Efficiency Testing of an Electronic Speed Controller

BPD Industries

Cal Poly - San Luis Obispo

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Executive Summary

This project required the development of a rig that could experimentally determine the efficiency of an Electronic Speed Controller (ESC). The selected design focuses on measuring the losses due to heat from the device and comparing this to its input power. The selected design is a flow rig that utilizes the heat equation $q=\dot{m}cp\Delta T$. The rig provides a steady state measurement of the ESC heat output by passing a known mass flow rate of air across the ESC and measuring the temperature difference. It uses a flowmeter to determine $\dot{m}$, thermocouples to determine ΔT, and a table lookup to determine cp. After testing with a known heat source of a DC-powered silicon heater, It was found that at a flowrate of 30 L/min, the rig is able to capture greater than 90% of the heat emitted from a range of 2.5 to 10 Watts. This rig is recommended for use in testing the heat losses of an Electronic Speed Controller as well as any other small form factor, constant heat-emitting devices.

Chapter 1: Introduction

Electronic Speed Controllers (ESCs) have steadily increased in popularity over the last decade. Their main purpose is simple - to vary an electronic motor's speed and rotational direction. This task has been accomplished by taking a DC input and converting it to a 3-phase AC output which powers the load. ESCs have been utilized in a variety of applications such as quadcopters, cars, and other electric vehicles and continue to find their way into more. They specifically have become very popular because of their efficiency, power, longevity, and light weight and are the focus of our study. One example of an ESC is shown in Figure 1.

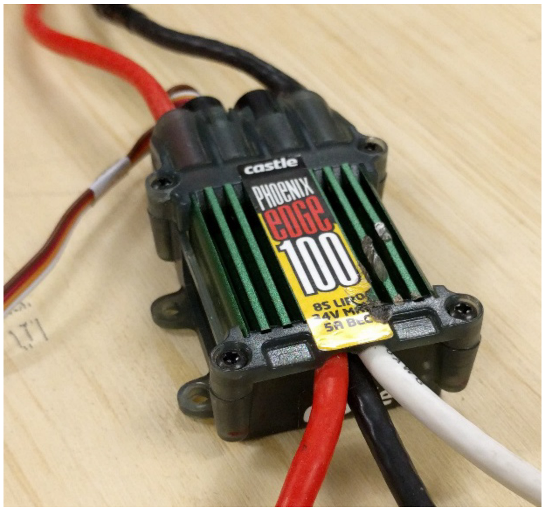

Figure 1. An example of an ESC used in RC applications.

Our sponsor for this project is Dr. Russell Westphal, a Mechanical Engineering professor at Cal Poly, specializing in fluid dynamics. According to him, many ESC producers claim power efficiencies of over 95%, but there are a number of problems with this. First, these efficiencies are rated at max load and not at any amount below that point. Therefore, these rated efficiencies are only valid when the ESC is being pushed to its limits. Secondly, these companies have not divulged how they acquired these values. With no way to verify their methods, we have no way of determining if their values are correct.

In simple uses, designing around the efficiency of the ESC is not necessary. For something like a children's remote controlled car, the ESC efficiency does not really matter to the end user. However, it may play a greater role for more complex design considerations. For example, aeronautical applications like an Unmanned Aerial Vehicle (UAV) have severe constraints on weight. The efficiency of the ESC may come into play when designing the battery unit. With a higher efficiency, you could theoretically have a smaller battery and thus less weight, improving your overall design of the vehicle. It is these particular purposes that have inspired this project.

By request of our sponsor, we would like to develop a rig that can determine the efficiency of ESC devices. Our design focuses on measuring the losses due to heat from the ESC and comparing this to the DC input power.

Management Plan

We have created a management plan to assist us in completing this task. The following lists each team member's respective assignments, however, we will be assisting one another on each other's tasks as needed.

Grace Cowell

- Data error analysis
- Rig design and construction
- Equipment calibration and testing

Matthew Hudson

- Insulation application and machining
- Wiring systems
- Rig design and construction

Marcus Pereira

- Communicate with project sponsor
- Test planning and data acquisition
- Document and poster design

In addition, we created a timeline with tasks that will needed to be completed throughout the year. This prospective Gantt chart is located in Appendix A.

Chapter 2: Background

This senior project was inspired by a master's degree thesis from a Cal Poly aerospace engineering student named Clayton Green. His goal was to measure the efficiency of the electronic speed controller by comparing the DC input power to the three phase AC output power. He was ultimately unsuccessful in this goal due to the difficulty he encountered in measuring the AC output power. This difficulty stemmed from the fact that the AC output was actually comprised of choppy DC segments. The DC voltage rapidly changed value in order to approximate an AC sine wave. As a result of this rapid change, it was difficult to match an accurate DC voltage value to its corresponding DC current to determine power.

We discovered a number of alternatives for measuring ESC efficiency, but many had other flaws. Instead of measuring the electric output as Clayton Green did, one could measure the mechanical motor power output and estimate the motor heat losses. These would sum to be the electric output power of the ESC. The problem with this method is that the loading is not consistent with actual operation. Also, the motor losses would need to be estimated, adding further uncertainty to the result.

Another option would be to smooth out the quasi-three phase output with electronic circuits consisting of resistors, inductors, and capacitors, then measure the sinusoidal output. Again, this method would not provide a realistic electric source for the motor. Additionally, the electronics used to smooth out the sine wave would have their own losses that would not be measured.

If the motor were replaced with resistors connecting the three phases, the heat created by the resistors could be measured. Once again, this method would not closely represent the load a real motor would place on the ESC, mainly because no back electromotive force (EMF) would be present.

We can reasonably assume that all of the three phase electric power leaving the ESC goes to the motor. If the motor were loaded in a manner that converted mechanical power to heat, the collective heat of the motor efficiency losses and the conversion of mechanical work to heat could be combined and measured. However, like the previous three methods, the loading is not accurate.

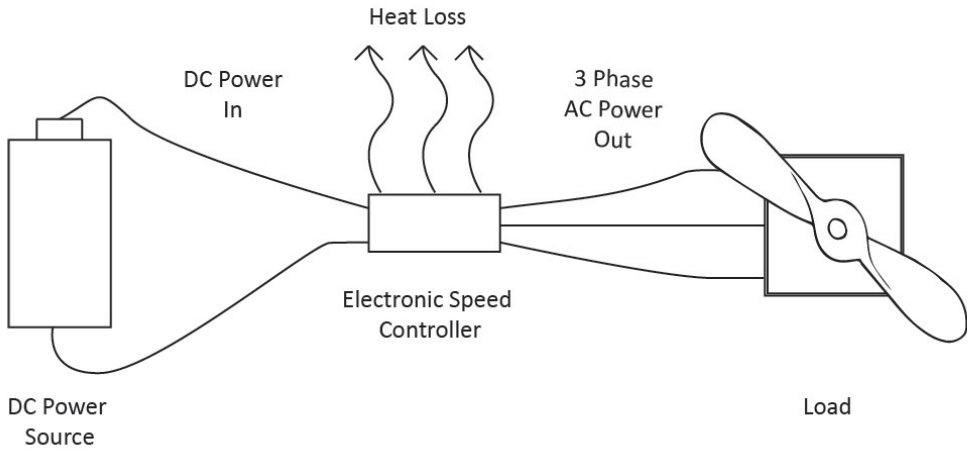

Figure 2. A layout of the DC power source connected to the ESC, which provides 3 phase AC power to the load, along with power lost through heat.

All of the ideas previously mentioned involve measuring the electric output power, or mechanical or heat power that has been converted from the electric output. These setbacks can be worked around by measuring the heat output from the ESC, as seen in the set-up in Figure 2. All of the losses of efficiency are dissipated as heat. If we know the DC input power and the thermal losses, we can easily calculate the efficiency of the ESC. The challenge then becomes measuring the heat output of the ESC.

Chapter 3: Design Development

Requirements and Specifications

The objective of this project is to measure the efficiency of an electronic speed controller for our customer, Dr. Westphal. We will design and build a test rig that can accomplish this task. When meeting with our sponsor, we concluded that his requirements were as follows:

- Accurate test rig-- While this may seem obvious, it is important the test rig measures the heat loss as close to the true value as possible. This will be achieved by choosing a method that gives us the least amount of error.
- Compatibility with other heat sources-- In order to ensure that the system measures the heat correctly, this rig should be able to measure the heat output of other items, such as a DC heater. In addition, the process of interchanging ESCs with other heat sources should be performed in a reasonable amount of time.
- Relatively low cost-- Dr. Westphal would like this method to be an affordable experiment.

- Compact-- It is important that the system does not take up unnecessary space.

The customer requirements were entered into a house of quality sheet, known as the QFD method, which can be seen in Appendix A. As a result, the engineering specifications were developed and can be seen in Table 1. The relationships between all of these specifications and requirements were evaluated by symbols representing "strong", "medium", and "weak" in the house of quality sheet. Therefore we concluded the most important items that need to be considered when developing our design are the method of insulation, size and cost.

- Insulation-- It is important that heat does not escape. Therefore good quality insulation is required so that there is no heat lost, meeting the sponsor's requirement of an accurate test rig.
- Size-- Our client requested a compact rig, so we expect our design to be smaller than a cubic meter. This will also make it more convenient to move around if necessary.
- Cost-- Dr. Westphal commissioned this project partially because other methods were too expensive, and suggested our target budget will be under $1500.

