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Final Design of Secondary Refrigeration System and Wind Tunnel

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Team I.C.E.C.O.L.D

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The goal of the secondary refrigeration system project was to design and build a secondary refrigeration loop to interface with an existing primary refrigeration loop for the testing and research of micro-encapsulated phase change material, as well as an educational tool for students interested in refrigeration. The aim of this report is to discuss and explain the final version of the design, the testing methods, results, conclusion, and any future recommendations. The wind tunnel is operational, reaching an average maximum air velocity close to what the group had aimed for. The heaters were able to heat the air to the desired range. Piping and most components and instrumentation have been connected and mounted. LabVIEW has been set up to read the outputs of the instruments. Unfortunately, the steam generator has not been mounted and the system has not been charged due to time constraints. Since much time was spent fixing the primary loop to an operational state, it is recommended that future groups working on the existing refrigeration loops ensure that they are working prior to the start of a new project. Overall, the client who requested this system is satisfied with the outcome, despite not meeting certain design criteria.

1 Executive Summary

The group has succeeded in the design and construction of a secondary refrigeration test loop and test wind tunnel compatible with testing a water based, microencapsulated phase change material (MPCM) slurry's effectiveness as a secondary refrigerant.

The secondary loop complements the primary loop. Therefore, its design is dependent on the operating parameters of the primary loop. As this technical information was not available, operating parameters, such as temperatures, pressures and primary flow rate, were obtained by direct measurement and reverse engineering. On a basis of these parameters, thermodynamic analysis was completed to determine the operating parameters of the secondary loop. These include fluid flow rates and temperatures at different points around the loop.

The desired operating conditions of the secondary loop were used to size the equipment that would be included in the secondary loop. These included the major refrigeration equipment and appropriate research instrumentation. A great deal of compatibility between components was necessary. This meant that a design had to be finalized before equipment was specified.

While the group finalized the component selection, construction, preparation and layout planning were well underway. A mobile cart was designed to support and display the secondary system. A piping and instrumentation flow diagram was also developed. A design of the physical layout followed this drawing. Construction of the cart followed these plans. Once built, mounting of the major equipment began to take shape.

The last piece of the project is the wind tunnel. Construction of the housing and mounting system is complete. This unit also monitors air conditions on both sides of the head exchanger.

The final step in the construction is the electrical wiring for pump motor and controller, fan motor and measurement equipment. This has been completed by Ernest Romo, the Engineering Departments Electrical Technician.

Thus far, the group has come a long way from the projects beginnings. Although preliminary loop tests are still underway, the group feels that all of the inherent obstacles have been thought through. All of the necessary materials have been purchased. The group is confident that they will carry out the remainder of the preliminary testing.

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5 Introduction

This report intends to communicate the final design of the secondary loop transport system as well as the design of its corresponding wind tunnel. The wind tunnel is used to control different loads on the system for purposes to test and research MPCM in an educational environment. Included in this report are discussions of the cart that houses the two systems, the layout of each system and its instrumentation. It also will discuss the methods of testing different design criteria as well as the results of this testing.

6 Final Design

The overall goal of the project was to design and construct a secondary refrigeration loop and wind tunnel that is compatible with the existing primary refrigeration loop at Trinity University to establish a suitable laboratory for experimentation and research in order to study the refrigeration properties of microencapsulated phase change material (MPCM). The final design was built to stand next to the primary loop and for aesthetic purposes look close to identical. The cart has the ability to withstand the weight of the entire system which includes the instrumentation and their respected controller as well as the wind tunnel and piping. The cart has three shelves and the ability to roll around. On the bottom shelf is located the steam generator to controller the relative humidity in the wind tunnel as well as the pump and the pump motor. The second shelf is where the flow meter, blower and blower controller are mounted. The top shelf is where the wind tunnel along with all of its variable testing equipment, the air cooled heat exchanger and the flat-plate heat exchanger are located. The mounting of certain equipment was constructed to dampen the vibration of the cart. The design met most of the design criteria, however, a few were altered to better simulate real situations.

6.1 Design Criteria

The design criteria have not changed much since its original draft at the beginning of the year. The few additions include those discussing a manual for the system, the LabVIEW VI, and instrument specifications. A complete description of those notated can be seen in Appendix H.

From the very beginning, the design specifications as well what needed to be measured were very explicitly stated in the design proposal that was given to the group by Dr. Terrell as to what he wanted out of the project. These were mass flow rate, inlet and outlet temperature of the MPCM around each heat exchanger, MPCM and air pressure drop across the heat exchanger, the humidity at the inlet and outlet of the heat exchanger, inlet and outlet temperatures of the air before and after the heat exchanger, and velocity of the air flowing through the wind tunnel. The thermocouples and pressure devices have been tested and/or calibrated and function correctly. The entire system was modeled using Engineering Equation Solver (EES) so the desired testing ranges should be reachable with the instrumentation and devices purchased. All devices / instruments were also compared with one another as well with system conditions before purchasing to ensure compatibility.

Extensive design and specifications were completed before anything was purchased. Several schematics for the component layout as well as the piping and instrumentation were created before ordering items. Because of this, the system exterior is very easy to follow and is ideal for lab and research purposes. Because of the VI that already existed from the previous senior design project, it was easy to add the necessary additions from the secondary loop into the same VI. This makes the data easy to obtain and visualize. These additions are still being added however and no data have been collected, mostly because the system is not up and running quite yet.

The system was designed with the dimensions of the lab door as well as the elevator in mind. As a result, the system can fit through these doors and is easily movable and accessible. The cart was also built with the idea that it would be moved around a great deal so it is robust and reinforced with angle iron and plywood. It was also desired to have all the equipment operate at a noise level below 50dB. This level was chosen because it is the typical indoor sound level that lecturers speak at for a small classroom setting. This has not been verified however since not all of the components have been turned on together yet. The only components that are expected to produce loud noise are the pump, steam generator, and blower. The blower has been tested and is very quiet when in use.

The system is modular in the areas that were specified. The most important of these being that the heat exchanger can be replaced with different types of heat exchangers so that the MPCM can be tested in a variety of conditions. The main point of this project is the design needs to address certain needs to be used in research of MPCM in refrigeration systems. This was accomplished by not having the wind tunnel one long corridor, but instead breaking it up into sectional pieces. The section with the heat exchanger can be easily removed as it is only held in place using flanges on the wind tunnel and clamps.

The whole basis of the project was to be able to operate tests on the MPCM in a variety and wide range of conditions. These include the temperature of the air inlet to the heat exchanger in the wind tunnel, air velocity, and ambient humidity. The minimum and maximum of these values were used when determining the wind tunnel cross sectional area as well as the heat exchanger load and all instruments related to these conditions. An EES model was created to input these values to check that the right dimensions were chosen for the wind tunnel and the right instruments were chosen with the correct range of functionality. Because of this, the system should be able to operate in these conditions because of the instruments chosen as well as chosen control devices for each of the instruments. The items tested thus far have been the heaters and the blower. The blower has produced an air velocity of 2.5m/s, slightly below the desired 3m/s, but this seems attainable with some design adjustments in the duct as well as possible adding a diffuser at the beginning of the wind tunnel. The heater produces the desired maximum air temperature, but has not yet been tested with the controller to vary the temperature.

As far as safety of the system is concerned, the cart and the devices on the cart are constructed and securely fastened so that none of the components on the cart can move around. This is so that people operating this system cannot injure themselves and items cannot fall off of the cart. Because the system is not completely finished yet, no leak tests have been administered and not all the voltage or high temperature areas have been labeled yet. The pipes have not been pressure tested but the pump specifications are known so there should not be a problem with the piping that exists in the system as is. All the materials that are used in the piping are compatible with one another and the correct size/fit so corrosion and leaking should not occur.

It is not known whether the system can operate at long lengths of time but it is assumed that none of the components will be running continuously for days at a time. The system should also be able to operate with minimal assistance due to the ease and accessibility with which it was designed, but this will not be known for sure until it is completed and users are given access. All the parts which are used should be easy to remove and to install new ones. The components that are anchored on the cart were done so with unistructs, wood, and bolts, which can be easily removed and reshaped to any type or size of new component.

The MPCM should also be easy to remove from the system. This was made possible by designing a charging hopper and purging valve into the piping and instrument diagram for the system. These two sections have not been tested yet, but when completed they will satisfy this criterion.

The system satisfies the criterion of containing the needed instruments at all desired measurement points. This includes the thermocouples, thermal dispersion unit, hygrometers, pressure gauges, and pressure differentials. Each of these is placed at the desired location in order to obtain the desired data set. What still needs to be accomplished is labeling these points and wires so that there is no confusion from the user. This will also help students understand the system and the refrigeration cycle as well as heat transfer measurements.

Lastly, the criteria of writing a standard operating procedure for filling the system as well as turning it on was written so it should be easily operable.

6.2 Design Constraints

Constraints on this project include economic, environmental and sustainability concerns. The first of these constraints are the economic considerations. The design budget is constrained to the initial donation from Trinity of $1,000 as well as an additional grant from The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) of $7,200 for a total budget of $8,200. The economic factors considered in the budget are the cost materials and cost of labor. The design will be set to perform at a specific efficiency which is decided by the group and is considered an environmental factor as well as an economic factor, even though the overall energy costs to run the system are not considered in the budget.

Another environmental factor that is considered is that the primary loop contains a stream of refrigerant (R-134A), which cannot be allowed to leak throughout the system into the ambient atmosphere as it is hazardous to one's health and the environment. This is also a health consideration. R-134A is denser than air and may cause a health hazard if inhaled. Because safety is of large concern, health hazards such as these are not acceptable. For this reason, every precaution was made to contain the R-134a safely in the piping and confirm that there were no leaks in the primary system.

Because the system will be used as a class room experimental device, it had to run at a noise level suitable for an academic environment. The system's design is set on a moving module and cannot cause harm when in use. Therefore, various safety measures were put in place on the existing system. The parts of the system that are of the most concern such as the heat exchanger and the pressurized pipes are designed in such a way that they are obvious risks and should not be tampered with by those that will be working on the system. The design has the points of interest of the system for the experiment such as the fan in the wind tunnel, humidifier, dehumidifier, and the pump well labeled as well as easily accessible. This is due to the initial design purpose that this system is meant to be a learning and research tool.

There are several durability constraints that need to be considered. The design is constructed to be robust and in order to have the system remain sustainable, a training guide will be provided to those in the academic environment. The system is designed so that it can go through various cycles without breakdown and is to last for several years. If problems do occur, the system is designed for easy accessibility to the myriad of components so that repairs can be implemented. The device is constructed to be mobile as well as modular so that the system can be updated to keep up with the academic environment. This means it has to be transported to different areas and that the components can be replaced and interchanged easily.

6.3 Cart and Frame Design

The group originally had planned to build an extended platform off of the primary refrigeration loop cart in order to mount the secondary loop components. However, after considering the amount of parts required for the final design, a separate three-shelved cart has been constructed to meet the space capacity required to mount all the equipment. The cart consists of ¾ inch plywood for the platforms and angle iron for the supporting frame. The cart design is simple and changes have been made from its initial design.

Several details have been considered when constructing the cart in order to meet certain design criteria. To satisfy the criterion of the system being aesthetically pleasing, the plywood is painted black to match the color scheme of the primary loop cart. Casters on a rotating axis are installed so that the unit has full range of motion and mobility, but also have brakes so that the cart can remain stationary. The size of the cart is purposefully chosen such that it utilizes most of the space in the elevator while still having room in the elevator for two people to ride with the cart. The final cart design can be seen in Figure 1.

