster-Carr	0224MTRINCHERO	Shipping		1	$ 15.30
West Coast Plastics	63554	BEN24G6SKH	2kW Immersion Heater	1	$ 549.00
West Coast Plastics	63554	Shipping		1	$ 12.19
West Coast Plastics	63554	TAX		1	$ 43.92
MSC	34533184	54014774	Power Distribution Block	1	$ 27.92
MSC	34533184	Shipping		1	$ 10.98
MSC	34533184	TAX		1	$ 2.49
Cole-Parmer	7203106-00	RZ-98651-00	Proportioning valve	1	$ 580.00
Cole-Parmer	7203106-00	RZ-98651-50	"D" connector	1	$ 48.00
Cole-Parmer	7203106-00	EST. Shipping		1	$ 17.23
Cole-Parmer	7203106-00	EST. Tax		1	$ 47.10
McMaster-Carr	0227MTRINCHERO	44675K42	1"-2" tube reducer	1	$ 36.22
McMaster-Carr	0227MTRINCHERO	8989K828	3/4" OD tube, 1'	1	$ 12.50
McMaster-Carr	0227MTRINCHERO	8989K828	3/4" OD tube, 1'	1	$ 12.50
McMaster-Carr	0227MTRINCHERO	TAX		1	$ 4.60
McMaster-Carr	0227MTRINCHERO	Shipping		1	$ 5.63
Home Depot	1052 06 16359 02/19/2014 5943	51411205171	3/8"NM connector	1	$ 1.05
Home Depot	1052 06 16359 02/19/2014 5943	51411282714	1/2" EMT connector	1	$ 1.39
Home Depot	1052 06 16359 02/19/2014 5943	45564606732	3/8" NPT regulator	1	$ 29.94
Home Depot	1052 06 16359 02/19/2014 5943	040892538885	30A Disconnect	2	$ 61.94
Home Depot	1052 06 16359 02/19/2014 5943	040892538885	30A Disconnect	1	$ (33.44)
Home Depot	1052 06 16359 02/19/2014 5943	091111150470	EMT 1/2"x5'	1	$ 1.75
Home Depot	1052 06 16359 02/19/2014 5943	047569071232	100A indoor main lug	1	$ 19.77
Home Depot	1052 06 16359 02/19/2014 5943	047569071232	100A indoor main lug	1	$ (19.77)
Home Depot	1052 06 16359 02/19/2014	051712111010	15A cartridge fuse	1	$ 2.28

	5943				
Home Depot	1052 06 16359 02/19/2014 5943	047569062759	15A 2 pole breaker	2	$ 16.50
Home Depot	1052 06 16359 02/19/2014 5943	047569062759	15A 2 pole breaker	2	$ (16.50)
Home Depot	1052 06 16359 02/19/2014 5943	047569517327	ground bar kit	1	$ 4.98
Home Depot	1052 06 16359 02/19/2014 5943	0000-155-933	10-3 600V wire	20	$ 37.20
Home Depot	1052 06 16359 02/19/2014 5943	Tax		1	$ 14.14
AirGas	8025503543	RAD64001547	ER308L SS filler rod	1	$ 22.97
AirGas	8025503543	Hazmat fee		1	$ 3.30
AirGas	8025503543	TAX		1	$ 2.10
McCarthy Steel	302064	386SSF	3/8"x6" SS flat plate	5.73	$ 24.35
McCarthy Steel	302064	13-13	Cut charge	1	$ 5.00
McCarthy Steel	302064	TAX		1	$ 2.35
McCarthy Steel	30419		1/4"x6" S/S nipple	1	$ 4.48
McCarthy Steel	30419		1"SCH40 304SS pipe	0.5	$ 4.62
McCarthy Steel	30419	TAX		1	$ 0.73
McCarthy Steel	30339		1-1/2" SCH40 304SS Pipe	2.5	$ 37.40
McCarthy Steel	30339	TAX		1	$ 2.99
Home Depot	W259398904	124168	Desiccant Dryer	1	$ 99.97
Home Depot	W259398904	TAX		1	$ 7.50
McMaster-Carr	0228MTRINCHERO	8989K848	1" OD tube, 1'	1	$ 13.37
McMaster-Carr	0228MTRINCHERO	TAX		1	$ 1.00
McMaster-Carr	0228MTRINCHERO	Shipping		1	$ 5.63
Automation Direct	4186410	P0806	8"x6" Sub panel	1	$ 4.25
Automation Direct	4186410	Shipping		1	$ 6.00
McMaster-Carr	0414MTRINCHERO	8927K56	4140 Steel Rod	1	$ 33.31
McMaster-Carr	0414MTRINCHERO	6554K31	4140 Steel Bar Stock	1	$ 28.25
McMaster-Carr	0414MTRINCHERO	98381A624	Steel Dowel Pin 25pkg	1	$ 11.17
McMaster-Carr	0414MTRINCHERO	89895K769	304SS tubing 1" OD	1	$ 14.89
McMaster-Carr	0414MTRINCHERO	8989K418	304SS tubing 2" OD	1	$ 20.90
McMaster-Carr	0414MTRINCHERO	3626T16	Strut Channel Trolley	2	$ 46.80
McMaster-Carr	0414MTRINCHERO	33085T753	SS strut channel	1	$ 37.59
McMaster-Carr	0414MTRINCHERO	5416K43	Hose clamps 5pkg	1	$ 9.23
McMaster-Carr	0414MTRINCHERO	shipping		1	$ 9.12
McMaster-Carr	0414MTRINCHERO	TAX		1	$ 18.19