Table 1. Engineering specifications for the ESC Efficiency project. Under the "Risk" column, H=High, M=Medium, and L=Low. For the "Compliance" column, A=Analysis, T=Test, S=Similarity to Existing Designs, and I=Inspection.

Specification Number	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Insulated	5-10% of heat loss	Max	H	A,T,I
2	Cycle Time	10 min	Max	L	T
3	Life Cycle	60 Hours	Min	L	A, S
4	Size	one cubic meter	Max	L	I
5	Cost	$1500	Max	M	A
6	Mass	80 kg	Max	L	I
7	Movement Time over 200 meters (includes any disassembling if necessary and resetting)	20 minutes	Max	L	I

Preliminary Design Development

In order to brainstorm different methods for measuring the efficiency of ESCs, we had an ideation session where we spent ten minutes in silence writing as many different ideas as we could on sticky notes. We then explained our ideas to each other and categorized the post-its to create a layout of concepts. A digital version of this layout can be seen in Appendix A. This graphic was created to make it easier to expand on concepts and view their relations to each other. We eliminated some ideas and divided the rest of the ideas among us to research their validity. The chosen ideas were presented to Dr.

Westphal, who gave us his opinion on them and helped us narrow our concepts down to three methods of measuring the efficiency. These methods are discussed below and shown in Figures 3, 4, and 5.

Calorimeter

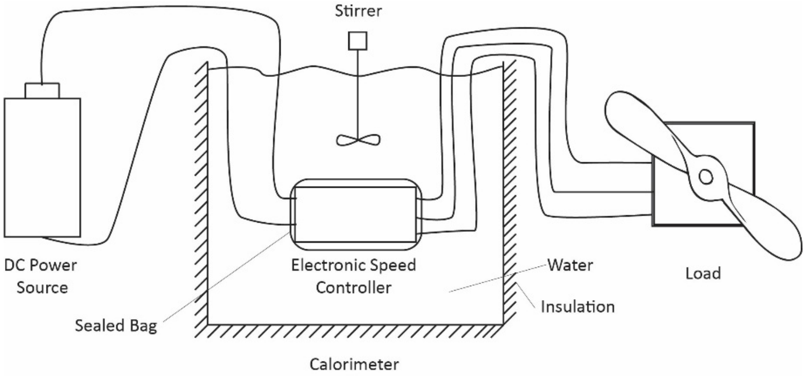

Figure 3. Layout of calorimeter measurement method.

One method of finding the heat losses would be using a calorimeter. For this method, we would place the ESC in fluid within an insulated vessel, and operate the ESC to raise the temperature of the fluid. The rate of temperature rise would then be measured to determine the heat output of the ESC. With the amount of fluid, the specific heat capacity of the fluid, and the rate of temperature rise, heat output could be calculated. This method was not selected due to its higher level of error and longer measurement time when compared to the flow rig.

Natural Convection

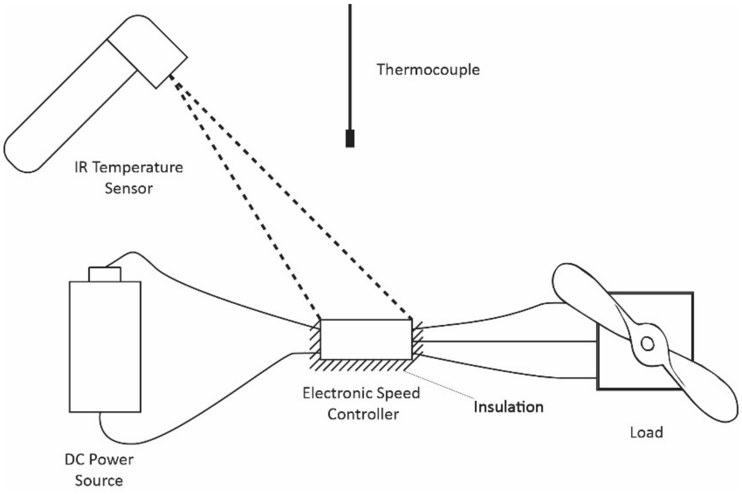

Figure 4. A layout natural convection measurement method.

The natural convection method would be the easiest to construct. The ESC would run in open, still air and reach steady state operation. Then, we would determine the temperature of the ESC's surface as well as the temperature of the ambient air. Finally, we would run calculations based on natural convection correlations and be able to determine the total heat loss of the system. This method seemed the most promising at the outset due to its simplicity.

After performing some preliminary hand calculations, we found analytical proof that this method is not valid due to the small size of the ESC surface. In addition, based on a study done by Massimo Corcione of the University of Rome, the heat transfer correlations presented in accepted literature is not consistent. He found that these numbers may differ up to 50%, which for our needs would not be acceptable. Because the prospective Rayleigh number did not meet the correlation requirements and there is a discrepancy of the accepted correlations, we determined that this would not be our method of determining the heat losses.

Flow Rig

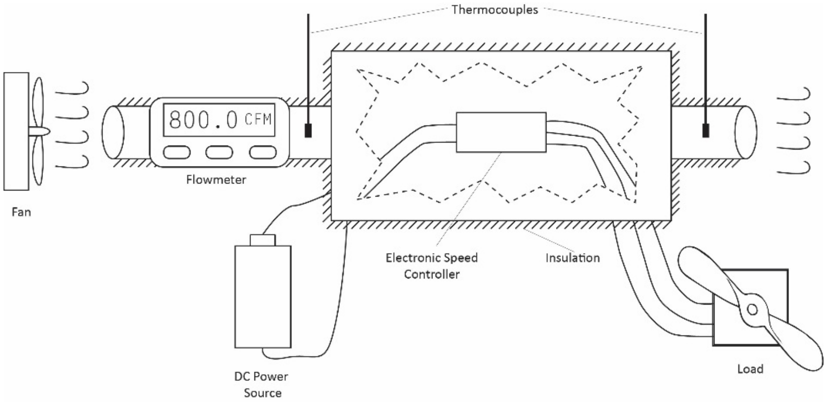

Figure 5. Flow rig measurement method.

The final method we studied was building a flow rig. This would provide a steady state measurement of the ESC heat output by passing a known mass flow rate of a fluid past the ESC and measuring the temperature difference. The mass flow and temperature would be measured by equipment installed as part of the rig, and the specific heat would be determined by a table, using the known average temperature and pressure of the flow. These values would be input into the heat transfer equation, $q=\dot{m}c_p\Delta T$, to solve for the heat coming off of the ESC.

We chose our final design based on a weighted objectives table, seen below in Table 2. Each of our design goals was assigned a weighting value to indicate its importance. The flow rig was selected to be

Table 2. Weighted objectives table comparing three methods of measuring heat leaving an ESC. The assigned value was given on a scale of 1 to 10 and then weighted by the percentage shown. The chosen design was the flow rig based on it achieving the highest score.

Selection criteria	Weighting (%)	Flow Rig		Calorimeter		Natural Convection Method	
		Assigned Value	Weighted Score	Assigned Value	Weighted Score	Assigned Value	Weighted Score
Error	60	8	4.8	5	3.0	2	1.2
Cost	20	6	1.2	6	1.2	5	1.0
Assembly Complexity	10	5	0.5	7	0.7	8	0.8
Measurement Time	5	8	0.4	4	0.2	8	0.4
Ease of Transport	5	8	0.4	8	0.4	8	0.4
			7.3		**5.5**		**3.8**

our best option due to the high marks the flow rig earned in the error category, which was the most heavily weighted design factor. This design was given the highest value for error because it did not lose heat over a long period of time like the calorimeter, nor did it have inconsistent heat transfer correlations like the natural convection model. Instead, the flow rig's only sources of error were due to the accuracy of the instruments which measured mass flowrate and temperature change.

Basic Description

We selected a flow rig as the best option for measuring the efficiency of an ESC. This idea is based on the heat transfer equation:

$$q = \dot{m} c_p \Delta T \tag{1}$$

where q represents the heat coming off the ESC, $\dot{m}$ is the air mass flow, c_p is the specific heat for air, and ΔT is the change in temperature from the inlet to the outlet of the air flow. With that in mind, we needed to establish the best way to design and construct the rig. The basic components are a fan, a mass flowmeter with a low range, two temperature sensors, and an insulated container. It would require us to directly measure three properties: temperature at the inlet and outlet and the mass flowrate of the system. The specific heat would be determined by a table, using the known average temperature and pressure. These values would then be used to solve for the heat transfer rate, which would give us the heat coming off of the ESC. With the ESC heat transfer rate and the DC input power, the overall efficiency can easily be calculated.

Preliminary Calculations

Error

In order to determine the accuracy of our values, we predicted the error that occurs from our instrumentation. This includes the accuracy and resolution error of the TSI flowmeter and the Omega thermocouple reader, whose specifications are displayed in Appendix D. The accuracy and resolution were combined for each variable using the root sum squared equation. Then these errors were further combined using the propagation error equation, resulting in the final error of our measured heat leaving the ESC as 14%. These calculations are not shown but the revised calculations after the final tests can be seen in Appendix E. Although this is over 10%, these values were based on measured temperature, mass flow, and heat values from a trial in our proof-of-concept experiment, detailed later. We expect to have higher differential temperature measurements in our future experiment because we will not be using a large box to house the flow over the ESC, and should therefore be able to account for most of the heat lost.