Unistructs, slotted-framing units of various lengths and shapes, were used to provide a framing structure for certain components and piping. These were used extensively to support the flat-plate heat exchanger, the wind tunnel, the blower, the pump, and various valves and fittings.

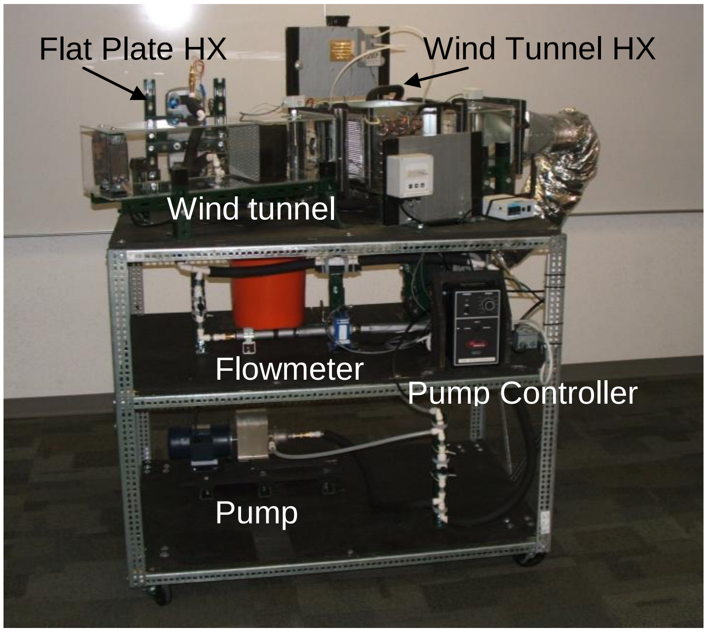

Figure 1: Secondary Refrigeration Loop Cart.

6.4 Component Layout

The layout of the components has been subjected to several changes. The initial layout only contained the flat-plate heat exchanger, wind tunnel/wind tunnel heat exchanger of arbitrary size, and the pump and did not account for other major components such as the flow meter, steam generator, and blower because, at the time, the dimensions were not known. The design layout was further developed after the dimensions were calculated. The pre-construction design can be seen in Appendix A.

The pump is placed on the lowest shelf of the cart, as illustrated in Figure 2. Out of all the components, the pump is the lowest point in the loop so that the fluid gravitates towards the inlet and prevents air pockets from entering the pump. The pump can be damaged if it is operated with no fluid. In the original plans, the pump was placed towards the front of the cart due to speculation that the inlet would be facing upwards. However, the pump inlet actually faces to the front of the cart and the decision was made to put the pump towards the back for a more convenient orientation.

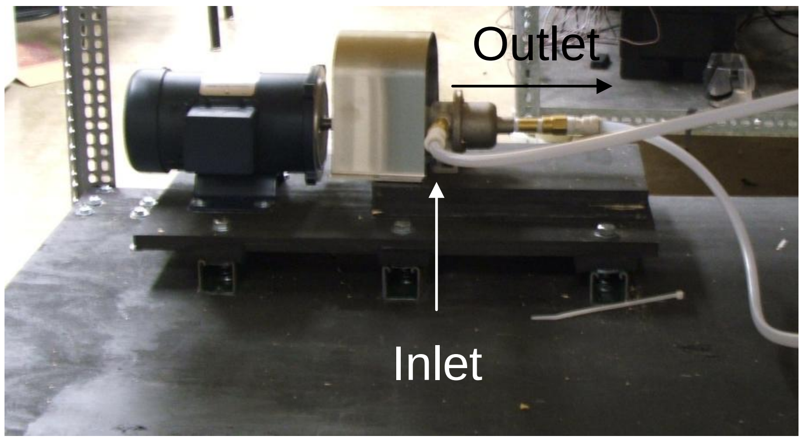

Figure 2: Pump placement.

After the slurry exits the pump, it enters the magnetic flow meter. The flow meter is positioned on the second shelf of the cart, in the center. This was done to allow for one foot of straight pipe to be installed before and after the flow meter, which is required for the flow meter to operate correctly. Originally, it was to be situated towards the front of the cart as the pump was originally planned to be towards the front. It is currently positioned so that the motor controller is in front of the piping to allow for easy access, the blower is behind the piping to allow for an easy orientation for the wind tunnel, and the flow meter is closer to the pump. This can be seen in Figure 3.

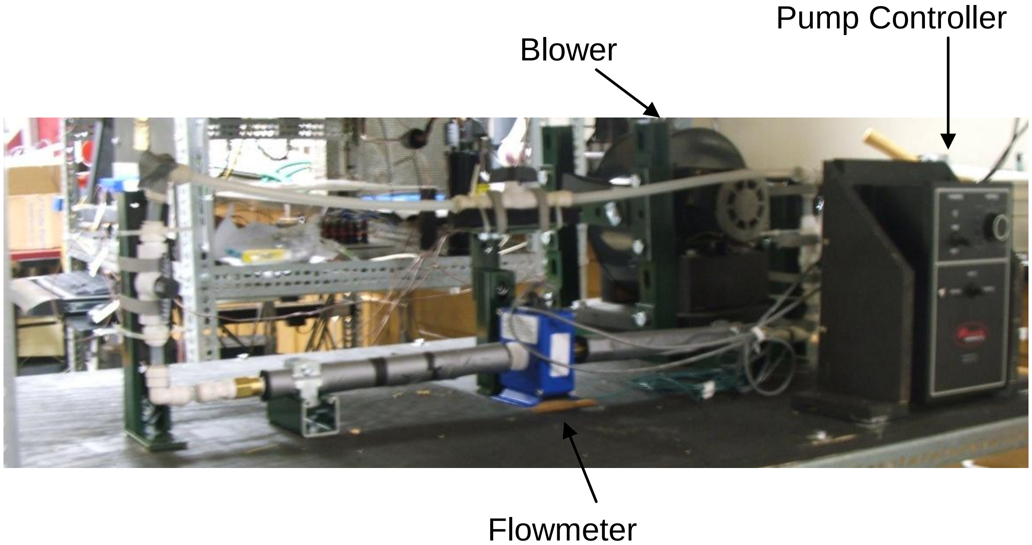

Figure 3: Flow meter, Blower, and Motor Control placement.

From the flow meter, the slurry reaches the flat-plate heat exchanger, which is placed in the rear-left corner of the top shelf, shown in Figure 4. Since the flat-plate heat exchanger is the interface between the primary and secondary loop, its position allows it to be in close proximity of the primary loop and the wind tunnel heat exchanger, making piping connections easy. Threaded refrigeration hoses instead of copper pipes were purchased so that connection between the loops would be simple, alleviating any need for gas welding. The heat exchanger is insulated to prevent condensation from forming, which could be hazardous if it comes into contact with the electrical wiring. The position has not changed from the original plan.

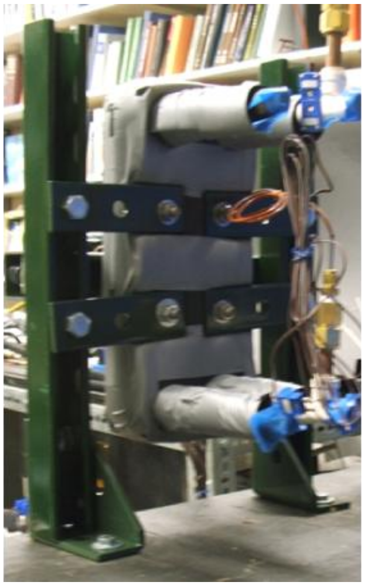

Figure 4: Flat-plate Heat Exchanger Placement.

The last component of the loop is the wind tunnel heat exchanger. The position is largely determined by the length and orientation of the wind tunnel. The wind tunnel heat exchanger is situated near the center of the top shelf and oriented so that the inlet and outlet face towards the flat-plate heat exchanger. The wind tunnel is situated diagonally for two purposes: First, the diagonal orientation makes full use of the cart space, seeing as the wind tunnel is the largest component. Second, it divides the top shelf in half, leaving the front section for controls and the rear section for piping. Neither the wind tunnel nor the heat exchanger has deviated from original planning. Both of these components can be seen in Figure 5.

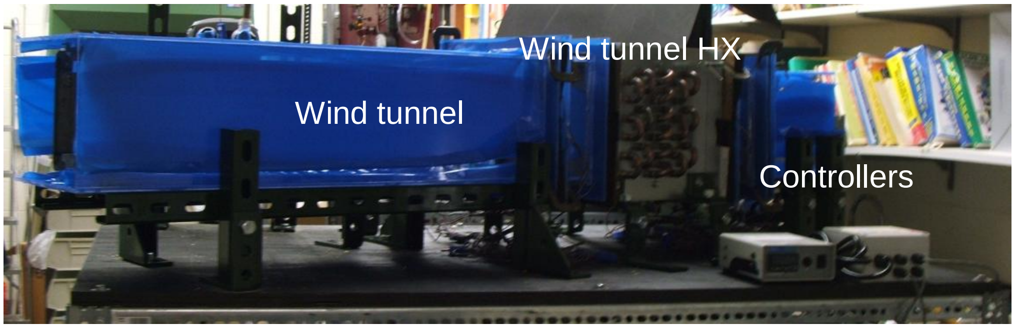

Figure 5: Wind tunnel (blue) with wind tunnel heat exchanger, and heater and flow meter controls (front-right).

The blower sits on the second shelf in the rear-right section of the cart, illustrated in Figure 3: Flow meter, Blower, and Motor Control placement.. The position makes it easy to connect ducting to the wind tunnel. It is oriented so that the outlet faces towards the right, behind the controllers, so that the exiting air does not disturb any of the users.

Currently, the steam generator has not been mounted and piped. The group has plans to put it on the bottom shelf on the front-left section of the cart. This situates the steam generator directly under the wind tunnel, which will allow for easy piping to the wind tunnel. The pipes will be insulated and blocked by plexiglass to eliminate the risk of being burned. Plexiglass is ideal in this situation as it has a low thermal conductivity and is clear, allowing users to see the other components behind it. There is a safety release valve built into the steam generator that will discharge excess steam buildup. This discharge will be directed into a container of water, where the steam will condense. The container will have an overflow drain that will direct excess water to the appropriate drainage. This is illustrated in Figure 6.

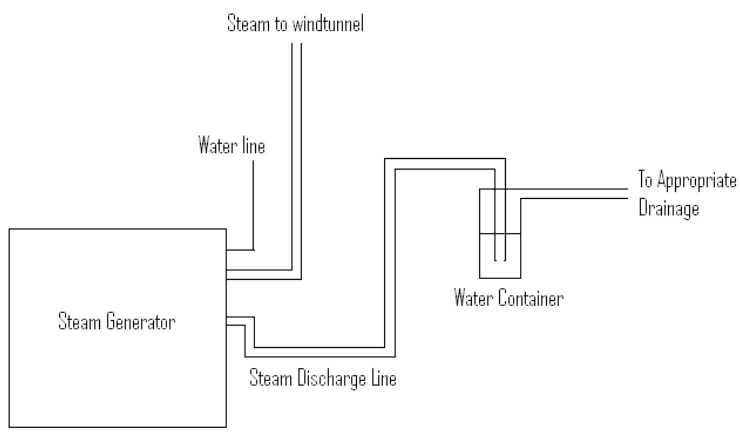

Figure 6: Steam Discharge Design.

Currently, the only control mounted is the motor control. Originally, all controls were to be situated on the top shelf, in the front-right portion in front of the wind tunnel. The heater, blower, and flow meter control are still going to be situated there. Only the motor control is situated on the second shelf due to its size. This position is still ergonomically accessible. The humidity control was planned to be electronically controlled using an on/off controller. However, because the on/off controller would not provide a continuous flow of steam, a manual control was chosen in the form of a ball valve. This will be situated on the second shelf as the steam will enter from the bottom portion of the wind tunnel and the controller has to be situated before the wind tunnel. The ball valve will be close to the motor controller and within reach of the other controllers for the convenience of the users.