McMaster-Carr	0421MTRINCHERO	50915K724	Compression tube fitting 90	1	$ 5.48
McMaster-Carr	0421MTRINCHERO	8989K761	3/8" SS Tubing	1	$ 3.26
McMaster-Carr	0421MTRINCHERO	Shipping		1	$ 5.46
McMaster-Carr	0421MTRINCHERO	TAX		1	$ 0.65
McMaster-Carr	0421MTRINCHERO	7473T126	Thru-wall tube fitting	1	$ 9.22
McMaster-Carr	0421MTRINCHERO	50915K251	Tube reducing fitting	1	$ 8.03
McMaster-Carr	0421MTRINCHERO	Shipping		1	$ 5.46
McMaster-Carr	0421MTRINCHERO	TAX		1	$ 1.29
Omega	404907324	PX142-002D5V	Diff. Press. Transducer	1	$ 119.00
Omega	404907324	CX136-3	Connector	1	$ 2.50
Omega	404907324	SSR330DC25	Solid state relay	2	$ 54.00
Omega	404907324	FHS-8	Heat sink	2	$ 40.00
Omega	404907324	AU-2C10UL	2pole 10A Breaker	2	$ 104.00
Omega	404907324	AU-2D2UL	2Pole 2A Breaker	1	$ 52.00
Omega	404907324	Shipping		1	$ 34.00
Omega	404907324	TAX		1	$ 26.93
Automation Direct	4199668	B080606CH	NEMA12 Enclosure	1	$ 55.00
Automation Direct	4199668	P0806	8"x6" Sub panel	1	$ 4.25
Automation Direct	4199668	Shipping		1	$ -
Automation Direct	4199668	TAX		1	$ -
Kurt J Lesker Co.	CSR270641	QF-SDC-AL1	Clamp, Double claw ISO 63-100	4	$ 26.00
Kurt J Lesker Co.	CSR270641	Shipping		1	$ 23.29
Kurt J Lesker Co.	CSR270641	Tax		1	$ 3.28
Home Depot	1052 00058 24271	45565613143	1/4" NPT coupler kit	1	$ 4.98
Home Depot	1052 00058 24271	30699203918	#10 Tooth lock washers	1	$ 1.18
Home Depot	1052 00058 24271	8.8748E+11	#10-32 machine screw nut pkg	1	$ 1.18
Home Depot	1052 00058 24271	TAX		1	$ 7.93
Home Depot	1052 00007 69935	45564605568	1/4" coupler	1	$ 4.98
Home Depot	1052 00007 69935	45564605728	3/8" x 1/4" reducer	1	$ 1.98
Home Depot	1052 00007 69935	45564613228	1/4" plug	1	$ 1.78
Home Depot	1052 00007 69935	78575126029	SS Clamp	1	$ 0.78
Home Depot	1052 00007 69935	42805446591	3/8" NPT close nipple	2	$ 5.22
Home Depot	1052 00007 69935	42805446539	3/8"x1/4" reducer	1	$ 4.30
Home Depot	1052 00007 69935	TAX		1	$ 1.52
McMaster-Carr	0425AWOOD	5416K52	SS clamp	1	$ 10.99
McMaster-Carr	0425AWOOD	TAX		1	$ 0.82
McMaster-Carr	0425AWOOD	Shipping		1	$ 5.46
PCHEMLABS		P104068	SS ISO flange clamps	4	$ 40.00
Castercity		SN10x2-3/4	New Caster wheels	4	$ 100.00