Heat Transfer

The risk in using a flow rig is that the heat leaving the ESC can escape through the capsule walls and not be accounted for in our final heat transfer value. In order to establish a prediction of these specific heat losses for the flow rig, we needed to find an appropriate formula to make the appropriate assumptions. We decided to use a heat transfer equation that calculates the heat transfer through a cylinder with uniform inner and outer temperatures. The outer temperature would be room temperature, and the inner temperature would be our expected final exit temperature of the flow rig. This is a worst-case scenario since the inlet air would not be heated until it reached the ESC. A summary of this formula and the ideas it is based on can be found in Appendix E. The results of the calculation indicate a maximum heat loss of 0.31 W, or 6.2% of the 5 Watts of heat we expect to be released from the ESC.

Consideration was given to the idea that the PVC pipe inside the foam would more readily conduct heat than the foam. This heat conduction could hypothetically happen toward the cool air inlet, or toward the outlet. If the PVC on the inlet side were to heat up, the cool air passing over it would draw out the heat before reaching the ESC, thus accounting for most of the heat transfer through the PVC. Heat would unlikely be conducted through the PVC past the outlet temperature measurement due to the lack of temperature differential in this part of the flow rig. The insulation would continue past the outlet temperature measurement, meaning that minimal temperature reduction of the air would occur until well beyond the insulation. If these two factors were ignored, the minimal cross-sectional area of the PVC pipe would also minimize the heat to be conducted and lost.

In addition to convection of heat to the flowing air and conduction of heat through the insulation, we need to be aware that the ESC will radiate heat. We used the Stefan-Boltzmann Law to determine if radiative heat transfer would be a significant factor in our design. Assuming a temperature differential of approximately 23°C and a surface area of about 0.008 m^2, we found that approximately 2% of the heat could be lost through radiation. This calculation can be shown in Appendix E. However, this amount can be minimized by covering the inside surface of the containment pipe with a reflective material. We will use aluminum foil, shiny side toward the ESC, on the surface of the PVC pipe. This will reduce the amount of radiation transmitted out of the container.

Proof of Concept

Once the flow rig was selected, an exact design layout was needed. To help accomplish this, we created a proof-of-concept prototype, seen in Figure 3. Our first prototype did not contain a functioning ESC, but instead had a DC heater with heat sinks on its surface. This allowed us to compare our results with a known heat source. The design consisted of a Styrofoam cooler (12"x11"x2.75", 1.5" insulation) with a removable lid. A small DC fan was installed on one end of the container, with an outlet on the other end. The DC heater was wired to a DC power source and placed at the center of the cooler, in the path of the incoming air. Two K type thermocouples were attached to a thermocouple reader to measure the differential temperature between the inlet and the outlet of the flow rig. The power of the DC heater was calculated from the current and the voltage shown on the DC power supply. The flow rig was operated with the fan, DC heater, and thermocouple reader running, and allowed to reach steady state.

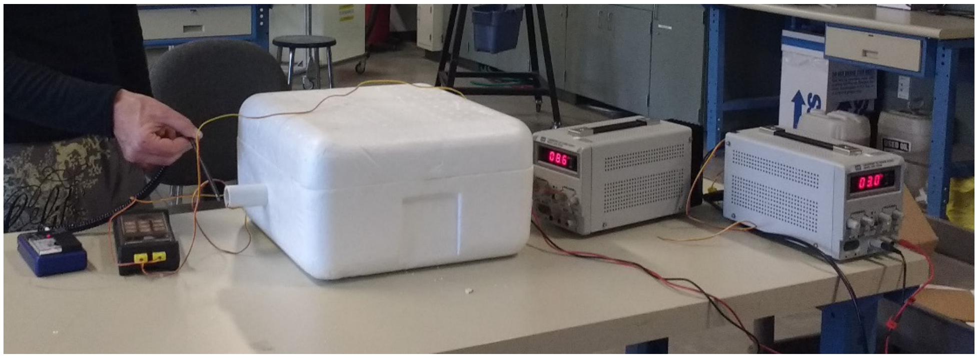

Figure 6. The set-up of our proof of concept experiment. Flow through box is from right to left. Student shown holding an anemometer wand to the flow exit to measure flow speed.

For the prototype, a mass airflow sensor was not used. Instead we used a hot wire anemometer to measure airspeed coming from an outlet with a known cross-sectional area. Knowing the air speed and area, we were able to calculate volumetric flowrate. Atmospheric pressure was recorded during the tests, which allowed us to find the air density. With air density and volumetric flowrate, mass flowrate of the air was calculated. With the mass flowrate of the air, the differential temperature, and the specific heat capacity of the air (from a table based on average temperature), we were able to measure power from the DC heater.

We ran a number of tests at different DC heater power levels and air flowrates. The measured power values from the flow rig were consistently lower than the power indicated by the DC power supply connected to the DC heater. The results varied for the different flow and power values, but we were only able to account for about 30% of the total heat put off by the DC heater. The lower flowrates resulted in larger differential temperatures, and also a larger percentage of lost heat. The temperature difference across the insulation created larger heat losses than the increased airflow. For this reason we want to minimize the ΔT across the device to minimize the heat transfer through the insulation. However, we need to take into account the effect a lower ΔT has on thermocouple error. For a certain thermocouple error (inherent to the devices), a low ΔT would result in a higher percent error. Therefore, a balance between these two factors must be found experimentally. A document of the test data can be found in Appendix H.

We were able to identify a few reasons why the results were so poor. We noticed that it took a long time for our experiment to reach steady state. The cooler available to us was significantly larger than the DC heater, meaning that there was more surface area through which to transfer heat. A much smaller container would allow us to lose lees heat. In addition, while the cooler was made out of an adequate insulating material, the walls were not as thick as our final product would be. Thicker insulation would reduce the heat transfer from the vessel, allowing for a better measurement. Finally, the flow rig we constructed was not perfectly sealed, allowing for some hot air to escape. This loss in heat would be prevented in the final flow rig by perfectly sealing the vessel.

We learned a few notable lessons from our proof-of-concept prototype. The vessel should be as small as possible. This will minimize surface area through which heat can be lost and will result in a faster response time to steady state. The insulation needs to be thicker than that of the foam cooler, and made of a better insulating material if possible. Hot wire anemometers have poor resolution and a great deal of variation in readings. A digital mass airflow sensor will likely be a huge improvement. Perfectly sealing the flow rig will prevent unnecessary losses of heat. While ease of access will not improve accuracy of the flow rig, the large opening in the cooler made setup easier. Without sacrificing quality of measurement or ease of manufacture, we intend to make the vessel as simple as possible to open.

Chapter 4: Final Design Development

Once we confirmed our flow rig design with our proof of concept, we looked into further detail of how the capsule containing would be designed. After coming up with various configurations we concluded with the design below.

Cylinder and Tray

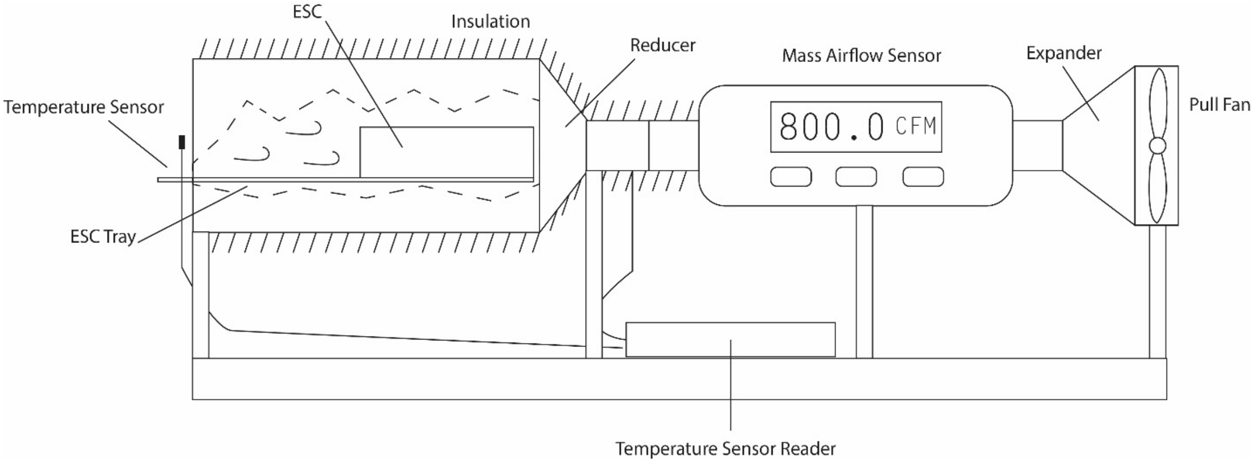

Figure 7. Diagram of cylinder and tray design to measure temperature difference and mass flow across a heat source.

The final design incorporated the ESC in a cylinder with a slightly larger diameter than the ESC, as seen in Figure 4. The cylinder would be fully insulated and allow flow of air from the fan to pass through. A mass airflow sensor would be in line with this to measure how much air passed by the ESC during the test. Inlet and outlet temperature measurement devices would provide a differential temperature, and the ESC and wiring would be accessed through on end of the flow rig. The ESC would be attached to a heat sink and a platform to keep it from directly contacting the pipe, minimizing heat transfer to the cylinder. This platform would keep the wires from being tangled and would act as a tray to set the ESC on before inserting it into the cylinder.

We believe the cylinder with tray to be easiest to manufacture and assemble. We had considered another design that included an insulated box with a lid to allow for easy placement, however, this would have required us to develop a strong sealing method for the box. In addition, the opening and closing of the box could negatively affect our sealing mechanism. We would also have to ensure it was sealed each run which would negatively affect our cycle times. The cylinder and tray turned out to be an easier and more reliable solution in the long run.