6.5 Wind tunnel

The wind tunnel dimensions ultimately depended on the dimensions, instrumentation, and components that would be mounted to it. The cross-sectional area of the wind tunnel depends on the size of the heat exchanger and the total length depends on the instrumentation spacing requirement. Currently, the instrumentation devices have not been mounted to the wind tunnel. A few changes to the wind tunnel layout have been made since the original wind tunnel design. The sprayer for the humidifier has been changed from a nozzle to a straight, closed pipe with several discharge holes in different directions. This is preferred over the nozzle as it allows for a more even distribution of steam. The steam sprayer has not been installed as steam generator has not been installed as well. Placement of the thermocouple meshes before and after the heat exchanger has been changed. The thermocouple meshes have been integrated into the flange insulation and, therefore, are closer to the heat exchanger. This was done mainly for ease of construction and assembly. The thermocouple mesh after the heaters have not been installed yet as there are no more thermocouple slots left on the front panel of the primary refrigeration system and the thermal dispersion unit has not been installed due to a delay in delivery. A hotwire anemometer will be used to measure velocity in the meantime. Figure 7 illustrates the final layout design. The spacing of the components can be found in Appendix C.

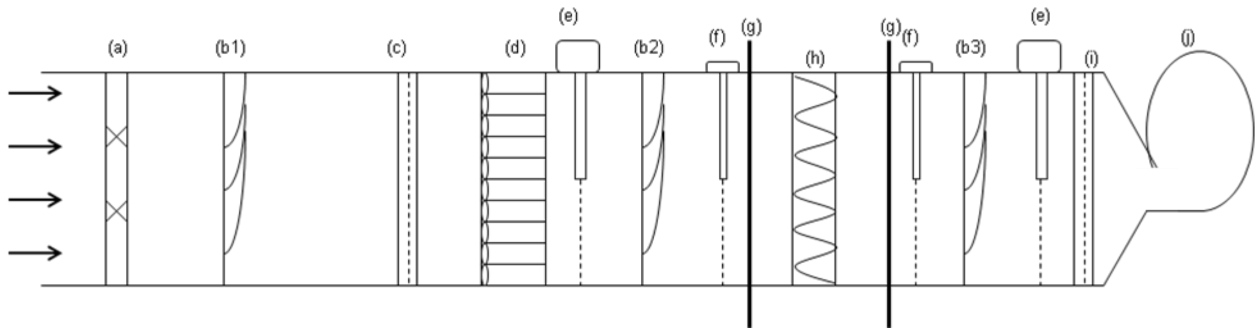

Figure 7: Final Wind tunnel Layout Design of Instrumentation and Components, which include heaters (a), thermocouple mesh (b1-3. b1 not installed), steam sprayer (c. not installed), honeycomb (d), hygrometers (e), pressure differential probes (f), flanges (g), heat exchanger (h), thermal dispersion unit (i, not installed), and blower (j).

6.6 Piping and Valve Schematics

The piping and instrumentation diagram, Fig. B-1, can be found in Appendix B. This figure includes the major pieces of refrigeration equipment, measurement instruments, valves and lines that will be included in the final setup. This diagram is not meant a scaled drawing of the process layout. The figure is meant to for process organization and understanding purposes. The process flow is counter clockwise when looking at the drawing. The pump will be the vertically lowest piece of equipment in the loop. This will ensure that the pump head has fluid on both the inlet and outlet at all times. The charging hopper is located directly behind the pump in the process loop. This will be used when filling the system with secondary refrigerant. It is located behind the pump so that during filling, the pump will be pulling directly from this source.

The next piece of equipment following the pump is the flow meter. The flow meter is equipped with a bypass line to help with calibration and service of the unit. The flow meter must have static fluid surrounding it during calibration. Should calibration be needed while the system is running, the flow meter can be placed in bypass to be calibrated.

Following the flow meter is the flat plate heat exchanger. The flat plate heat exchanger will intake the MPCM slurry at 10°C and will discharge MPCM slurry at 2°C. The flat plate will transfer thermal energy to the primary loop to accomplish this temperature change. Following the flat plate is the wind tunnel heat exchanger. This unit will receive water at 2°C and discharge water 10°C. The wind tunnel heat exchanger is equipped with a bypass line so that the loop can be brought in and out of steady state when transferring energy from the primary loop. With the wind tunnel heat exchanger in bypass, the flat plate heat exchanger will cool the secondary loop without recovering this energy. This will be useful when the system is first turned on at room temperature. The bypass will be used to bring the secondary refrigerant down to the 2C-10C range. Once this is achieved, the wind tunnel heat exchanger will be placed in service and a steady state condition will develop. From here the fluid returns to the pump to complete the secondary cycle.

6.7 Instrumentation

Utilizing the data acquisition equipment donated to Team REFRIDGE in 2006, Team Ice Cold could bypass setting up the hardware necessary for acquiring signals from measurement devices. The preexisting hardware setup includes a data acquisition (DAQ) terminal block that is serially connected via a chassis to the computer. The computer contains two DAQ cards, each of which corresponds to either the current or voltage analog outputs in the primary and secondary systems as well as in the wind tunnel.

Each type of input required a method of sending a signal to a computer that would monitor its activity. Panels are built into the primary loop that can directly receive input from the measurement devices and transfer them to the computer in real time. National Instrument's LabVIEW Virtual Instrument software is used to interface, monitor and plot the data. The thermocouple panel creates access to 20 channels with built in cold junction compensation for the systems and wind tunnel. The analog current input panel contains 16 channels as well as a DC power supply for instruments to be wired to the panel. Current input instrumentation for the secondary loop and wind tunnel includes the magnetic flow meter, two pressure transducers, two velocity measurement units and two hygrometers, all of which output between 4-20 mA.

6.8 Electrical

With the exception of the pump, each of the components in the system can be powered via a standard 120V outlet plug in the wall. The pump and motor requires a 220V power supply to operate as desired. There are outlets that can provide this kind of power in the lab, so the pump is plugged in there. This will also be necessary when the steam generator is implemented as it requires the same power supply.

All of the controllers and components are wired to the power strip which is housed on the extreme right of the second level of the cart. Instruments are also grounded to a common ground that is housed in its own flip-box on the right side of the cart.

Other measurement devices, including the thermocouples and the pressure differentials, are powered by a 5V DC output supplied through the primary loop. For the thermocouples, the power is supplied through the measurement panels. For the pressure differentials, the power is supplied through the power panel that sits next to the current input panel on the second level of the primary loop.

6.9 Methods

This section of the report provides an overview of the testing methodology for the secondary loop and wind tunnel. The tests range from initial mechanical operability of each system to measuring performance of different refrigerants to quantifying the effectiveness of the design as a teaching tool.

6.9.1 Initial Mechanical Operability of Secondary Loop

Once the secondary loop is constructed, it will be necessary to check for fitting and connection leaks. This leak test is conducted by filling the secondary loop to capacity with the initial working fluid, distilled water. Visual inspection of the connections and fittings around valves, gauges, and system equipment is the first leak test. Once it is determined that the loop holds stationary fluid without leaking, we need to determine if the loop can hold the pressure induced by the pump. See Fig. 8 for an example of how these operating points can be read from the manufacturer's performance curve.

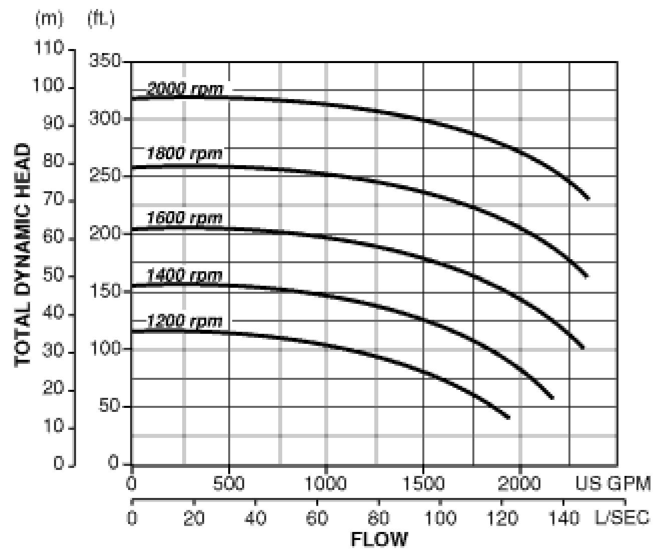

Figure 8: Performance curve of pump with flow rate with respect to discharge pressure [1]

Prior to starting up the secondary loop, the instruments will first need to be determined to be working properly. Once filled with the working fluid, readings will be taken from the flow meter, temperature devices, hygrometer, and pressure transducers. As the loop is not in operation it will be expected to have ambient temperature, humidity and pressure values returned by these instruments. It is expected to see a flow rate of zero. The return of these values will determine that these instruments are operating correctly at ambient conditions. The next step will be to determine if they perform correctly during the initial start-up of the secondary loop.

The initial start-up of the secondary loop will be a test run which will be used to check the operation of the mechanical components in the secondary loop. This test will also be conducted with distilled water as the working fluid. Once the first leak test has been completed successfully and the instruments are in working order, the secondary loop will be turned on for the first time. This run will be carried out independent of the primary loop. As this run will not be a thermal test, the primary loop will not be running during this procedure. This run will begin by turning the pump on and setting it at the lower end of its operating speed. Once the pump is running the secondary loop will again be visually inspected for leaks. If no leaks are present, the pump speed will be increased in increments to its maximum operating speed. At each increment, the operator will perform a visual leak inspection.

The manufacturer's pump performance curves will used in combination with the voltage set point on pump-motor controller and the flow meter reading to determine is these are operating correctly. Given a voltage set point, the operator can use the pump motor performance specifications to see what speed the motor should be running at. This information will be used to verify that the motor controller is calibrated correctly. The operator can use the pump performance curve to see what flow rate and head pressure the pump should be operating at, given the motor speed. The flow meter will be calibrated by the manufacturer before it is shipped. If all things are working properly, this flow rate should match the reading from the separate flow meter on the secondary loop. If there are major discrepancies in these values, it will be necessary to troubleshoot the controller and the flow meter to determine which piece of equipment is in error.

The pressure differentials will first need to be calibrated before they can be checked for operational accuracy in the secondary loop. Dr. Terrell has performed this task in his lab before and allows access to the correct equipment to do so. Given a motor speed, the operator can use the pump performance curves to predict a value for the pressure he/she should expect the pump to generate. The pressure values found on the curve should match that given from the pressure transducer immediately following the pump in the loop. If there are discrepancies between these, this information can also be used to troubleshoot any discrepancies found between the manufacturer's flow rate values and that measured from the flow meter.

Consider a situation where the motor is running at a given voltage set point. If the pressure reading matches what one would expect from the performance curve, but the flow meter reading is exceptionally high or low. These results could mean that the pump is performing correctly, and the flow meter's readings are erroneous.

Alternately, consider a situation where the pump is running at a given set point, but the pressure and flow meter readings do not match what one would expect to see according to the performance curve. If the pressure and flow meter readings correspond to another point on the performance curve, a reasonable conclusion could be that the voltage controller is generating a voltage different to the set point.

The successful completion of these tests will be sufficient to prove that the secondary loop is ready for thermal analysis.   The next test will determine the mechanical operability of the wind tunnel.