S&S Welding & Supply		220675867042	SS Welding Flux	1	$ 10.49
AirGas	1024663029	RAD64000459	Acid Brush 6 Pack	1	$ 2.30
AirGas	1024663029	TAX		1	$ 0.18
Home Depot	1052 08 34598 05/19/2014 4939	887480014273	Expanded sheet metal	2	$ 39.94
Home Depot	1052 08 34598 05/19/2014 4939	887480011111	Sheet metal screws	1	$ 1.18
Home Depot	1052 08 34598 05/19/2014 4939	Tax		1	$ 3.29
MSC	135170302	04662102	1-1/4-11-1/2 NPT Pipe Tap	1	$ 101.57
MSC	135170302	03900107	1 1/4-11 1/2 NPT Die	1	$ 101.17
MSC	135170302	Tax		1	$ 16.48
MSC	135170302	Shipping		1	$ 10.98
Total					**$ 5,436.32**
			Approved Budget		**$ 5,759.22**
			% Under (Over)		**5.6%**

Analysis of immersion heater used to heat air flow in an insulated tube

by Mario Trinchero

1/15/2014

Assume constant heater surface temperature

Assume fully developed flow

Assume constant properties

Assume uniform tubing temperature

Assume only Natural Convection on outside

Assume only Radiation and Forced convection inside

Assume 1-D heat transfer to outside

Geometry

$r_1 = r_2 - thick_{wall}$ *heater tube inner radius*

$r_2 = 1$ [in] *Heater tube outer radius*

$thick_{wall} = 0.12$ [in] *Tubing wall thickness*

$P_{heater} = 4 \cdot \pi \cdot 0.315$ *Perimeter of WATROD heater*

$A_{heater} = \pi \cdot 0.315^2$ *Cross sectional area of WATROD heater*

$A_{hyd} = \pi \cdot r_1^2 - A_{heater}$ *Hydraulic area inside enclosure*

$A_{s,heater} = P_{heater} \cdot L$ *Surface area of heater element*

$A_{pipe} = \pi \cdot r_1^2$ *cross sectional area of channel*

$A_{s,wall} = 2 \cdot \pi \cdot r_1 \cdot L$ *surface area of tube inner wall*

$A_{s,pipe} = 2 \cdot \pi \cdot r_2 \cdot L$ *surface area of tube outer wall*

$D_{hyd} = \dfrac{A_{hyd}}{P_{heater} + 2 \cdot \pi \cdot r_1}$ *hydraulic diameter of flow area*

$D_{out} = 2 \cdot r_4$ *overall diameter of assembly*

$t_{ao} = r_3 - r_2$ *thickness of inner alumina oxide insulation*

$t_{ao} = 1 / 8 \cdot t_{insulation}$

L = 1 [in]

Length of assembly

$t_{mw} = r_4 - r_3$ *thickness of mineral wool outer layer*

$t_{insulation} = r_4 - r_2$ *overall insulation thickness*

$t_{insulation} = 4$

Temperatures and Pressures

T_h = **ConvertTemp** [F , R 1600 [F]] *heater element temperature*

T_{in} = **ConvertTemp** [F , R 60 [F]] *Inlet air temperature*

T_{out} = **ConvertTemp** [F , R 1500 [F]] *Outlet air temperature*

T_{outF} = **ConvertTemp** [R , F , T_{out}] *Outlet temperature in Fahrenheit*

T_{r3} = ConvertTemp(F,R,1200_F)

Temperature at interface of inner and outer insulation

T_{r4F} = **ConvertTemp** [R , F , T_{r4}] *Outside surface temperature*

P_{atm} = 14.7 [psia] *Atmospheric pressure*

T_{∞} = **ConvertTemp** [F , R 60 [F]] *Temperature of outside air*

$T_{avg} = 1 / 2 \cdot [T_{in} + T_{out}]$ *Average flow temperature*

T_{avgF} = **ConvertTemp** [R , F , T_{avg}] *Average flow temperature in F*

$T_{film,h} = 1 / 2 \cdot [T_h + T_{avg}]$ *Film temperature at heater element*

$T_{film,hF}$ = **ConvertTemp** [R , F , $T_{film,h}$] *Heater film temperature in F*

$T_{film,w} = 1 / 2 \cdot [T_{wall} + T_{avg}]$ *Film temperature at wall*

$T_{film,wF}$ = **ConvertTemp** [R , F , $T_{film,w}$] *wall film temperature in F*

$T_{film,out} = 1 / 2 \cdot [T_{r4} + T_{\infty}]$ *Film temperature at insulation exterior*

$T_{film,outF}$ = **ConvertTemp** [R , F , $T_{film,out}$] *Insulation exterior film temperature in F*

$$\Delta_{T,lm,h} = \frac{\Delta_{T,out} - \Delta_{T,in}}{\mathbf{ln}\left[\frac{\Delta_{T,out}}{\Delta_{T,in}}\right]}$$ *Log-mean temperature difference between flow and heater*

$\Delta_{T,in} = T_h - T_{in}$ *Inlet temperature difference between flow and heater*