Design Components

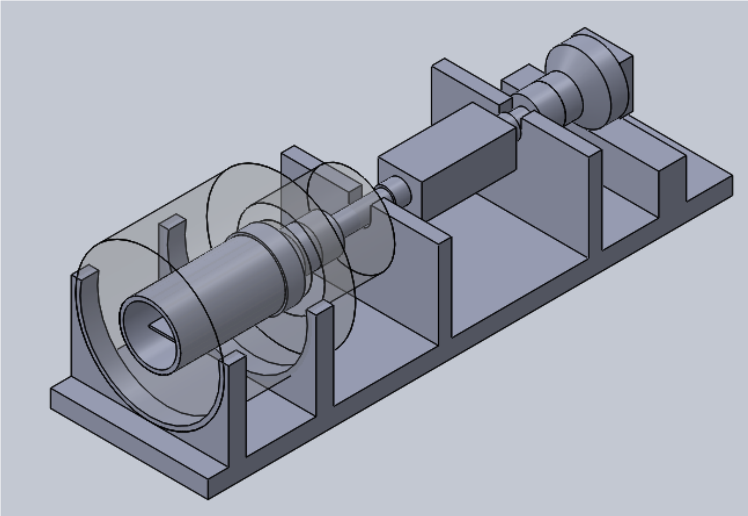

Figure 8. Solidworks assembly of flow rig with PVC piping, mass flowmeter and fan connected in series. Insulation is represented by the transparent cylinder.

Piping Network and Fan Configuration

One component that we needed to design was the piping network that connected our capsule to the instruments. A layout of this can be seen in Figures 5 and 6. Detailed Solidworks drawings with dimensions and labels can be found in Appendix C. The capsule itself is 3" diameter PCV pipe. The inlet temperature will be measured at the beginning of the capsule. It is connected to a 3" to 1 ½" reducer which in turn is connected to a short piece of 1 ½" pipe. This is then connected to a 1 ½" to ¾" reducer and a length of ¾" pipe. The ¾" pipe is its specified length because the mass airflow sensor requires at least 5 diameters length of pipe before its inlet for accurate results.

The reducers serve a couple of purposes. The first is to hopefully induce a small amount of flow mixing, a process we discuss further into the report. After the contraction, the second temperature will be taken

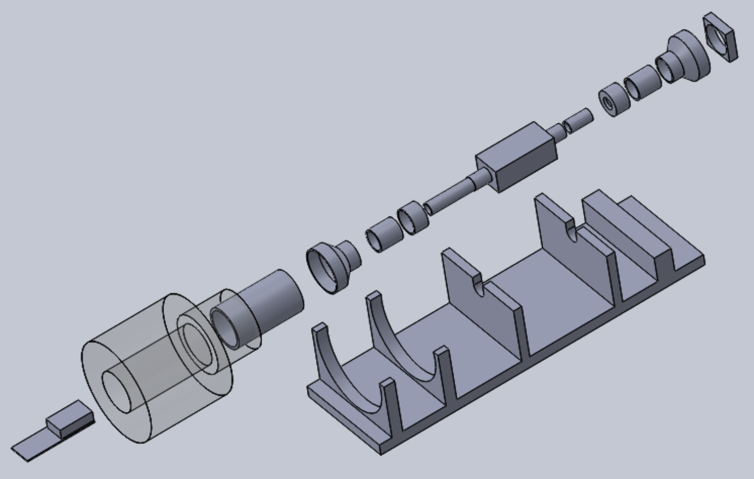

Figure 9. Solidworks exploded view of flow rig.

to give us the change in temperature across the ESC. The second purpose for the reducers is that the mass airflow sensor has ¾” inlets, so the pipe needs to be reduced to match this size. Once the ¾” pipe is coupled to the mass airflow sensor, it will also be connected to the other side of the senor and lead to a mirrored design up to the 3” to 1 ½” reducer. The fan will be attached to this reducer and thus complete the piping network. We decided on a pull configuration for this fan because we wanted to leave the fan in permanently. With a push fan at the beginning of the system, we would have to remove it each time to insert the ESC into the capsule. There is not much functional difference between a push or pull fan besides pressure regions which is not our concern in this application.

The ESC will be set on a thin piece of material and slid into the capsule. This will minimize heat transfer to the pipe surface via conduction but still allow flow around the ESC. This design will allow for easy access of our ESC and will help us in wiring the mechanism. The ESC and tray are also the only nonpermanent components of this piping network, hopefully increasing the reliability of the system.

Insulation

The capsule that the ESC will be placed in must have sufficient insulation so that heat will not be lost through the walls as it is carried by the flow to the exit, where the final temperature is measured. The two insulation materials considered were polystyrene, also known as Styrofoam, and polyurethane in the form of pourable foam. Table 3 displays these two materials and their corresponding thermal conductivities as well as an assessment of how they would be constructed. In the end, both materials had similar thermal conductivities, so the two part pourable foam became the chosen insulation material because it is easy to manipulate. We will need at least 2 ½” of insulation based on our heat transfer calculations seen in Appendix E.

Table 3. Evaluation of insulation material. Thermal conductivity found from Engineering ToolBox (http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html).

Material	Thermal Conductivity, k (W/m K)	Form	Method of Construction
Polystyrene	0.033	Styrofoam boards	Cut and glue, not very efficient
Polyurethane	0.03	Pourable Foam	Pour an even layer around entire capsule

Mass Airflow Meter

In order to calculate the heat output of the ESC, we need to measure the mass airflow rate. For our proof-of-concept experiment we used a hot wire anemometer and a known cross-section pipe, but the resolution of the meter was very poor, resulting in a large error band. In general mass airflow sensors have smaller error. The meters considered can be seen in Table 4 below. We decided on the TSI 4045 mass airflow sensor (see specifications in Appendix D) because it displayed a low accuracy error of ±2% and it could be used at a low range (0-300 L/min) which is necessary to detect reasonable temperature change values. This model was more expensive than a similar model without a digital display, but having a digital read out allowed for simpler data recording. One important design consideration for this device is flow conditioning. According to the specification sheet, we need a pipe that is at least five pipe diameters in length at the inlet side of the mass airflow meter. This length allows the flow to stabilize, yielding a better mass airflow measurement. Therefore tubing was later implemented in the design, at the entrance of the flow meter.

Table 4. A range of flow meters to consider, with their prices, accuracy, and tube size listed.

Company/ Name	Range (L/min)	Price	Accuracy	Tube size
CDI 5100 Inline Low-Flow Flowmeters	85-566	$ 445	±2% + 0.5% of indicated range	3/8" Steel
TSI Mass Flowmeter 4045	0-300	$960	±2% or 0.05StdL/min, whichever greater	0.75"
TSI Mass Flowmeter 40241 (no display)	0-300	$405	±2% or 0.05StdL/min, whichever greater	0.75"

Temperature Measurement

Another vital measurement to our calculation is air temperature. A differential temperature value between the inlet and the outlet of the capsule allows us to calculate the heat released by the ESC. We had a few preliminary options from which to select, such as thermocouples and resistance temperature detector (RTD) sensors, both seen in Figure 7.

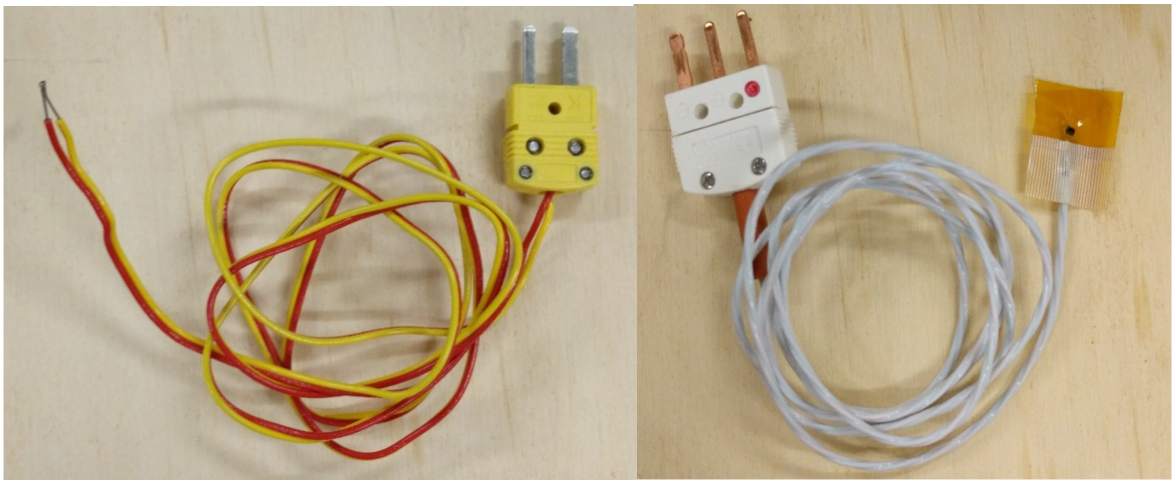

Figure 10. An example of thermocouple type K wires on the left and RTD sensors on the right. Both must be plugged into a reader to get a temperature.