6.9.2 Mechanical Operability of Wind tunnel

The equipment of interest for this experiment will be the steam generator, air heater, blower, and their associated controllers. This test will also check to determine if the temperature, air speed, and humidity measurements are being recorded accurately. The first device to be tested will be the blower and the air speed measurement device. The blower controller will be calibrated by making air speed measurements with a working hand-held anemometer. This calibration will also test and verify that the blower can meet the desired wind test velocity: 1m/s-3m/s. Once calibrated, the blower is controlled using a damper. Once the blower is running, the accuracy of the settings will be determined by taking readings from the air measurement device. If there are discrepancies between the set points and the air speed readings a hand held anemometer will be used to determine which device is in error.

Once the blower and blower controller are functioning properly, the air heating system will be tested. The thermocouples will initially be checked at ambient conditions to determine that they are working properly. Secondly, the heaters will be turned on at a specified set point. The temperature devices will be monitored to determine if the set points are accurate or if they need to be adjusted manually.

The final pieces of equipment to be tested in the wind tunnel are the steam generator and hygrometer. The hygrometer will first be tested at ambient conditions to determine if it is collecting data properly. Determining the correct operation of the steam generator will be a more involved process. The settings on the steam generator regulate the production of steam in terms of weight of steam per units of time (lbs steam / hr). Computer simulation models have been built to determine relative humidity results given a volumetric flow rate of air and an air temperature. The steam-generator will be used in conjunction with the model calculations and hygrometer readings to determine if the steam-generator is operating correctly.

This concludes the procedure to determine the mechanical operability of the secondary loop and wind tunnel. The next step in the experimentation will be a thermal analysis to confirm that the secondary loop is functioning as an energy transport system.

6.9.3 Test procedures to determine range of controlled variables

Once the components are proven to be adequate on an individual basis, the next step is to understand the total system being designed. Specifically, the equipment must be tested to determine an operable range for the system while maintaining control over certain variables.

Within the wind tunnel, heat and water vapor are added to meet the desired temperature and relative humidity. It is imperative to understand the capabilities of conditioning so that the entire range of operable conditions is utilized to its fullest. One of the first things to understand about the wind tunnel is the importance of maintaining some type of volumetric air flow in order to avoid a stagnation point, a point where air remains in the same spot, near the center. Because instruments will be placed in this area, a stagnation point could render some measurements and control systems useless. To ensure that the velocity measurement occurs where the profile is mostly uniform, the lower limit of the volumetric flow rate must be determined. By lowering the speed of the blower at the end of the wind tunnel using the damper, the experimenter can test for stagnation points within the wind tunnel. To be more specific, at each increment of the blower speed, an air velocity measurement should be taken at different parts of the wind tunnel starting six inches and moving away from the blower in increments of six inches. Note that measurements are taken off-axis as well as in the center of the wind tunnel to get a more complete velocity profile. As long the measurement is greater than zero, testing should continue as planned. However, if a measurement of zero is recorded, the experimenter should slowly move the measuring device closer until the limit is found. More importantly, the experimenter should note that the air speed of the blower is inadequate to supply the airflow necessary for the designed wind tunnel. A basic setup of this experiment can be seen in Figure 9.

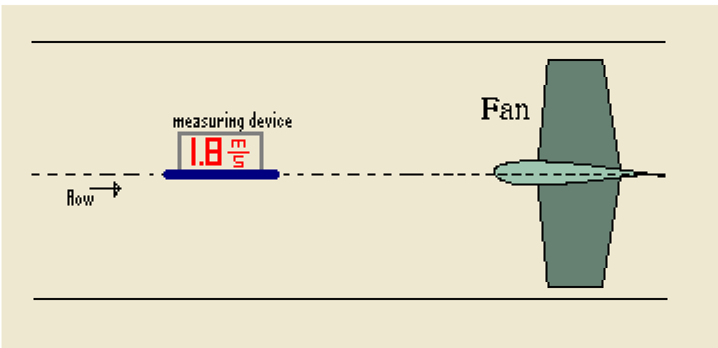

Figure 9: Setup of Velocity Measurement in Wind tunnel

The next wind tunnel variable to be tested is the relative humidity. In order to find the range of operable humidity, the steam generator should simply be set to operate at full capacity. By measuring the humidity of the air prior to conditioning and the relative humidity of the air as it travels through the wind tunnel, the effective ranges can be determined, assuming the air can hold all of the water vapor. While the initial range of 40-80% relative humidity was specified in the project proposal, this testing could possibly exceed those bounds. The lower limit of operable humidity ranges is determined by the ambient conditions of the laboratory. To effectively understand the upper limit on humidity, the steam generator should be tested at full capacity for the range of blower speeds found in the test procedure prior to this one. The major concern during this type of testing is water condensing and the interaction between electric components and water. To prevent this, all pipes are insulated and covered to avoid unwanted interactions.

The final wind tunnel variable to be taken into account is the temperature of the air. Similar to the humidity specifications, the temperature ranges have the possibility of exceeding the 25-30 C range. To measure the full effectiveness of the strip heaters, they should be set to operate at full capacity and tested over the range of operable blower speeds. Similar to the humidity measurements, the lower limit of the temperature range will be determined by the ambient conditions of the laboratory.

The pump will need to be tested to ensure it is operating at the projected flow rate in the secondary loop. There is a maximum and minimum flow rate the pump can produce and this range will be to be found. This will be done using the flow meter as well as the pressure differentials. The flow meter will indicate these maximum and minimum values when the pump is operating at its maximum and minimum speeds.

6.9.4 Procedures for analyzing MPCM/Refrigerant performance

To determine the heat transfer and refrigerant efficiency throughout the secondary loop, temperatures, pressure drops, humidity, and flow rate measurements need to be recorded in specific locations as illustrated in Fig. 10 and Table 1:

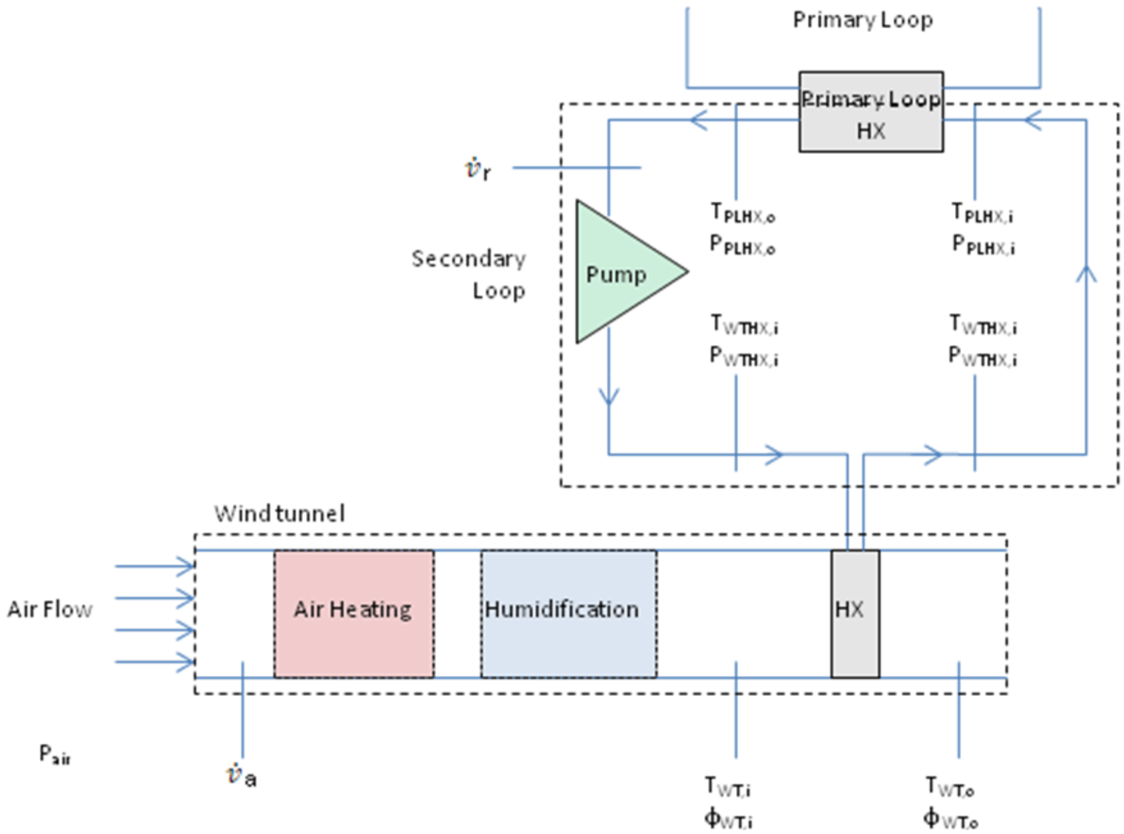

Figure 10: Specified locations of temperature, pressure, humidity and mass flow rate measurements on system diagram.

Table 1: Description of measurements found in Fig. 10.

Nomenclature	Description
$T_{PLHX,o}$ and $T_{PLHX,i}$	Temperature measurements of the secondary refrigerant at the outlet and inlet of primary loop heat exchanger
$P_{PLHX,o}$ and $P_{PLHX,i}$	Pressure differential measurements of the secondary refrigerant at the outlet and inlet of primary loop heat exchanger
$T_{WTHX,o}$ and $T_{WTHX,i}$	Temperature measurements of the secondary refrigerant at the outlet and inlet of wind tunnel heat exchanger
$P_{WTHX,o}$ and $P_{WTHX,i}$	Pressure differential measurements of the secondary refrigerant at the outlet and inlet of wind tunnel heat exchanger
$T_{WT,o}$ and $T_{WT,i}$	Temperature measurements of air flow after and before wind tunnel heat exchanger
$\phi_{WT,o}$ and $\phi_{WT,i}$	Relative humidity measurements of air flow after and before wind tunnel heat exchanger
$\dot{v}_r$	Volumetric flow rate of refrigerant
$\dot{v}_a$	Volumetric flow rate of air (in wind tunnel)
P_{air}	Pressure measurement of the ambient air

It should be noted that though the temperature and pressure measurements will only be used to monitor the status of the MPCM as it traverses the secondary loop. The temperatures and pressure drops in the loop will be measured using insertable type T thermocouples and pressure differentials while the mass flow rate of MPCM will be measured using a magnetic flow meter. The temperatures in the wind tunnel will be measured using exposed-wire type T thermocouples and the relative humidity will be measured using hygrometers. Volumetric flow rate of air will be determined using a measurement device that calculates velocity using principles of thermal dispersion and can be correlated to a volumetric flow rate. The air pressure will be measured using a pressure transducer.

In order to determine the refrigerant effectiveness, both the heat load provided by the wind tunnel and the heat absorbed by the refrigerant need to be calculated. The heat load provided by the wind tunnel can be described in Eq. 1 as:

$$\dot{Q}_{load} = \dot{m}_a(h_{a,i} - h_{a,o}) + \dot{m}_a(\omega_i h_{a,g,i} - \omega_o h_{a,g,o}) - \dot{m}_a(\omega_i h_{a,f,o} - \omega_o h_{a,f,o}) \qquad (1)$$

$$\omega_i = 0.622\left[\frac{\phi_i P_{a,g,i}}{P_{air} - \phi_i P_{a,g,i}}\right] \qquad (2)$$

$$\omega_o = 0.622\left[\frac{\phi_o P_{a,g,o}}{P_{air} - \phi_o P_{a,g,o}}\right] \qquad (3)$$

$$\dot{m}_a = \dot{v}_a \rho_{air} \qquad (4)$$

Where the variables are described in Table 2:

Table 2: Variable description for equations 1, 2, 3, and 4.