$\Delta_{T,out} = T_h - T_{out}$ *Outlet temperature difference between flow and heater*

Material Properties

$\rho_{spec} = \rho[Air_{ha}, T = 1300$ [F], $P = P_{atm}]$ *Air density at 1300F*

$\rho_{avg} = \rho[Air_{ha}, T = T_{avgF}, P = P_{atm}]$ *Average air density of flow*

$\rho_{out} = \rho[Air_{ha}, T = T_{film,outF}, P = P_{atm}]$ *Air density of outside film*

$\mu_{avg} = \mathbf{Visc}[Air_{ha}, T = T_{avgF}, P = P_{atm}]$ *Viscosity of flow*

$\mu_{out} = \mathbf{Visc}[Air_{ha}, T = T_{film,outF}, P = P_{atm}]$ *Viscosity of outer film air*

$\nu_{out} = \dfrac{\mu_{out}}{\rho_{out}}$ *Kinematic viscosity of outside film*

$\beta = \beta[Air_{ha}, T = T_{film,outF}, P = P_{atm}]$ *Coefficient of volumetric expansion of outside film*

$KF_{ss} = 160$ [Btu-in/hr-ft^2-R] *K-factor of 304 stainless steel*

$KF_{ao} = 0.48$ [Btu-in/hr-ft^2-R] *K-factor of aluminum oxide inner layer*

$KF_{mw} = 0.23$ [Btu-in/hr-ft^2-R] *K-factor of mineral wool outer layer*

$k_{pa,h} = \mathbf{k}[Air_{ha}, T = T_{film,hF}, P = P_{atm}]$ *Conductivity of air film around heater*

$k_{pa,w} = \mathbf{k}[Air_{ha}, T = T_{film,wF}, P = P_{atm}]$ *Conductivity of air film at inner tubing wall*

$k_{air,out} = \mathbf{k}[Air_{ha}, T = T_{film,outF}, P = P_{atm}]$ *Conductivity of outer air film*

$k_{ss} = KF_{ss} \cdot \dfrac{1\ [ft^2]}{144\ [in^2]}$ *Conductivity of 304 stainless steel*

$k_{ao} = KF_{ao} \cdot \dfrac{1\ [ft^2]}{144\ [in^2]}$ *Conductivity of alumina oxide*

$k_{mw} = KF_{mw} \cdot \dfrac{1\ [ft^2]}{144\ [in^2]}$ *Conductivity of mineral wool*

$c_{p,avg} = \mathbf{Cp}[Air_{ha}, T = T_{avgF}, P = P_{atm}]$ *Average specific heat at constant pressure of flow*

Flow Characteristics around heater

$\dot{V}_{spec} = 12$ [ft^3/min] *Volumetric flow rate*

$\dot{m} = \dot{V}_{spec} \cdot \dfrac{1\ [min]}{60\ [s]} \cdot \rho_{spec}$ *Mass flow rate*

$U_{avg} = \dfrac{\dfrac{\dot{m}}{\rho_{avg}}}{A_{hyd} \cdot \dfrac{1\ [ft^2]}{144\ [in^2]}}$ *Average flow velocity*

$Re_D = \rho_{avg} \cdot U_{avg} \cdot \dfrac{D_{hyd}}{\mu_{avg}} \cdot \dfrac{1\ [ft]}{12\ [in]} \cdot \dfrac{3600\ [s]}{1\ [hr]}$ *Reynold's #*

$Pr_{film} = \mathbf{Pr}[Air_{ha}, T = T_{film,hF}, P = P_{atm}]$ *Prandtl #*

$\overline{Nus}_D = \mathbf{If}[Re_D, 2300, 3.66, 3.66, 0.023 \cdot Re_D^{(4/5)} \cdot Pr_{film}^{0.3}]$ *Nusselt # assuming constant surface temperature*

$$\overline{h}_{heater} = \overline{Nus}_D \cdot \frac{k_{pa,h} \cdot \frac{1 \text{ [ft]}}{12 \text{ [in]}}}{D_{hyd}}$$ *average convection coefficient*

Flow Characteristics along inner wall

$$Pr_{wall} = \mathbf{Pr}\left[Air_{ha}, T = T_{film,wF}, P = P_{atm}\right]$$ *Prandtl #*

$$\overline{Nus}_W = \mathbf{If}\left[Re_D, 2300, 3.66, 3.66, 0.023 \cdot Re_D^{(4/5)} \cdot Pr_{wall}^{0.3}\right]$$ *Nusselt # assuming constant surface temperature*

$$\overline{h}_{wall} = \overline{Nus}_W \cdot \frac{k_{pa,w} \cdot \frac{1 \text{ [ft]}}{12 \text{ [in]}}}{D_{hyd}}$$ *average convection coefficient*