Our priorities were high accuracy and low cost. We were given both types of instruments from two professors, therefore cost was not an issue. In addition, a comparison of thermocouples and RTD sensors on Ultra Electronic's website shows that RTDs have higher accuracy. This was confirmed by comparing the accuracy of each instrument according to the specification sheets provided by the manufacturer, Omega. However, these sheets assumed we were measuring absolute temperature. This is not the case for our rig, which measures a difference in temperatures in two locations. This application is, in essence, what thermocouples are meant to do. Their dissimilar metals produce a small electromotive force (EMF) that directly points to temperature difference. To perform a differential temperature measurement with RTDs, we would need to find the difference between two distinctly different values, each with their own error. But as for thermocouples, we expect a precise differential result when wiring them in series. For this reason, we decided to use Type K thermocouples to measure temperature in our flow rig. Their corresponding specifications can be seen in Appendix D.

One temperature measurement will be located at the inlet of the capsule pipe. This will be our inlet temperature, which we expect to be close to room temperature. The second measurement is taken after the pipe contracts to ¾". We want to have the minimal length of pipe between the ESC and the second temperature measurement in order to reduce heat loss of the system between measurements. The longer the pipe length, the more total heat loss and thus the farther away we get from determining the actual heat loss of the device.

Flow Mixer

One potential problem we foresaw was in the mixing of our flow before we took the outlet temperature measurement. Because of the low flowrates, the flow through the capsule is relatively laminar. The flow over the ESC will have some turbulent characteristics, but for the most part we have straight, laminar flow. This means we may get erroneous measurements as a result of varying temperature measurement, depending on the location of the temperature sensor.

We hope to counteract this in a couple of ways. We need to change the pipe size from the 3" capsule to the ¾" flow meter no matter what due to the inlet size of the flow meter. The contraction of the flow may create small disturbances that would help mix the flow. We have determined that at the ¾" diameter pipe at an expected flowrate of 25 L/min, we will be in the turbulent region. Therefore, we would be able to get flow mixing based on the properties of turbulent flow. The problem with this method alone is that it takes distance to create fully-developed turbulent flow (approximately 10 pipe diameters). This means we would have to add an additional 7.5" of pipe to our system which would increase the total amount of heat lost in the system. We hope that the combination of the turbulent elements created by the ESC, the reducers, and the smaller pipe size will result in turbulent (or nearly-turbulent) flow that will give us a more accurate mean temperature.

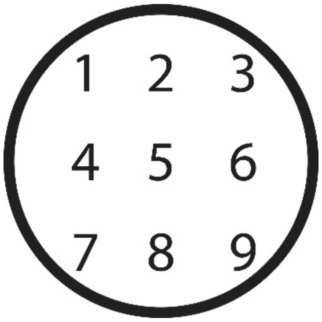

Figure 11. Layout of temperature measurement points for flow mixing testing.

We decided to test this through construction of different mixing methods. Once we obtained our pipes and fittings, we set up the rig from the capsule to the ¾" pipe before the flow meter. We took our probe and moved it to nine different locations within the circular cross section of the exit tube as we test each method, as seen in Figure 8. Taking the standard deviation of the nine temperatures indicated whether the test was successful. A low standard deviation was desired because it would indicate that there was even temperature distribution across the exit. One option was to put an obstruction in the exit to cause the air to move around it, thus mixing the air. However, the standard deviation increased. A piece of paper with a hole in it was stretched across the exit. This decreased the standard deviation, but it also noticeably decreased the average temperature, compared to the other tests at the same conditions, indicating that this was not an accurate method. A stainless steel mesh and a plastic mesh were each installed in the exit of the capsule and tested with the same method, but neither helped mix the exit temperature. Therefore, it was decided to use no mixer at all, and instead weld five thermocouples in parallel and spread them across the exit pipe so that the final temperature would be an average of five locations.

Cost Analysis

The above description of the design requires the purchase of an additional instrument (a mass flow meter) and material to build the rig. The entire bill of materials with their associated vendors, model numbers, description, and price can be seen in Appendix F. The total cost of this project amounted to $1,401.75, which met our cost requirement. This included the materials tested but not utilized, a couple of extra tools, and the instruments purchased. This did not include the price of instruments borrowed from the Cal Poly Mechanical Engineering department, such as the Omega Digital Thermometer and the DC power supplies. If the cost of all the materials and instruments actually integrated into the rig were to be calculated, the price would round to $2,100. This can also be seen in Appendix F.

Chapter 5: Product Realization

Manufacturing Process

After receiving all of the materials, a mock-up assembly of the flow rig became our next task. The piping sections were first dry-fitted to ensure operation of the unit. The initial trials were conducted with no insulation to verify that the flow rig would function properly. Once we were confident with our layout and dimensions, we joined the sections using PVC cement.

The selection process for the fans was dependent on the inlet filter that came with the flow meter. We were initially under the impression that the filter was required for safe operation of the flow meter. Based on this assumption, we assembled the flow rig with the filter, which drastically reduced the flow capabilities of the fans. We attempted to solve this by ordering stronger fans and placing them in series. This increased flow, but not enough for our requirements. A test was performed to compare air flowrate to the differential pressure across the filter, and the two were found to have a linear relationship. With the filter in line and fans at maximum voltage we were able to flow 9 L/min of air with a differential pressure of 0.34" of water. Our goal was to flow 30 L/min of air past the ESC/heater. Given the linear relationship, we needed more than an inch of water differential pressure across the fan, and thus the filter. Most fans are not able to provide this pressure at any flowrate. We contacted TSI, the flow meter manufacturer, and discovered that the filter would not be required for measuring clean air. Without the filter we were able to achieve a maximum of 35 L/min, solving our flow problem.

Once the rig was assembled tests were run with the DC heater to determine how much heat was being measured. The trials yielded lower results than we expected, and we determined that this was due to heat loss through radiation. Our previous calculation, outlined in Appendix E, underestimated the heat loss due to radiation. To solve this problem, the aluminum foil design was discarded, and instead a reflective shell was constructed from a beverage can. The reflective property of the aluminum allowed the heat lost through radiation to be reabsorbed, then accounted for with the temperature measurement. The top of the can was removed, and a small hole was drilled in the bottom to allow for the ESC/heater wires and airflow. Figure 9 shows the can with the heater installed.

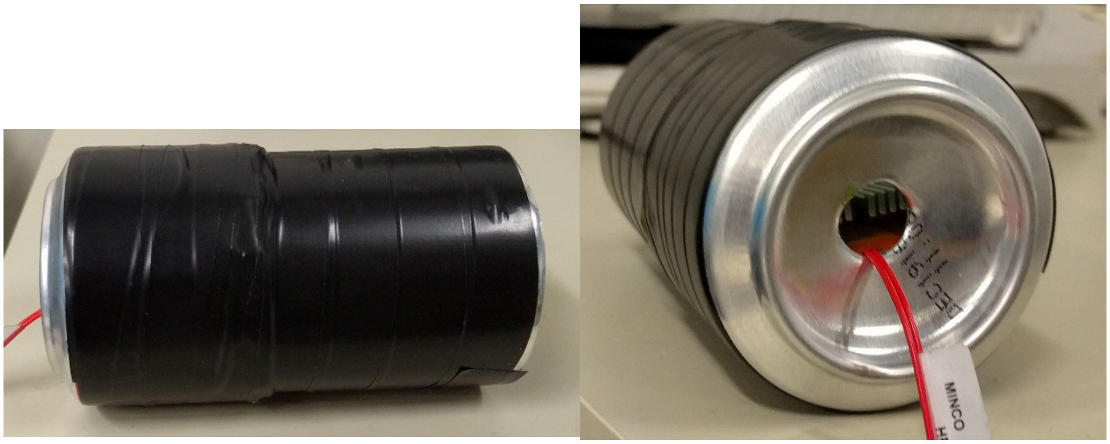

Figure 12. The beverage can used to reflect radiative losses, with DC heater installed.

As discussed above, we ran tests on the temperature profile of the air leaving the heating element. The tests showed that the flow was not fully mixed. We attempted to increase flow mixing by placing wire mesh in line with the flow, but this yielded no improvement. A stationary bladed flow mixer was also tested, but again did not significantly improve flow mixing. To account for the temperature profile, multiple thermocouples were installed with parallel wiring to average the temperature of the air. These thermocouples were installed in the pipe through a single hole, which was sealed to prevent leakage of air. The thermocouple ends were arranged to measure air at different parts of the cross section of the pipe. The inlet thermocouple measured room-temperature air and was simple to wire. Figure 10 shows the layout of the thermocouples in the outlet pipe. The differential temperature was provided by the thermocouple reader based on the differential voltage between the inlet and outlet measurements.

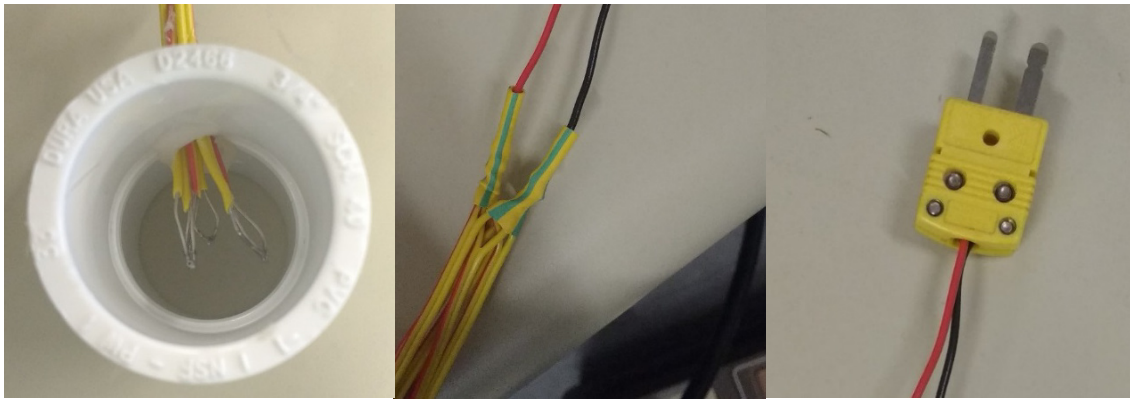

Figure 13. Thermocouple distribution at pipe outlet, parallel wiring of thermocouples.