Variable	Description
$\dot{m}_a$	Mass flow rate of dry air
$h_{a,i}$ and $h_{a,o}$	Enthalpy of air evaluated at $T_{WT,i}$ and $T_{WT,o}$ (respectively)
$h_{a,g,i}$ and $h_{a,g,o}$	Enthalpy of saturated steam vapor evaluated at $T_{WT,i}$ and $T_{WT,o}$ (respectively)
$h_{a,f,o}$	Enthalpy of saturated steam vapor evaluated at $T_{WT,o}$
ω_i and ω_o	Humidity ratio before and after (respectively) the wind tunnel heat exchanger
$P_{a,g,i}$ and $P_{a,g,o}$	Saturated steam vapor evaluated at $T_{WT,i}$ and $T_{WT,o}$ (respectively)
P_{air}	Pressure of the ambient air
ρ_{air}	Density of ambient air

Note that if temperature of the air is known, the enthalpy of dry air can be found using thermodynamic tables. The heat load equation can be simplified such that it becomes a function of $T_{WT,i}$, $T_{WT,o}$, $\dot{v}_a$, and P_{air}. This can be seen in Eq. 5:

$$\dot{Q}_{load}(T_{WT,i}, T_{WT,o}, \dot{v}_a, P_{air}) = \dot{v}_a \rho_{air} \left[\left(h_{a,i} - h_{a,o}\right) + 0.622 \left(\left[\frac{\phi_i P_{a,g,i}}{P_{air} - \phi_i P_{a,g,i}}\right] h_{a,g,i} - \left[\frac{\phi_o P_{a,g,o}}{P_{air} - \phi_o P_{a,g,o}}\right] h_{a,g,o} \right) - 0.622 h_{a,f,o} \left(\left[\frac{\phi_i P_{a,g,i}}{P_{air} - \phi_i P_{a,g,i}}\right] - \left[\frac{\phi_o P_{a,g,o}}{P_{air} - \phi_o P_{a,g,o}}\right] \right) \right] \tag{5}$$

This equation takes into account the sensible heat of the air-water mixture and latent heat of condensation of the water vapor. Because all the measurement devices are DAQ compatible, the heat load will be calculated and recorded using LABVIEW.

On the MPCM side of the heat exchanger, the heat absorbed can be described by Eq. 6. The method used is the Number of Transfer Units (NTU) method.

$$\dot{Q}_{WTHX} = \varepsilon C_{min} (T_{WT,i} - T_{HXWT,i}) \tag{6}$$

$$\varepsilon = 1 - exp\left[\frac{C_{max}}{C_{min}} NTU^{0.22} \left(exp\left(-\frac{C_{min}}{C_{max}} NTU^{0.78} \right) - 1 \right) \right] \tag{7}$$

$$C_{min} = \dot{m}_r Cp_r \tag{8}$$

$$C_{max} = \dot{m}_a Cp_a \tag{9}$$

$$\dot{m}_r = \dot{v}_r \rho_r \tag{10}$$

$$NTU = \frac{UA}{C_{min}} \tag{11}$$

where C_{min} and C_{max} are the heat capacity rates for the MPCM and air (respectively), ε is the heat exchanger heat transfer efficiency, UA is a heat transfer-area coefficient specified by the manufacturer of the heat exchanger, ρ_r is the density of the refrigerant, and NTU is the ratio between UA and C_{min}. Like the heat load equation, the heat absorbed equation can be simplified such that it is a function of $\dot{v}_r$, $\dot{v}_a$, $T_{WT,i}$, and $T_{HXWT,i}$, as shown in Eq. 12:

$$\dot{Q}_{WTHX}(\dot{v}_r, \dot{v}_a, T_{WT,i}, T_{HXWT,i}) = \varepsilon \dot{v}_r \rho_r Cp_r (T_{WT,i} - T_{HXWT,i}),$$
$$\varepsilon = 1 - exp\left[\frac{\dot{m}_a Cp_a}{\dot{m} Cp_r} NTU^{0.22} \left(exp\left(-\frac{\dot{m} Cp_r}{\dot{m}_a Cp_a} NTU^{0.78} \right) - 1 \right) \right] \tag{12}$$

Using this equation, the heat absorbed by the MPCM can be calculated and recorded using LabVIEW because the measurement devices are DAQ compatible. Once both the heat load and the heat absorption are calculated, a criterion for success can be set. Assuming that the wind tunnel heat exchanger is operating correctly, most of the heat load produced in the wind tunnel will transfer to the MPCM, as expressed by Eq. 13:

$$\dot{Q}_{load} \cong \dot{Q}_{WTHX} \tag{13}$$

Slight differences between the two heat quantities may be attributed to inherent measurement errors and heat absorbed by the heat exchanger interface material as well as heat loss through the walls of the wind tunnel. If there are differences greater than 20% between the two values, the measurement devices need to be checked for calibration or damage.

Even though efficiency of a refrigerant can be measured in several ways, the team has defined the efficiency of the secondary loop refrigerant as the ratio between the heat load absorbed by the heat exchanger and the power required to overcome the pressure drop in the heat exchanger. This coefficient of performance (COP) can be described in Eq. 14:

$$COP_{WTHX} = \frac{Q_{WTHX}}{W_{\Delta P}} \tag{14}$$

$$\Delta P = P_{WTHX,i} - P_{WTHX,o} \tag{15}$$

where $\dot{W}_{\Delta P}$ is the power needed to overcome the pressure loss in the heat exchanger and assuming $\dot{Q}_{WTHX}$ = $\dot{Q}_{load}$. It was decided to solely calculate the COP around the wind tunnel heat exchanger rather than the whole system because most of the system remains constant throughout its operation. For example, the only major component that would be changed out is the wind tunnel heat exchanger whereas the piping, pump and pump motor, and the other components will remain the same. The power needed to overcome the pressure drop can be expressed in Eq. 16:

$$\dot{W}_{\Delta P} = \dot{v}_r \Delta P \tag{16}$$

where $\dot{v}_r$ is the volumetric flow rate of the refrigerant. Therefore, COP_{WTHX} is ultimately a function of $\dot{v}_r$, $\dot{v}_a$, $P_{WTHX,i}$, $P_{WTHX,o}$, $T_{WT,i}$, and $T_{WTHX,i}$. This is described in Eq. 17 below and can also be calculated and recorded in LabVIEW since it is a function of parameters which are measured through DAQ compatible devices.

$$COP_{WTHX}(\dot{v}_r, \dot{v}_a, T_{WT,i}, T_{HXWT,i}, P_{WTHX,i}, P_{WTHX,o}) = \frac{Q_{WTHX}(\dot{v}_r, \dot{v}_a, T_{WT,i}, T_{HXWT,i})}{\dot{v}_r[P_{WTHX,i} - P_{WTHX,o}]} \quad (17)$$

Another criterion for success to determine the effectiveness of the MPCM as a secondary refrigerant is introduced here: $COP_{WTHX}|_{MPCM} > COP_{WTHX}|_{water}$. A high COP means that the refrigerant can transfer more heat per unit of power. Low heat capacity and high density refrigerants, which may require more power to overcome pressure drop in the heat exchanger, contribute to a low COP. If the COP of MPCM were greater than that of water, it would mean that MPCM is a more efficient refrigerant than water.

6.9.5 Test Procedures for instructional effectiveness of design

It is imperative that the initial goal of creating a system that would have value in an academic setting is evaluated. To do this, the following procedure should be run in a laboratory setting. The demographics for this test experiment should include students who are currently enrolled in or have taken thermodynamics class at Trinity University. The experiment should be a hands-on experience for students to see how certain scientific phenomena occur. The professor should have the secondary loop setup to operate under conditions that would allow it to run continuously and steadily. Then, after understanding the data acquisition system, the students could then look at the pressures and temperatures across the wind tunnel heat exchanger to calculate the change in enthalpy. Once this is done, the mass flow rate could be adjusted and the change in enthalpy could be calculated based on measured values again. A third run could be done with MPCM in the flow stream and the students would be able to see effect of the latent heat being used and how lesser inputs could obtain certain outcomes. This procedure would most likely occur over the course of a month as the changing of refrigerants is not a simple task. The professor could then suggest using measurements to find the efficiencies and coefficients of performance for each run as well as analysis of the lab in the form of a lab report, memo, etc.

After this experiment takes place, a survey of qualitative and quantitative questions would be given to the students involved in the experience to see if the secondary system helped them to better understand the concepts of thermodynamic principles. Some questions to ask include:

- Which concepts did the experiment help you understand?
- What was the most interesting feature about the secondary loop and why?
- What was the most difficult feature to use?
- What other concepts are you struggling with?
- How might a lab help you understand those better?
- Did you feel this lab helped you? Why or why not?
- What was the most interesting thing (good or bad) about this lab?
- Respond to the following statements on a scale of 1 to 5 with 1 being the worst and 5 being the best with an explanation of why you chose the rating:
    - This system seemed safe to be around and operate.
    - This system was simple enough to follow what was going on.
    - The user interface was easy to use.
    - This system helped me learn about thermodynamics and its practical use.

7 Results

After months of designing, specifying, modeling, and building, the only way to know if the system was performing as it should was to test it. The tests that have been completed so far include the thermocouples in both the wind tunnel and the insertable types in the piping. These were all plugged into the DAQ board to check that they were all recording accurate ambient temperatures and responding to temperature changes. The pressure differential across the heat exchanger on the air side has also been tested and works properly. The numbers recorded on Lab View from the static pressure probes were compared with a handheld pressure differential. These values were the same thus the pressure probes were calibrated and were functioning properly. The pressure differential across the heat exchanger on the fluid side has not yet been tested however. The magnetic flowmeter also has been turned on to ensure that it functions, but has not yet been tested with fluid flow in the system. Because of the fact the system has not been charged with fluid yet, it is not know if the pump controls fluid flow properly or if the heat exchangers performing as they should. The blower has been tested and performs within 80% of specification. This was tested using a hot wire anemometer on several different occasions. The air flow is very even over the entire cross sectional area of the wind tunnel which means the flow straighteners in place are working properly. The damper was also tested and can adequately control the flow of air from the desired 1m/s to the maximum 2.5m/s. It has been discussed that several things can be changed on the system to increase this velocity to the desired 3m/s such as installing a diffuser and changing the duct work from the blower to the wind tunnel. The heaters have been tested and can heat the inlet air up to the desired 30C. However, they have not been tested in conjunction with the controller so it is now know the accuracy or delay in adjusting the heaters. The hygrometers have also not been tested to determine their accuracy. Because the steam generator has not been installed yet, it cannot be tested nor can the ball valve that was intended to control the amount of steam released into the wind tunnel. The piping has not been tested for leaks yet but will be as soon as it is charged with the fluid.

Final testing on the entire system is expected to be completed this week as the piping will be charged with fluid today. Eventually, other calculations can be found such as efficiency of different fluids in the system and other heat transfer measurements. After the fluid is charged, the inlet and outlet temperature of the water can be recorded, and eventually the slurry so that other tests can be conducted for research purposes.

8 Conclusions and Recommendations

This project involved reverse engineering a previous senior design project, familiarizing oneself with current refrigeration technologies, thermodynamic analysis, design and construction of a secondary refrigeration system. Reverse engineering was required because although the previous design group's report was available, the flowmeter on the system did not work. This was a necessary component to designing the secondary loop. Because of this, the team had to find other means of calculating this value. The only remaining tasks are integration of the measurement instruments into the LabVIEW VI and steam generator installation and testing. Although there is one piece holding up the completion of construction, all of the needed materials have been purchased.