Heat Flow out of pipe via natural convection assuming uniform surface temperature

$$\overline{Nus}_{D,out} = C \cdot Ra_{D,out}^{\ n}$$ *Nusselt-Rayleigh correlation*

$$\overline{h}_{nc} = \frac{\overline{Nus}_{D,out} \cdot k_{air,out} \cdot \frac{1 \text{ [ft]}}{12 \text{ [in]}}}{D_{out}}$$ *average convection coefficient*

$$Ra_{D,out} = g \cdot \beta \cdot \left[T_{r4} - T_{\infty}\right] \cdot \frac{\left[D_{out} \cdot \frac{1 \text{ [ft]}}{12 \text{ [in]}}\right]^3}{\left[\nu_{out} \cdot \frac{1 \text{ [hr]}}{3600 \text{ [s]}}\right]^2} \cdot Pr_{nc}$$ *Rayleigh #*

$$Pr_{nc} = \mathbf{Pr}\left[Air_{ha}, T = T_{film,outF}, P = P_{atm}\right]$$ *Prandtl #*

$g = 32.174$ [ft/s^2] *gravity*

Nusselt-Rayleigh correlation coefficients for natural convection

IF statement unstable/slow in program. Set value for C & n, then check Rayleigh number once solved and adjust coefficients accordingly

$C = 0.125$ *IF(Ra$_{D,out,10}$(-2),0.675,0.675,IF(Ra,D,out,10,2,1.020,1.020,IF(Ra,D,out,10,4,0.850,0.850,IF(Ra,D,out,10,7,0.480,0.480,0.125))))*

$n = 0.333$ *IF(Ra$_{D,out,10}$(-2),0.058,0.058,IF(Ra,D,out,10,2,0.148,0.148,IF(Ra,D,out,10,4,0.188,0.188,IF(Ra,D,out,10,7,0.250,0.250,0.333))))*

Radiation exchange between heater and wall

$\varepsilon_h = 0.7$ *heater element emmisivity, assuming incoloy*

epsilon$_{ss}$ = 0.4

tube wall emmisivity, assuming lightly oxidized stainless steel at 1000F

$F_{hw} = 0.796$ *Calculated view factor from heater element to wall*

$reflectivity_{ss} = 1 - \varepsilon_{ss}$

Thermal Resistances

$$R_{ss} = \frac{\ln\left[\frac{r_2}{r_1}\right]}{2 \cdot \pi \cdot k_{ss} \cdot L}$$ *resistance of stainless steel*

$$R_{ao} = \frac{\ln\left[\frac{r_3}{r_2}\right]}{2 \cdot \pi \cdot k_{ao} \cdot L}$$ *resistance of alumina oxide*

$$R_{mw} = \frac{\ln\left[\frac{r_4}{r_3}\right]}{2 \cdot \pi \cdot k_{mw} \cdot L}$$ *resistance of mineral wool*

$$R_{rad} = \left[\frac{1 - \varepsilon_h}{\varepsilon_h \cdot A_{s,heater}} + \frac{1}{A_{s,heater} \cdot F_{hw}} + \frac{1 - \varepsilon_{ss}}{\varepsilon_{ss} \cdot A_{s,wall}}\right] \cdot \frac{144 \ [in^2]}{1 \ [ft^2]}$$ *radiation thermal resistance*

$$R_{nc} = \frac{1}{\bar{h}_{nc} \cdot A_{s,pipe}}$$ *natural convection thermal resistance*

Heat flow tracking

$$q_{air} = q_{fch} - q_{fcw}$$ *heat flow into and out of flow*

$$q_{air} = \dot{m} \cdot c_{p,avg} \cdot [T_{out} - T_{in}] \cdot \frac{3600 \ [s]}{1 \ [hr]}$$ *heat absorbed by air*

$$q_{fch} = \bar{h}_{heater} \cdot A_{s,heater} \cdot \Delta_{T,lm,h}$$ *heat transfered from heater to flow via forced convection*

$$q_{fcw} = \bar{h}_{wall} \cdot A_{s,wall} \cdot [T_{avg} - T_{wall}]$$ *heat transferred from air to inner wall via forced convection*

$$q_{rad} = 1.712E{-}09 \ [Btu/hr\text{-}ft^2\text{-}R^4] \cdot \left[\frac{T_h^{\ 4} - T_{wall}^{\ 4}}{R_{rad}}\right]$$ *heat transferred from heater to wall via radiation*

$$q_{nc} = \bar{h}_{nc} \cdot A_{s,pipe} \cdot [T_{r4} - T_{\infty}]$$ *heat transfered to surroundings via exterior natural convection*