With the inlet section of the piping assembled, we were able to apply the insulation. The two-part pourable foam was selected over the spray foam because of its superior ability to conform to the exact shape we needed. Both types of foam have similar thermal conductivities, so manufacturability became the deciding factor. The process of pouring the foam is shown in Figure 11. The top of the foam covered the sealed hole for the thermocouple wires, which is why the final pouring of the foam occurred last. About 6 ounces of each solution was poured into a cup and then mixed before being poured into the mold. Over time the mixture expanded into a hard insulation.

Figure 14. Pouring of insulation.

The base was constructed to support all of the components in the flow rig assembly and allow for easy mounting to the cart. A wood board was cut to shape then screwed together. The fully assembled flow rig is shown in Figure 12.

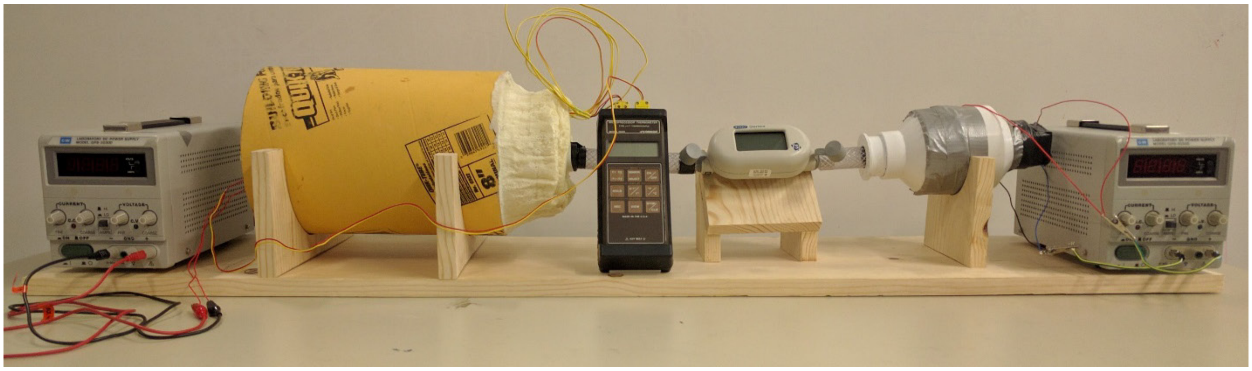

Figure 15. Fully assembled flow rig.

We have included a Hazard Identification Checklist in Appendix I which describes minor safety concerns of our apparatus.

Manufacturing Recommendations

While we were pleased with what we built, if we were to build this rig again, we would make some minor changes. We would prefer a single, larger fan instead of two smaller fans in series. The process of pouring the two part foam could made easier by measuring the exact amount of each ingredient needed to yield the correct volume of cured foam. This might require some trial and error, but could result in more efficient construction of the insulated rig.

Chapter 6: Design Verification

Experimental Procedure

Multiple tests were run with our rig to obtain data for us to analyze and verify our design. Our testing involved using our silicon heater, shown in Figure 13, at three different power levels (2.5, 5, and 10 W) and three different flowrates (10, 20, and 30 L/min). An individual test thus had nine total trials. We took date for a total of four tests, but omitted one for reasons described later.

The heater itself outputs heat approximately equivalent to the electrical input power. We attached heat sinks to dissipate heat similarly to an ESC. Its dimensions are also similar to that of an ESC as well. The heater's input is a DC source which we can easily determine the power into the device. The only output is heat, so we know exactly what value of total heat to expect. If the calculated heat loss were within error tolerance of the DC electric power value, then we would know that the flow rig worked properly. This would allow others to move forward with an analysis of the actual ESC device.

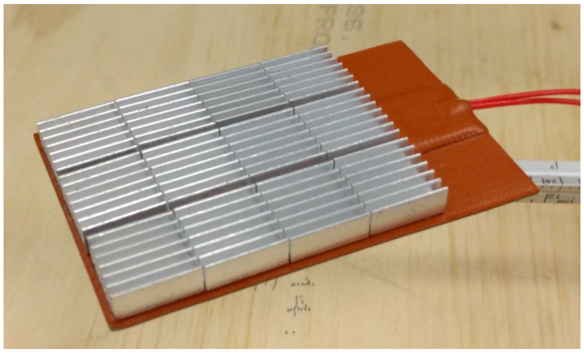

Figure 16. A 2” x 3” silicone rubber heater, with heat fins, capable of producing 5 watts needed for validation.

Each test involved a total of nine trials with every variation of power level and flowrate. The order of these trials was important. We decided to go from low power levels to higher power levels in order to minimize the time to equilibrium. We found that when the trials ran from high to low, inaccurate results were obtained. This may have been caused by residual heat from previous greater power levels. By going from low to high, the system increased incrementally rather than starting high and then having to wait for the residual heat to dissipate. In terms of flowrate, we ran the rig from high to low operating under the same principle. At higher flowrates, there would be a smaller differential temperature. This allowed our data to continually increase in differential temperature throughout our testing.

For each trial, we took a few pieces of data. From the flowmeter, we recorded the flowrate, temperature, and pressure of the device. The differential temperature was obtained from the thermocouple reader. Though we did have the thermocouples to give us our temperature, we also used the flowmeter as a verification. By taking the difference from the flowmeter temperature during the cold test to the flowmeter temperature in a trial, we could obtain a differential temperature that would hopefully be close to what the thermocouple reader was giving us. If there was a significant difference, we would know something was wrong.

Before each set of trials, there were a few things we needed to check. We made sure that all connections were intact and that there were no leaks for air to leave. The flowmeter needed about ten minutes of flow in order to warm up and give us accurate numbers. Cold runs were made at each flowrate without powering the heater. Because there was no heat outputted by the heater, we expected the differential temperature to be zero. However, this was not the case. At each flowrate, the thermocouples gave us a value (usually less than 1°C) that we used to tare the thermocouple reader. Once these checks were made, our trials ran as follows:

1. Set the heater to output 2.5 W.
2. Run the rig at 30 L/min and wait for equilibrium. Take a data point.
3. Run the rig at 20 L/min and wait for equilibrium. Take a data point.
4. Run the rig at 10 L/min and wait for equilibrium. Take a data point.
5. Increase the heater to the next power level and repeat.

Results

The following graphs summarize the results of our three tests. Figure 14 shows the average percentage of heat captured by the rig at various flow rates and heat outputs of the heater. An alternative way to view the results can be seen in Figure 15. Here, the average calculated power out is shown at different flowrates and heat outputs of the heater. The error bars are based on error analysis of the temperature and mass flow recordings. These errors include resolution errors of the instrument readings, instrument errors, and standard deviation of the sample measurements. Sample calculations of the error analysis can be seen in Appendix E. A more comprehensive look at the results can be found in Appendix H.

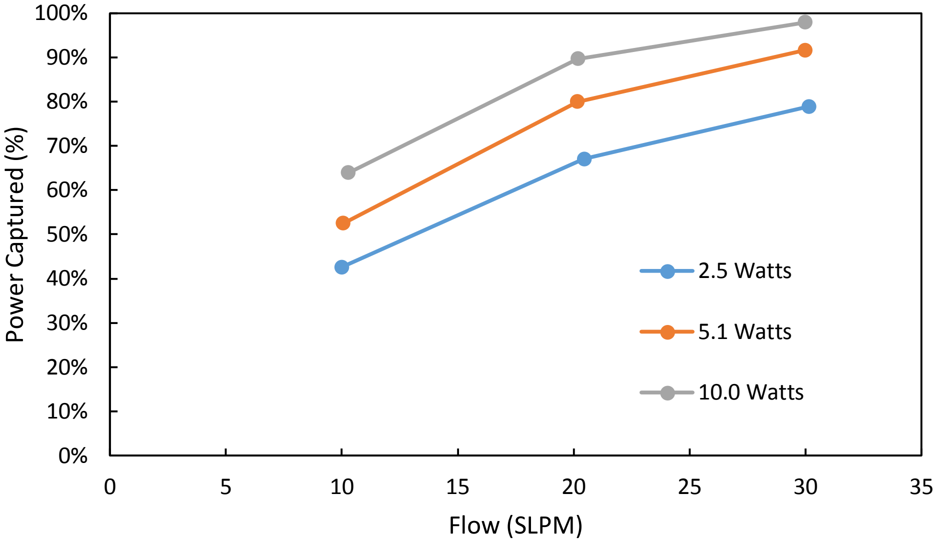

Figure 17. The percentage of power captured by the rig for tests at different flow rates and known heat outputs. This trend indicates higher flows will lead to less heat loss from the rig.