Preliminary loop testing is in its early stages and may not be completed in its entirety. This is because some unprecedented obstacles slowed down the initial progress of the project. On the onset of the project a timeline was developed on the assumption that the primary loop was functioning properly and that the needed operating parameters could be readily obtained from the system. The group lost about two months due to the primary loop being dysfunctional. We have done well to overcome this obstacle and to make up the lost time. In the future, if a project is suggested to design and construct a third sequential loop, it will be essential to ensure that both subsequent loops are in working order before the onset of the project.

At the onset of the project, the group as a whole was unfamiliar with refrigeration systems and technologies. This project has taught us much about how direct expansion refrigeration loops work and the theory behind secondary refrigeration systems and their applications. The project has also given the group a wealth of hands on experience in the engineering machine shop and in Dr. Terrell's research lab. This technical experience has also included working with electrical components and wiring, working with and using refrigerant charging and discharging equipment. The plumbing has also given us the opportunity to learn how to sweat or solder copper connections. This project has also enabled us to increase our vocabulary with technical jargon.

Should our group not be able to complete the testing phase, the project is in a position that will be easy for a new student, unfamiliar with the system, to complete testing. If such should be the case we would like to recommend that this task be offered to a student in terms of a summer or semester research project. If completed in this manner the project will have met its final design goal: to function as an educational piece of equipment for future students.

9 Bibliography

1. **Cole Parmer.** Flow Curve for 75400-10. [Online] 2008. [Cited: April 30, 2008.]

A Comparison of Designs

It can be seen that the two designs seen in Figures A-1 and A-2 are slightly different. The reason for the change in the design is primarily due to adaptations during construction. Certain orientations and positions of particular components were more convenient or efficient than the initial design.

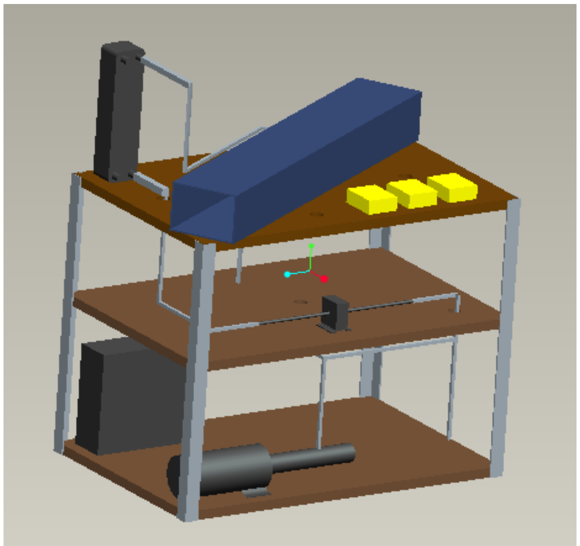

Figure A-1: Pre-construction secondary refrigeration loop design.

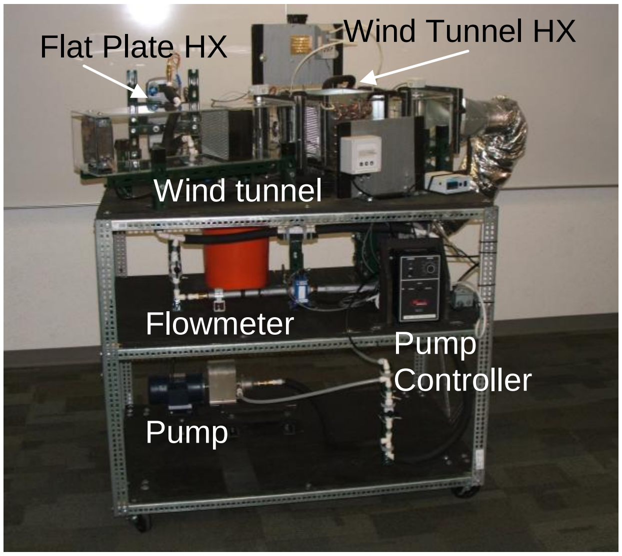

Figure A-2: Actual secondary refrigeration loop.

B Piping and Instrument Diagram

Figure B-1 represents the plumbing schematic of the refrigeration loop along with designation of instrumentation and valve placement.

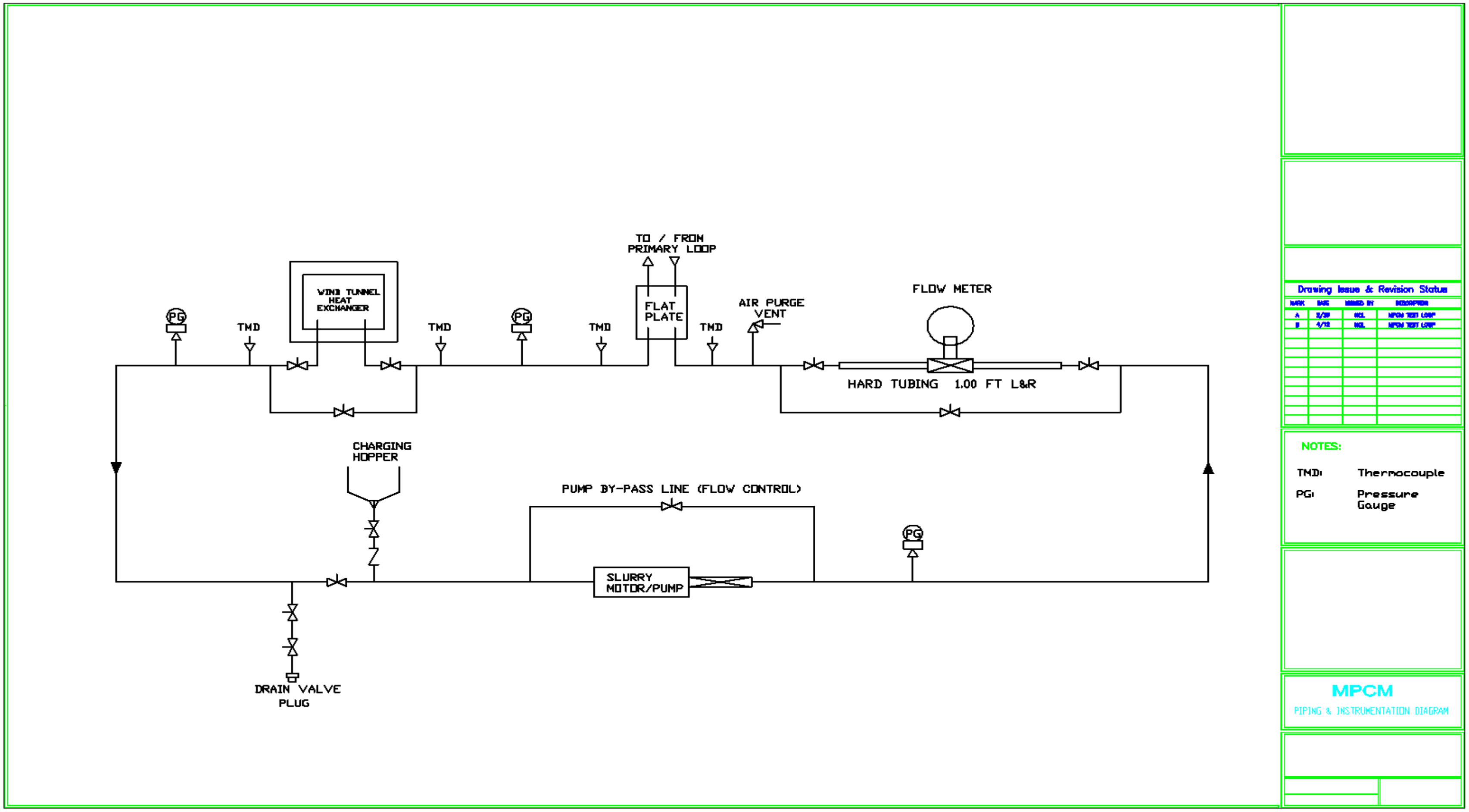

Figure B-1: Plumbing schematic of secondary refrigeration loop with valve and instrumentation placement.

C Wind Tunnel Instrumentation Layout

Figure C-1 illustrates the lengths between all the wind tunnel instrumentation and components as well as the layout.

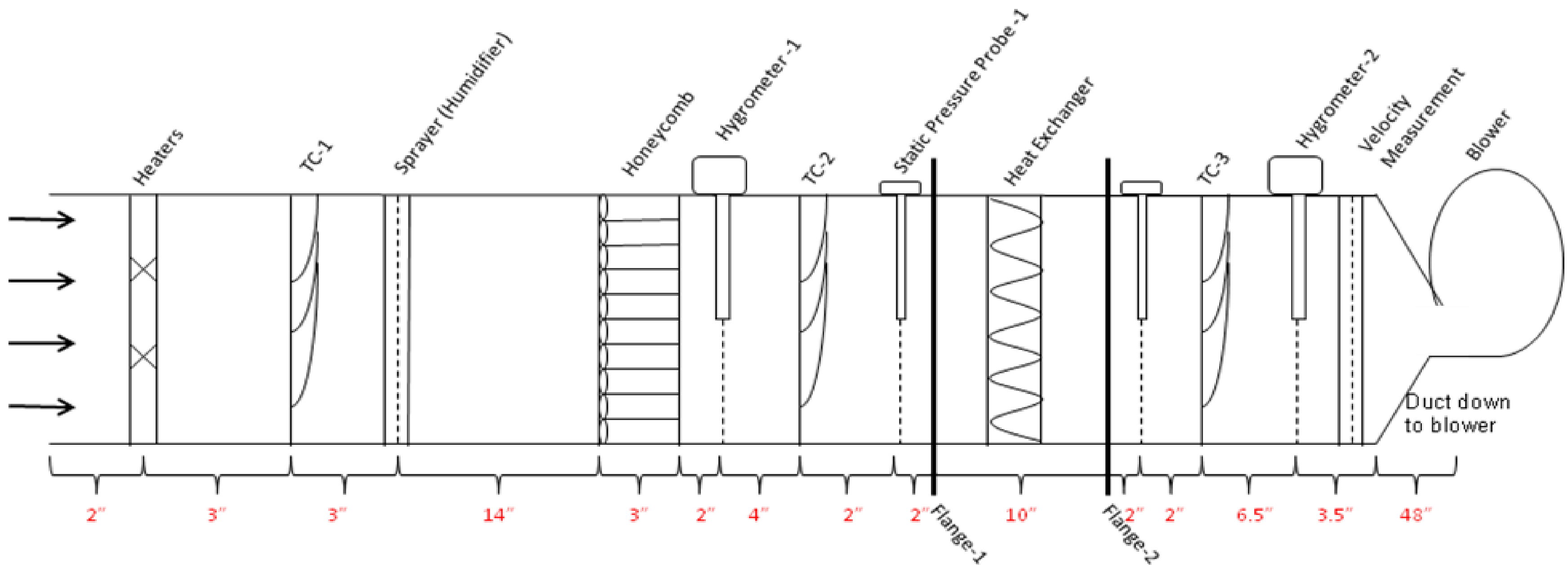

Figure C-1: Wind Tunnel Instrumentation Layout

D Bill of Materials

The following table is a bill of materials that list all the materials used to make the system.