$$q_{out} = q_{rad} + q_{fcw}$$ *heat leaving system through tubing/insulation*

$$q_{out} = \frac{T_{wall} - T_{r3}}{R_{ss} + R_{ao}}$$ *heat balance through steel and alumina oxide*

$$q_{out} = \frac{T_{r3} - T_{r4}}{R_{mw}}$$ *heat balance through mineral wool*

$$q_{out} = q_{nc}$$ *Heat transfer through insulation = external natural convection heat transfer*

$$q'_{wall2air} = -q_{fcw} \cdot \frac{\left|0.2931 \cdot \frac{W}{Btu/hr}\right|}{L}$$ *Heat transfered from wall to flow per unit length*

$$q'_W = q_{out} \cdot \frac{\left|0.2931 \cdot \frac{W}{Btu/hr}\right|}{L}$$ *Heat lost to surroundings per inch of length*

$Watt_{density} = \frac{q_{fch}}{A_{s,heater}} \cdot \left| 0.2931 \cdot \frac{W}{Btu/hr} \right|$ *Wattage density of heater*

Pressure Drop

$f = \frac{64}{Re_D}$ *friction factor assuming laminar flow*

$h_L = f \cdot \frac{L}{D_{hyd}} \cdot \frac{\rho_{avg} \cdot \left| 0.031080997 \cdot \frac{slug}{lbm} \right| \cdot U_{avg}^2 \cdot \frac{1 \; [ft^2]}{144 \; [in^2]}}{2}$ *head loss estimate*

Insulation Cost

$Cost_{ins} = \frac{C_{inner} + C_{outer}}{L}$ *Total insulation cost per unit length*

$C_{inner} = \pi \cdot \left[r_3^2 - r_2^2 \right] \cdot L \cdot C_{ao}$ *Cost of inner insulation*

$C_{outer} = \pi \cdot \left[r_4^2 - r_3^2 \right] \cdot L \cdot C_{mw}$ *Cost of outer insulation*

$C_{ao} = 0.55$ [\$/in^3] *Volumetric cost of alumina oxide*

$C_{mw} = 0.0055$ [\$/in^3] *Volumetric cost of mineral wool*

Two-layer insulation analyis

By Mario Trinchero for Mini-HTTU project

1/10/2014

Assumptions:

-Natural convection only from outside

-Forced convection only on inside

-Inside wall temperature = maximum theoretical temperature of internal element

-Ouside air behaves as ideal gas

-Electrical resistance model of 1-D cylinder wall valid

-Incompressibe flow (validated below)

Variables

$T_{inlet,air} = \mathbf{ConvertTemp}\left[F, R, 1300 \text{ [F]}\right] - \Delta_T$ *Temperature of inside air flow*

$T_{inlet,F} = \mathbf{ConvertTemp}\left[R, F, T_{inlet,air}\right]$

$T_{process,air} = 1 / 2 \cdot \left[T_{inlet,air} + \mathbf{ConvertTemp}\left(F, R, 1300 \text{ [F]}\right)\right]$

$T_{\infty} = \mathbf{ConvertTemp}\left[F, R, 80 \text{ [F]}\right]$ *Temperature of surroundings*

$KF_{ss} = 160$ [Btu-in/hr-ft^2-F] *K-factor of 304 stainless steel*

$KF_{ao} = 0.48$ [Btu-in/hr-ft^2-F] *K-factor of aluminum oxide inner layer*

$KF_{mw} = 0.23$ [Btu-in/hr-ft^2-F] *K-factor of mineral wool outer layer*

$P_{atm} = 14.7$ [psi] *Atmospheric pressure*

$L = 12$ [in] *Tube Length*

What ifs

Flow rate - Set to desired value or let float for parametric table population

$\dot{V}_{flow} = 1.25$ [ft^3/min] *ACFM*

Select only one of the following to constrain inner insulation thickness

$T_{r3} = \mathbf{ConvertTemp}\left[F, R, 1100 \text{ [F]}\right]$ *Temperature at interface between insulation layers*

t_{inner} = 0.75

Select only one of following to constrain outer insulation thickness

$T_{r4} = \mathbf{ConvertTemp}\left[F, R, 120 \text{ [F]}\right]$ *Sets desired outside skin temperature*

$t_{insulation,total}$ = 4 [in]

Sets overall insulation thickness

- Pipe dimensions (create table of values for different sizes)