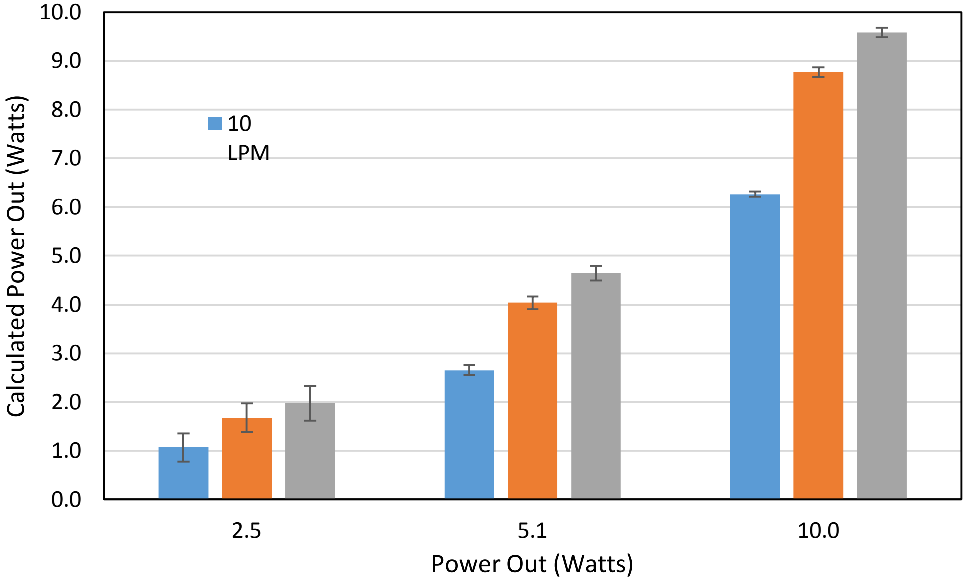

Figure 18. The calculated power captured by the rig for tests at different flow rates and known heat outputs, with error bars indicating amount of accuracy.

For one set of trials, we decided to run the experiment starting at the highest power level and lowest flow and work our way down. As mentioned above, we ran into an issue with residual heat. This was noticed because we were getting values that gave us more than the total amount of percent captured. This is not possible as the only component generating significant heat was the DC heater. Because of the extra heat in the system, the cycle time per trial increased significantly. This data set was omitted for our analysis due to its inaccuracy.

Table 5. Summary of final results for different power levels and flowrates.

Nom. Heat Out [Watts]	Flow [SLPM]	Actual Power Out [Watts]	Captured Power Out [Watts]	% Captured
2.5	10	2.49	1.07	43%
	20	2.49	1.68	67%
	30	2.49	1.97	79%
5.0	10	5.08	2.65	52%
	20	5.08	4.03	79%
	30	5.08	4.65	92%
10.0	10	9.97	6.26	63%
	20	9.94	8.77	88%
	30	9.95	9.58	96%

For a fixed heat output, the only variables are the flowrate and the differential temperature. These two variables share an inverse relationship; when one goes up, the other must go down. This can be seen from the data sets of all three power levels, which demonstrates that the rig is functioning as expected.

Analysis

There are two distinct trends that can be derived from our data. The first is that at greater flowrates, more of the total heat is captured. For reference, the flowrates we are working with (converted to English units) are 0.35, 0.7, and 1.4 cubic feet per minute, which are extremely small. Because of this, the thermal resistance for heat transfer to the air becomes larger than that related to the loss paths. This leads to more heat being lost and not transferred to the travelling air at low flows.

The second big trend is that for greater amounts of heat outputted, a larger amount of the total heat is captured. This is because for larger amounts of heat, the total heat not captured by the device becomes a significantly smaller portion of the total. Thus, for smaller amounts of heat outputted, a much greater portion of the total heat is lost. Because of this, the rig is more effective at higher expected power outputs.

The data we found essentially provides the framework for calibrating the rig. When the rig is run for an ESC, the user would be able to compare the heat captured by the device to the data we have found here. Hopefully, based on the expected ESC heat loss of about 5 Watts, the range of data from the heater outputs would be enough to determine the actual output from the ESC. If not, more tests could be ran with greater power levels of the heater in order to expand the calibration. It is quite likely that the heat loss would not fall right on 2.5, 5, or 10 Watts. Because of this, the user would need to interpolate the percentage captured to calculate the total amount of heat lost.

Chapter 7: Conclusion and Recommendations

Future Recommendations

Though the thermocouples in parallel in the comb formation improved our results, they did not solve our issue of flow mixing. Our volumetric flowrates are low and end up exhibiting laminar behavior. A consideration for the future would be to install a small stirrer just upstream of the second temperature measurement. Hopefully this would be able to churn the air a bit and mix the flow effectively.

Another thing to consider for the future would be to try to tare the thermocouple reader for each trial and run them independently. This proved too difficult as the cycle time per trial alone often exceeded 40 minutes for the greater power levels. The time to come back down to room temperature would have taken even longer. We tared our thermocouple reader before each set of trials, but not each one individually.

The testing for this project was time consuming because each trial needed time to reach an equilibrium temperature before data could be recorded. This process was based on looking at the readout of the thermocouple reader until it reached a steady value, however the value often fluctuated randomly. A future recommendation would be to use a data acquisition system (DAQ), connected to a computer, which would graph the temperature over time. These recorded temperatures could give a much more accurate equilibrium temperature, and would also make testing easier for the engineers.

Conclusion

When looking at our initial design criteria, we were able to meet almost all of them, as seen in Table 5. At the highest flowrate and power level, we captured around 90% of the total heat. The average heat loss however was 27%, but this included data not at our desired operating points. The rig weighs significantly less than 80 kg and takes up less than 1 cubic meter of space. It all fits within the confines of a pushcart, making it extremely portable. The total cost was less than $1500. Due to no moving parts, we expect the life cycle of the rig to last beyond 60 hours. The one criteria we did not succeed in was to have a cycle time of only 10 minutes. Each individual trial took at least 20 minutes to reach equilibrium. The higher the power level, the greater the time to equilibrium. As a whole, each set of trials took approximately 4 hours to perform.

Table 6. Engineering specifications reintroduced with results. All but two specifications were met, however, the device is usable and can be calibrated.

Specification Number	Parameter Description	Requirement or Target	Risk	Results
1	Insulated	5-10% of heat loss	H	27% Heat loss on average, with 4% lowest and 57% highest
2	Cycle Time	10 min	L	Avg 20 min
3	Life Cycle	60 Hours	L	Greater than 60 hours
4	Size	one cubic meter	L	Less than one cubic meter
5	Cost	$1500	M	$1400
6	Mass	80 kg	L	About 10 kg without cart
7	Movement Time over 200 meters (includes any disassembling if necessary and resetting)	20 minutes	L	Cart allows easy movement

This project tasked us with building a rig that would be able to determine the efficiency of an Electronic Speed Controller. We designed a rig that was able to determine the heat produced by a heater, but the same principle could be used for an ESC. For use, it is recommended that the rig be run at the highest flowrate possible and for expected heat losses greater than 5 Watts. Once the trial is run, the user would need to compare their results to something comparable (such as the DC heater). In doing so, they would be able to determine the heat lost from the device and thus the efficiency. Error could be reduced through running multiple trials. Based on our testing and results, this rig will be useful for finding the heat loss of an ESC as well as any other constant-heat emitting devices.

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Photo Credits

Figure 1. ESC example—Marcus Pereira/photo

Figure 2. ESC layout diagram—Marcus Pereira/Adobe Illustrator

Figure 3. Calorimeter method—Marcus Pereira/Adobe Illustrator

Figure 4. Natural convection method—Marcus Pereira/Adobe Illustrator

Figure 5. Flow rig method—Marcus Pereira/Adobe Illustrator

Figure 6. Proof of Concept set up—Grace Cowell/photo

Figure 7. Diagram of pipe and sleeve design—Marcus Pereira/Adobe Illustrator

Figure 8. Diagram of flow rig with lid—Marcus Pereira/Adobe Illustrator

Figure 9. Solidworks assembly of flow rig—Marcus Pereira/Solidworks screenshot

Figure 10. Solidworks exploded view of flow rig—Marcus Pereira/Solidworks screenshot