Table D-1: Bill of Materials

Item	*Type*	*Vendor*	*Model #*	*Quantity*	*Unit*
Hex Bolts	1/4"			9	
	3/8"			32	
	1/2"			125	
Nuts	Spring Frame			18	
	Frame			12	
	3/8"			50	
	1/2"			30	
	5/8"			7	
	3/4"			42	
Washers	1/4"			9	
	3/8"			32	
	1/2"			74	
Rebarb	1/2"			8	in
Piping	1/2" T-Connector			13	
	1/2"-3/8" Connector Adapters			26	
	1/2" Ball Valves			13	
	1/2" Elbows			6	
	1/2" Clamps			2	
	1/2" Tubing			40	ft
	1/2" Refridge Tubing	SA Belting & Pulley		10	ft
Unistrux	Triangular corner	Grainger		10	
	4 hole Corner	Grainger		9	
	2 hole Corner	Grainger		14	
	T-s	Grainger		3	
	Framing Channel (w/ holes)	Grainger		27	ft
	Framing Channel (w/o holes)	Grainger		1	ft

	3 hole lengths	Grainger		4	
	4 hole lengths	Grainger		7	
Plywood	3/4" thick			6822	in^2
	2" x 4"			16	in^2
Angle Iron	14 gauge			712	in
Plexiglass	1/4" thick			4462.5	in^2
Homey Comb	3" long			78.75	in^2
Screws	Flat Phillips			8	
	Round Phillips			6	
	Flat Head			2	
Nails	3/4"			5	
Pump	Progressive Cavity	Cole Parmer	EW75400-10	1	
Heat Exchanger	Flat Plate	Flat Plate Inc.	CH 3/4A	1	
	Tube and Fin	USA Coil & Air	CW12FM010007500001R	1	
Pump	DC Motor	Cole Parmer	K70071-00	1	
	DC Controller	Cole Parmer	K70100-00	1	
Coupling	1/2" Bore	Cole Parmer	K07127-57	1	
	5/8" Bore	Cole Parmer	K07127-59	1	
	Guard	Cole Parmer	K07127-69	1	
	Spider	Cole Parmer	K07128-52	1	
	Shim	Cole Parmer	K07001-28	2	
Strip Heater	120V	Omega	WS-605/120V	2	
	Controller	Omega	CSC32	1	
Transmitter Pressure	10 psi	Omega	EW-68071-08	1	
	2.5" W.C.	Omega	EW-68071-58	1	
	3 Valve Manifold	Omega	WU-68071-95	1	
Thermal Dispersion Unit		Holland Equipment		1	

Hygrometer	Duct Mount	Omega	HX92AC-D	2	
	Duct Kit	Omega	HX90DM-KIT	2	
	Power Supply	Omega	PSR-24S	1	
Blower	Centrifugal	Grainger	1TDT2	1	
Damper	6" Diameter	Grainger	3ZW16	1	
Duct Work	6" Diameter	Texas Air Products		4	ft
Steam Generator	Generator	SteamSaunaBath	SM-5	1	
	Control Package	SteamSaunaBath	TC-110	1	
	Ball Valve	Grainger	4NA72	1	
Thermocouple	Type T Insertable	Omega	HTTC36-T-18G-6	4	
	Type T Wire	Omega		14	
	Type T Fittings	Omega	BRLK-18-14	4	
	TI 24 Wire	Omega		70	ft
Flowmeter	Magnetic	Omega	FMG201-NPT	1	
Insulation	3/8"			2	ft^2
	1/2"			5	ft^2
Wheels	5" Casters	Dunn		4	
Paint	Black			1	can
Wire Connectors				12	
Pressure Taps	1/8"			3	
Velcro Strips	12" length			20	
Zipties	6" length			20	
Metal Wire	12" length			12	

E Budget list

The following table tracks the group's expenditure activity as well as any items that were donated to the group.

Table E-1: Budget List

Vendor	*Part #*	*Item Description*	*Cost*	*Quantity*	*Total*
Pump					$1,290.60
Cole Parmer	EW75400-10	Pump Head 1.5 GPM 316 SS	$539.10	1	$539.10
Cole Parmer	K70071-00	Motor 1750 RPM 1/3 HP 90VDC	$243.00	1	$243.00
Cole Parmer	K70100-00	DC controller 10 A 115/230V	$418.50	1	$418.50
Cole Parmer	K07127-57	Coupling ½" bore diameter	$8.10	1	$8.10
Cole Parmer	K07127-59	Coupling 5/8" bore diameter	$8.10	1	$8.10
Cole Parmer	K07127-69	Spider f/coupling	$4.63	1	$6.30
Cole Parmer	K07128-52	Coupling guard aluminum 6"H	$40.50	1	$40.50
Cole Parmer	K07001-28	Shim Aluminum 0.062" thick	$13.50	2	$27.00
Heat Exchanger					$358.55
Flat Plate Inc.	CH 3/4A	Flat Plate Heat Exchanger	$358.55	1	$358.55
Wind Tunnel Instruments					$3,400.43
Omega	WS-605/120V	Strip Heater	$124.00	2	$248.00
Omega	EW-68071-08	Transmitter Pressure	$395.00	1	$395.00
Omega	EW-68071-58	Transmitter	$255.00	1	$255.00
Omega	WU-68071-95	Manifold 3 Valve	$240.24	1	$240.24
Holland Equipment	Other	Thermal Dispersion Unit	$455.50	1	$455.50

Omega	HX92AC-D	Hygrometer	$195.00	2	$390.00
Omega	HX90DM-KIT	Hygrometer Duct Kit	$16.00	2	$32.00
Omega	PSR-24S	Hygrometer Power Supply	$60.00	1	$60.00
Omega	CNi3233	Humidity Controller	$255.00	1	$255.00
Grainger	1TDT2	Centrifugal Blower	$124.11	1	$124.11
Grainger	3ZW16	Damper	$27.23	1	$27.23
SteamSaunaBath	SM-5	Steam Generator	$839.95	1	$839.95
SteamSaunaBath	TC-110	SG Control Package	$79.95	1	$79.95
Grainger	4NA72	Steam Ball Valve	$39.45	1	$39.45
Other Instruments					$1684.40
Omega	HTTC36-T-18G-6	Type T Insertable Thermocouple	$19.00	12	$228.00
Omega	BRLK-18-14	Thermocouple fittings	$5.70	12	$68.40
Omega	FMG201-NPT	Magnetic Flowmeter	$1,388.00	1	$1,388.00
Cart Items					$795.22
Lowe's	Wood				
Dunn	Casters				
Insco Dist.	3/8" Insulation				
Lowe's	Plexiglass				
Grainger	Unistrux				
Plastic Supply	Plexiglass Glue				
Construction Items					$483.51
Lowe's	Nuts				
Lowe's	Bolts				
Lowe's	Washers				
Lowe's	Screws				
Lowe's	Nails				

Lowe's	Fittings				
Lowe's	Rebarb				
Piping					$146.32
Lowe's	1/2" T connectors				
Lowe's	1/2" Elbows				
Baker Dist.	1/2" Refrigeration hose				
Lowe's	1/2" Ball Valves				
Lowe's/Home Depot	1/2" Adapters				
Taylor Made Hose	1/8" Tubing				
Lowe's	1/2" Copper Piping				
Aesthetics					$8.65
Lowe's	Velcro				$4.67
Michael's	Thermocouple Wire				$3.98
TOTAL COST					**$8,209.36**
MAX FUNDING					$8,200.00
Donated Items	Paint				$20.00
	Zipties				$10.00
	Duct Work				$50.00
	1/2" Insulation				$30.00
	Electrical Wiring				$20.00
	Electrical Connections				$20.00
	Heater Controller				$500.00
	Tube/Fin Heat Exchanger				$700.00
	Nuts, Bolts				$100.00

	Unistrux Pressure Taps 1/2" Tubing				$50.00 $10.00 $30.00
INCLUSIVE COST					**$9,695.75**

F Wind Tunnel Model

The group ran into a bottle neck when trying to design the wind tunnel. There was a delicate balance between wind tunnel cross-section, humidity level, and UA value of the heat exchanger, which is a specification to help size the component. A model was generated to aid in determining the optimal solution. Figure F-1 are the code and equations used to develop the model. From the code, a graphical user interface was developed from the code, seen in Figure F-2. From the model, plots were produced to easily identify the optimal solution. For example, it was desirable to maintain a wind tunnel relative humidity of 70 percent. Using the plot in Figure F-3, it can be seen that the maximum volumetric flow rate of air to maintain the desired humidity is 270 ft^3/min. This volumetric flow rate can be used in the plot in Figure F-4 to determine the corresponding UA value. A UA value for a given air velocity in the wind tunnel can be used to determine the cross sectional area of the wind tunnel using the plot in Figure F-5.

$T_2 = T_3$ midsection temperature

$a_c = L \cdot W$ In diagram box, user inputs crossectional dimensions of tunnel in inches

******Conditioning Portion******

$P_{air} = 101.35$ [kPa] Ambient Air pressure

$conv_{flow,pow} = 3.51899$ [kw-lb/hr] conversion factor from lb/hr to kw

$\rho_a = \rho(\text{'Air'}, T = T_1, P = P_{air})$ density of air

$\rho_w = \rho(\text{'Water'}, T = T_1, P = P_{air})$ density of water

$P_{g,1} = \mathbf{P_{sat}}(\text{'Steam'}, T = T_1)$ Saturation pressure at inlet

$P_{g,2} = \mathbf{P_{sat}}(\text{'Steam'}, T = T_2)$ Saturation pressure at midsection

$P_{g,3} = \mathbf{P_{sat}}(\text{'Steam'}, T = T_3)$ Saturation pressure at outlet

$cp_a = \mathbf{Cp}(\text{'Air'}, T = T_3)$

$$\dot{v} = v \cdot a_c \cdot \frac{1}{\left| 0.016666667 \cdot \frac{min}{s} \right|} \cdot \left| 3.2808399 \cdot \frac{ft}{m} \right| \cdot \left| 0.006944444 \cdot \frac{ft^2}{in^2} \right|$$ Volumetric flow rate of air

$$\dot{m}_a = \rho_a \cdot v \cdot a_c \cdot \left| 0.00064516 \cdot \frac{m^2}{in^2} \right|$$ mass flow rate of air

$\delta_t = \mathbf{ConvertTemp}(C, K, T_2) - \mathbf{ConvertTemp}(C, K, T_1)$

$Q_{heater} = \dot{m}_a \cdot cp_a \cdot \delta_t$

Humidiy ratio (kg H20 / kg Dry Air)

$$\omega_1 = 0.622 \cdot \left[\frac{RH_1 \cdot P_{g,1}}{P_{air} - RH_1 \cdot P_{g,1}} \right]$$

$$\omega_2 = 0.622 \cdot \left[\frac{RH_2 \cdot P_{g,2}}{P_{air} - RH_2 \cdot P_{g,2}} \right]$$

$$\omega_3 = \omega_2 + \frac{\dot{m}_w}{\dot{m}_a}$$

$$\omega_3 = 0.622 \cdot \left[\frac{RH_3 \cdot P_{g,3}}{P_{air} - RH_3 \cdot P_{g,3}} \right]$$

$P_{air} - RH_1 \cdot P_{g,1} = P_{air} - RH_2 \cdot P_{g,2}$ Partial pressure of vapor remains same in heating process

$$q_w = \frac{\dot{m}_w \cdot \left| 3600 \cdot \frac{s}{hr} \right|}{\rho_w \cdot \left| 0.003785412 \cdot \frac{m^3}{gal} \right|}$$ Flowrate of water

$$\dot{m}_{H20,to,HX} = \omega_3 \cdot \dot{m}_a$$

$$\dot{m}_{air,to,HX} = \dot{m}_a$$

$$\dot{m}_{w,eng} = \dot{m}_w \cdot \left| 7937 \cdot \frac{lbm/hr}{kg/s} \right|$$

$$power_{req} = \frac{m_{w,eng}}{conv_{flow,pow}}$$

******HX Portion: Windtunnel side******

Enthalpy Calculations

$h_{a,3} = \mathbf{h}$ ('Air' , $T = T_3$) enthalpy of air going in

$h_{a,4} = \mathbf{h}$ ('Air' , $T = T_4$) enthalpy of air going out

$h_{g,3} = \mathbf{h}$ ('Steam' , $T = T_3$, $x = 1$) saturated vapor inlet

$h_{g,4} = \mathbf{h}$ ('Steam' , $P = P_{air}$, $x = 1$) saturated vapor outlet

$h_{f,4} = \mathbf{h}$ ('Steam' , $P = P_{air}$, $x = 0$) saturated liquid outlet