$r_1 = r_2 - t_{tubing}$ *Inner tube radius*

$r_2 = \frac{OD_{pipe}}{2}$ *Outer steel tubing diameter*

$t_{tubing} = 0.083$ [in] *Tubing wall thickness*

$t_{inner} = r_3 - r_2$ *Inner insulation thickness*

$t_{outer} = r_4 - r_3$ *Outer insulation thickness*

$OD_{pipe} = 0.75$ [in] *Pipe OD (no insulation)*

$ID_{pipe} = OD_{pipe} - 2 \cdot t_{tubing}$

Core equations - Assuming 1-D model is valid

$$q = \frac{T_{hw} - T_{r3}}{R_{ss} + R_{ao}}$$

$$q = \frac{T_{hw} - T_{r2}}{R_{ss}}$$

$$q = \frac{T_{r3} - T_{r4}}{R_{mw}}$$

$$q = \frac{T_{r4} - T_{\infty}}{R_{nc}}$$

$$q = \frac{T_{process,air} - T_{hw}}{R_{fc}}$$

Convert K factors to thermal resistance values

$k_{ss} = \frac{KF_{ss}}{144 \ [in^2/ft^2]}$ *304 stainless steel*

$k_{ao} = \frac{KF_{ao}}{144 \ [in^2/ft^2]}$ *alumina oxide*

$k_{mw} = \frac{KF_{mw}}{144 \ [in^2/ft^2]}$ *mineral wool*

Resistance values

$R_{ss} = \frac{\ln\left[\frac{r_2}{r_1}\right]}{2 \cdot \pi \cdot k_{ss} \cdot L}$ *Thermal resistance of stainless steel wall*

$$R_{ao} = \frac{\ln\left[\frac{r_3}{r_2}\right]}{2 \cdot \pi \cdot k_{ao} \cdot L}$$ *Thermal resistance of inner insulation*

$$R_{mw} = \frac{\ln\left[\frac{r_4}{r_3}\right]}{2 \cdot \pi \cdot k_{mw} \cdot L}$$ *Thermal resistance of stainless steel wall*

$$R_{nc} = \frac{1}{\overline{h}_{out} \cdot 2 \cdot \pi \cdot r_4 \cdot L}$$ *Thermal resistance of outside convection*

$$R_{fc} = \frac{1}{\overline{h}_{in} \cdot 2 \cdot \pi \cdot r_1 \cdot L}$$ *Thermal resistance of inside convection*

Outside Natural convection calculations

$$\overline{h}_{out} = \overline{N}_{D,out} \cdot \frac{k_{air,out}}{2 \cdot r_4}$$ *Average convection from a cylinder*

$$\overline{N}_{D,out} = C \cdot Ra_{D,out}{}^{n}$$ *Nusselt - Rayleigh correlation*

$$Ra_{D,out} = Gr_L \cdot Pr_{out}$$ *Rayleigh Number*

$$Pr_{out} = \mathbf{Pr}\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,out}\right), P = P_{atm}\right]$$ *Prandtl number*

$$Gr_L = g \cdot \beta \cdot \left[T_{r4} - T_{\infty}\right] \cdot \frac{\left[2 \cdot r_4\right]^3}{\nu_{out}{}^2} \cdot \left[\frac{1 \quad [ft]}{12 \quad [in]}\right]^3 \cdot \left[\frac{3600 \quad [s]}{1 \quad [hr]}\right]^2$$ *Grashof number w/ unit corrections*

$$T_{film,out} = 1 / 2 \cdot \left[T_{r4} + T_{\infty}\right]$$ *Film temperature*

$$\beta = \beta\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,out}\right), P = P_{atm}\right]$$ *Value for B*

$$g = 32.174 \quad [ft/s^2]$$ *gravity*

$$\nu_{out} = \frac{\mathbf{Visc}\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,out}\right), P = P_{atm}\right]}{\rho\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,out}\right), P = P_{atm}\right]}$$ *Kinematic Viscosity of air*

$$k_{air,out} = \mathbf{k}\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,out}\right), P = P_{atm}\right] \cdot \frac{1 \quad [ft]}{12 \quad [in]}$$ *Thermal conductivity of air*

Nusselt-Rayleigh correlation coefficients

Double check solution to make sure correct coefficients are used and set to hard values

IF statement unstable/slow in program

$$C = 0.125$$ *IF($Ra_{D,out,10}$(-2),0.675,0.675,IF(Ra,D,out,10,2,1.020,1.020,IF(Ra,D,out,10,4,0.850,0.850,IF(Ra,D,out,10,7,0.480,0.480,0.125))))*

$$n = 0.333$$ *IF($Ra_{D,out,10}$(-2),0.058,0.058,IF(Ra,D,out,10,2,0.148,0.148,IF(Ra,D,out,10,4,0.188,0.188,IF(Ra,D,out,10,7,0.250,0.250,0.333))))*

Internal Forced Convection - Assuming Fully developed flow

$$T_{film,in} = 1 / 2 \cdot \left[T_{process,air} + T_{hw}\right]$$ *Inside film temperature*

$$\rho_{air,in} = \rho\left[Air_{ha}, T = \mathbf{ConvertTemp}\left(R, F, T_{film,in}\right), P = P_{atm}\right]$$ *Inside air density*