$P_{g,4} = \mathbf{P}_{sat}$ ('Steam' , $T = T_4$) Pressure at saturation (outlet)

Relative humidities

$$RH_4 = 1$$

Humidity Ratios

$$\omega_4 = 0.622 \cdot \left[\frac{RH_4 \cdot P_{g,4}}{P_{air} - RH_4 \cdot P_{g,4}} \right]$$

$$- Q_{hx} \cdot \left| 0.000293071 \cdot \frac{kW}{btu/hr} \right| + \dot{m}_a \cdot (h_{a,3} - h_{a,4} + \omega_3 \cdot h_{g,3} - \omega_4 \cdot h_{g,4} - (\omega_3 - \omega_4) \cdot h_{f,4}) = 0$$

******HX Portion: Refrigerant Side********

$Cp_r = 8.41$ [kJ/kg-C]

$$\rho_r = \rho \left[\text{'Water'} , P = P_{ri} \cdot \left| 6.895 \cdot \frac{kPa}{psi} \right| , T = T_{ri} \right]$$ refrigerant density

$$\dot{m}_r = \rho_r \cdot \left| 0.0000630902 \cdot \frac{m^3/s}{gal/min} \right| \cdot flow_r$$ refrigerant mass flowrate

$$C_{min} = \dot{m}_r \cdot Cp_r \cdot \left| 1 \cdot \frac{kJ/kg-K}{kJ/kg-C} \right|$$ refrigerant side is Cmin

$C_{max} = \dot{m}_a \cdot cp_a$ Air side is Cmax

$$Cr = \frac{C_{min}}{C_{max}}$$

$$Q_{hx} \cdot \left| 0.000293071 \cdot \frac{\cdot kW}{btu/hr} \right| = \varepsilon \cdot C_{min} \cdot \left(\mathbf{ConvertTemp}\left(C , K , T_3 \right) - \mathbf{ConvertTemp}\left(C , K , T_{ri} \right) \right)$$

$$\varepsilon = 1 - \mathbf{exp}\left[\frac{1}{Cr} \cdot NTU^{0.22} \cdot \left(\mathbf{exp}\left(- Cr \cdot NTU^{0.78} \right) - 1 \right) \right]$$

$$NTU = \frac{UA}{C_{min}}$$ This finds the holy grail of HX values

$$UA_{eng} = UA \cdot \left| 1896 \cdot \frac{\cdot Btu/hr\text{–}F}{kW/K} \right|$$

Figure F-1: Wind Tunnel EES Code

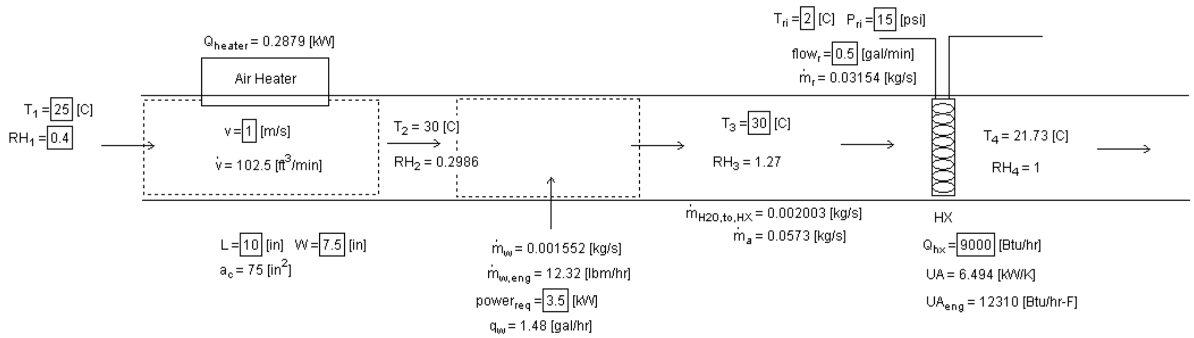

Figure F-2: GUI for Wind Tunnel Model

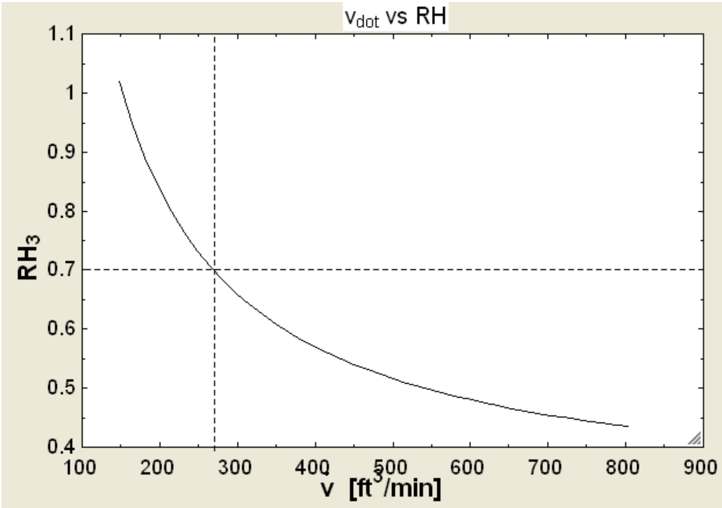

Figure F-3: Plot of Relative Humidity level with respect to volumetric flow rate of air through the wind tunnel.

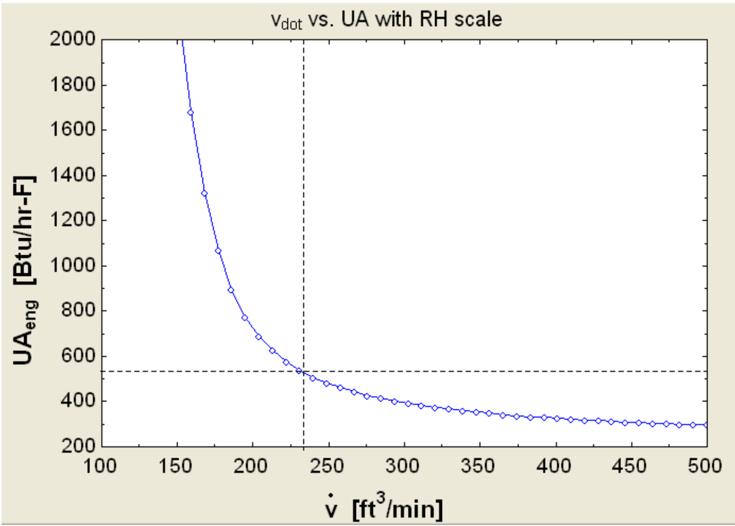

Figure F-4: UA value with respect to volumetric flow rate of air

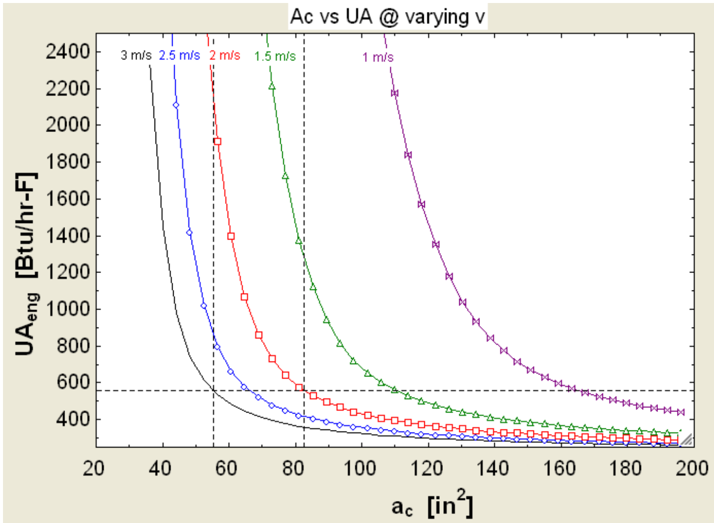

Figure F-5: UA value with respect to cross-sectional area of the wind tunnel at varying air velocities.

G List of Design Criteria

Below is a list of design criteria that determines the goals and aims of the project.

- System should be designed with the consideration to enhance student learning and aid research projects.

  Status: Complete

- System should have the capacity to obtain measurements in order to provide useful learning tool for students and for research projects. Measurements include:
  - Mass flow rate of MPCM through piping

    Status: Complete

  - Inlet, outlet refrigerant temperatures: 1º to 50º C

    Status: Complete

  - Refrigerant and air pressure drop across heat exchanger

    Status: Complete

  - Humidity at inlet and outlet of heat exchanger: 60% to 80%

    Status: Complete

  - Air velocity inside the wind tunnel

    Status: Incomplete, Velocity measurement device did not arrive in time, but velocity was measured using hot wire anemometer replacement

  - Air temperature before and after heat exchanger

    Status: Complete

- Data should be easy to obtain and visualize: Utilize LABVIEW

  Status: Complete

- System exterior should be aesthetically simple and easy to follow

  Status: Complete

- System should be mobile design that can fit through standard lab and classroom doors

  Status: Complete

- System should be modular design: Heat Exchanger should be accessible and easily removed/replaced

  Status: Complete

- System should operate at noise level conducive to academic laboratory environment (less than 50 dB)

  Status: Incomplete. Testing has not been completed with all equipment running.

- System should be able to operate tests on a variety of conditions
  - Room temperature: 25º to 50º C

    Status: Incomplete. Heaters reach maximum temperature but have not been tested in conjunction with controller
  - Air face velocity: 1 to 3 m/s

    Status: Changed. Air velocity reaches maximum of 2.5m/s, but changes will be made to the system to try to increase this to 3m/s.
  - Ambient Humidity: 60 to 80%

    Status: Incomplete. Steam generator has not yet been installed

    Status: Changed: Ambient humidity range is now specified as 40% to 70%.
  - Slurry inlet temperature: ~2º C

    Status: Incomplete. System has not yet been charged with fluid to test inlet fluid temperature.
- System should be safe for all to use
  - Refrigerant should not leak out of cycle

    Status: Incomplete. System has not been charged with fluid.
  - High temperature and voltage areas should be clearly marked.
  - Pipes should be able to withstand pressures produced from pumps/compressor

    Status: Complete. Piping can handle
  - Safe enough to touch points of interests (low temperature target region / exhaust region).

    Status: Complete.
  - Materials should be compatible with each other to prevent corrosion / leaks.

    Status: Complete.
- System should meet all EPA and ASHRAE safety and environmental standards for refrigeration

  Status: Incomplete.
- System should be robust
  - Materials should be compatible to prevent component corrosion

    Status: Complete.
  - Operate for long lengths of time and multiple times.

    Status: Incomplete. It is not known whether all components can operate for long periods of time.
- System should be sustainable

- Operate with minimal maintenance

  Status: Incomplete. Entire system has not been tested.
- Replacement parts should be easy to install

  Status: Complete.
- All components should be easily accessible for repairs.

  Status: Complete.

- MPCM should be easy to fill and remove from system.

  Status: Complete.
- System should contain instruments at needed measuring points.

  Status: Complete.
- Utilize Primary Loop Lab View VI to have secondary loop information as well.

  Status: Complete.
- Label and mark appropriate lines and wires so that they are easily seen.

  Status: Incomplete.
- System should cost less than $8200.00.

  Status: Incomplete. The group went $9.36 over budget (~ 0.11%)
- Manual of how to operate the system.

  Status: Complete.