$\mu_{air,in}$ = **Visc** [Air_{ha} , T = **ConvertTemp** (R , F , $T_{film,in}$), P = P_{atm}] *Inside air dynamic viscosity*

$\mu_{air,in,s}$ = **Visc** [Air_{ha} , T = **ConvertTemp** (R , F , T_{hw}), P = P_{atm}] *Inside air dynamic viscosity at wall temperature*

$$\nu_{in} = \frac{\mu_{air,in}}{\rho_{air,in}} \cdot \frac{1 \ [hr]}{3600 \ [s]}$$ *Inside air kinematic viscosity*

$$U = \frac{\dot{V}_{flow} \cdot \frac{1 \ [min]}{60 \ [s]}}{\pi \cdot \left[r_1 \cdot \frac{1 \ [ft]}{12 \ [in]} \right]^2}$$ *Inside flow velocity in ft/s*

$$Re_{D,inner} = U \cdot 2 \cdot \frac{r_1 \cdot \frac{1 \ [ft]}{12 \ [in]}}{\nu_{in}}$$ *Inside Reynold's #*

Pr_{in} = **Pr** [Air_{ha} , T = **ConvertTemp** (R , F , $T_{film,in}$), P = P_{atm}] *Prandtl number*

$\overline{N}_{D,in}$ = **If** [$Re_{D,inner}$, 2300 , $\overline{N}_{D,laminar}$, $\overline{N}_{D,laminar}$, $\overline{N}_{D,turbulent}$] *Inside Nusselt #, determined by Reynold's #)*

$\overline{N}_{D,laminar} = 3.66$ *Nusselt numbers for laminar flow, assuming uniform tubing temperature*

$\overline{N}_{D,turbulent} = 0.023 \cdot Re_{D,inner}^{[4/5]} \cdot Pr_{in}^{0.3}$ *Nusselt # for turbulent flow*

$k_{air,inner}$ = **k** [Air_{ha} , T = **ConvertTemp** (R , F , $T_{film,in}$), P = P_{atm}] $\cdot \frac{1 \ [ft]}{12 \ [in]}$ *Thermal conductivity of air*

$$\overline{h}_{in} = \overline{N}_{D,in} \cdot \frac{k_{air,inner}}{2 \cdot r_1}$$ *Inside convection coefficient*

Cost estimation

$A_{inner} = \pi \cdot [r_3^2 - r_2^2]$ *Cross-sectional area of inner insulation*

$A_{outer} = \pi \cdot [r_4^2 - r_3^2]$ *Cross-sectional area of outer insulation*

$C_{ao} = 0.55$ [\$/in^3] *Cost per unit volume of aluminum oxide wrap*

$C_{mw} = 0.0055$ [\$/in^3] *Cost per unit volume of mineral wool sheet*

$$Cost_{insulation} = [A_{inner} \cdot C_{ao} + A_{outer} \cdot C_{mw}] \cdot \frac{L}{L \cdot \frac{1 \ [ft]}{12 \ [in]}}$$ *Cost of insulation - per foot*

$t_{insulation,total} = t_{inner} + t_{outer}$ *Total insulation Thickness*

$Pipe_{OAD} = 2 \cdot [t_{insulation,total} + r_2]$ *Pipe Overall Diameter with Insulation*

Test assumption of incompressible flow

Ma >0.3 indicates flow compression

V_{sound} = **SoundSpeed** [Air_{ha} , T = **ConvertTemp** (R , F , $T_{process,air}$), P = P_{atm}] *Speed of sound in air at process temperature*

$$Ma = \frac{U}{V_{sound}}$$ *Mach # of flow*

Heat loss info

$$q = c_p \cdot \dot{m}_{flow} \cdot - \Delta_T$$ *Heat lost to walls from flow*

$$c_p = \textbf{Cp}\left[Air_{ha}, T = \textbf{ConvertTemp}\left(R, F, T_{process,air}\right), P = P_{atm}\right]$$ *Specific heat of air*

$$\dot{m}_{flow} = \dot{V}_{flow} \cdot \rho_{1300} \cdot \frac{60 \quad [min]}{1 \quad [hr]}$$ *Mass flow rate of flow*

Conversion of flow to SCFM/SCFH

Values used for comparison to published valve/heater data - Not related directly to analyis

$$\rho_{std} = \rho\left[Air_{ha}, T = 60 \quad [F], P = P_{atm}\right]$$

$$\rho_{1300} = \rho\left[Air_{ha}, T = 1300 \quad [F], P = P_{atm}\right]$$

$$\dot{V}_{std} = \frac{\dot{m}_{flow}}{\rho_{std}}$$