Figure 11. Examples of thermocouples and RTD sensors—Marcus Pereira/photo

Figure 12. Silicone rubber heater—Marcus Pereira/photo

Figure 13. Thermocouples in pipe, wiring, and plug— Marcus Pereira/photo

Figure 14. Pouring of insulation— Marcus Pereira/photo

Figure 15. Fully assembled flow rig— Marcus Pereira/photo

Figure 16. Silicon DC heater— Marcus Pereira/photo

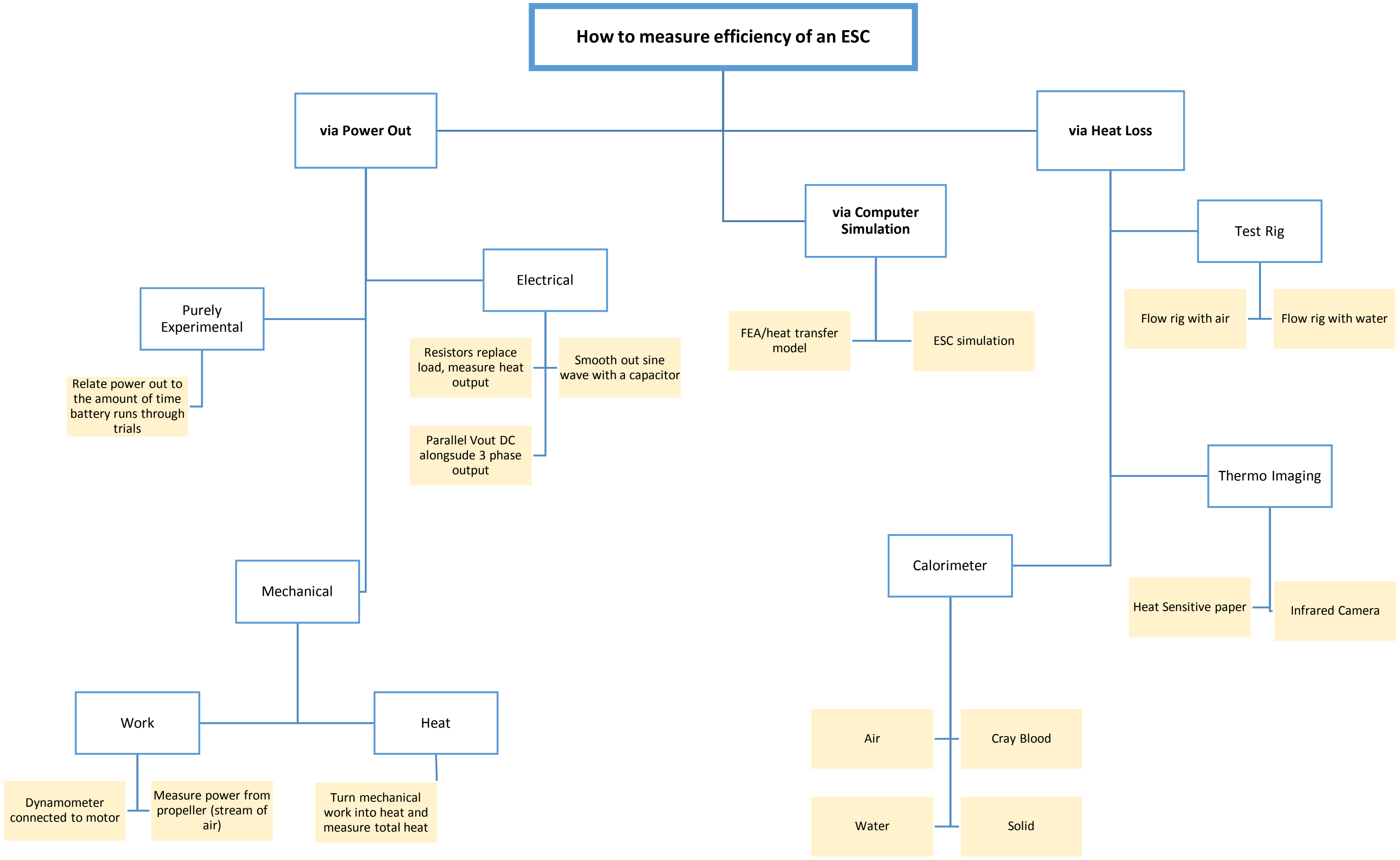
Figure 17. Power capture results—Grace Cowell/Excel

Figure 18. Power capture results chart with error bars— Grace Cowell/Excel

Appendices

A. Preliminary Design Documents
B. Proof of Concept Test Data
C. Drawing Packet
D. Specification Sheets
E. Example Calculations
F. Cost Analysis
G. Experimental Procedure Plan
H. Experimental Data
I. Hazard Identification Checklist

Appendix A – Preliminary Design Documents



ID	ℹ	Task Mode	Task Name	Duration	Start	Finish	Predecessors
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2	✓	📌	Letter of Introduction	7 days	Mon 10/5/15	Tue 10/13/15	
3	✓	📌	Team Contract	7 days	Mon 10/5/15	Tue 10/13/15	
4	✓	📌	Problem Statement	7 days	Mon 10/12/1	Tue 10/20/15	
5		📌	House of Quality	14 days	Mon 10/12/1	Fri 10/30/15	
6		📌	Engineering Specifications	14 days	Mon 10/12/15	Fri 10/30/15	
7		📌	Gantt Chart	21 days	Mon 10/19/1	Sun 11/15/15	
8		📌	Ideation and Brainstorm	14 days	Mon 10/19/15	Fri 11/6/15	
9		📌	Research Top Three	14 days	Wed 10/28/1	Sun 11/15/15	
10		📌	Final IDEA	6.38 days	Mon 11/2/15	Mon 11/9/15	
11		📌	Preliminary Design Report Rough	2.63 days	Mon 11/2/15	Wed 11/4/15	
12		📌	Preliminary Design Report FINAL	6.38 days	Wed 11/4/15	Wed 11/11/15	
13		📌	Presentation	4.88 days	Wed 11/11/1	Mon 11/16/1	
14		📌	Design Development	18.38 days	Wed 11/11/15	Fri 12/4/15	
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16		📌?					
17		📌	Equipment Selection	11.63 days	Mon 11/16/15	Mon 11/30/15	
18		📌	Locate Equipment	4.13 days	Mon 11/30/1	Fri 12/4/15	
19		📌	Establish Work Area	9.38 days	Mon 11/23/1	Fri 12/4/15	
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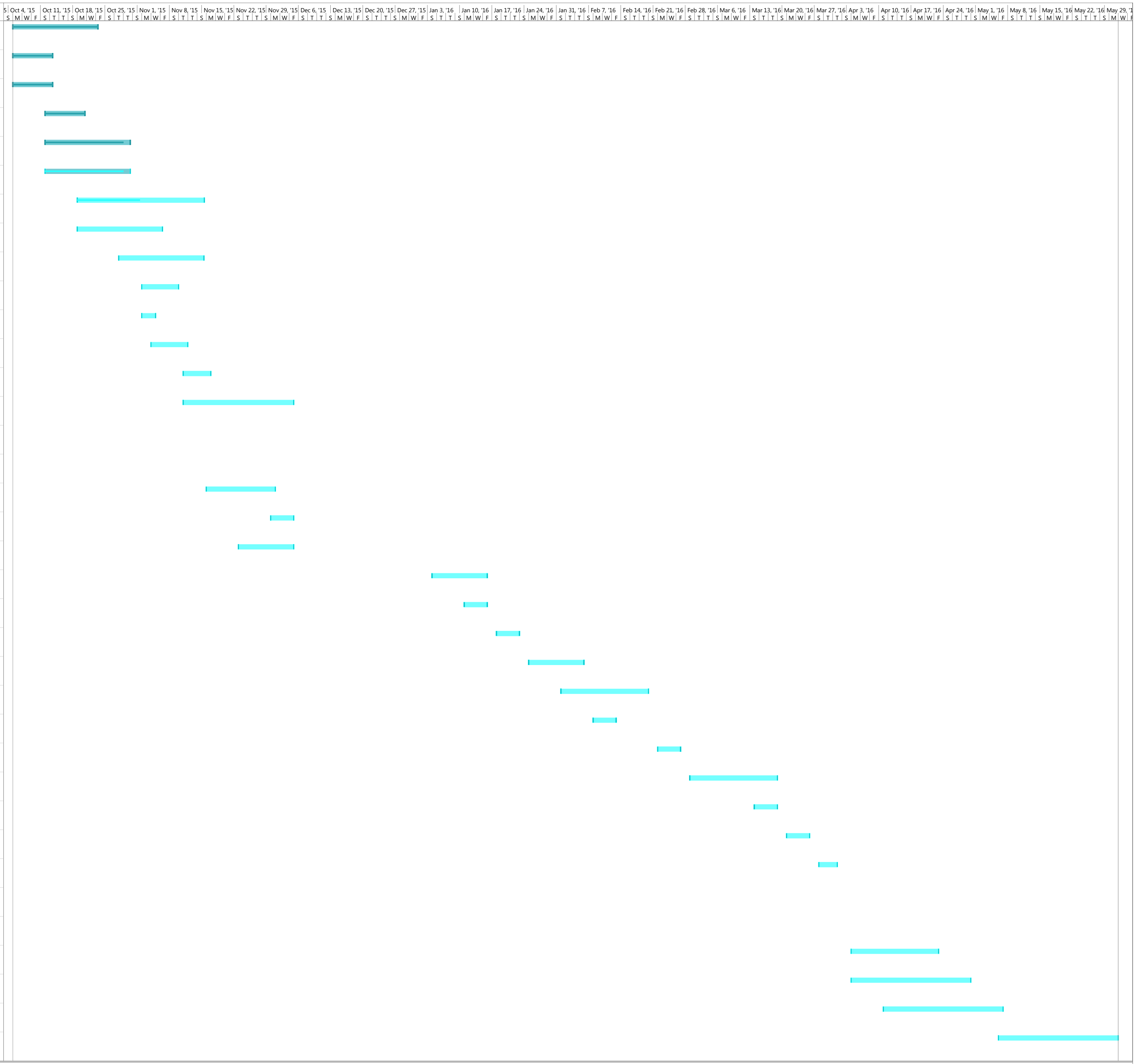
21		📌	CDR Presentations	4.13 days	Mon 1/11/16	Fri 1/15/16	
22		📌	Ordering	4.13 days	Mon 1/18/16	Fri 1/22/16	
23		📌	Shipping Items	9.38 days	Mon 1/25/16	Fri 2/5/16	
24		📌	Assembly	14.63 days	Mon 2/1/16	Fri 2/19/16	
25		📌	Calbirate Equipment	4.13 days	Mon 2/8/16	Fri 2/12/16	
26		📌	Verification	4.13 days	Mon 2/22/16	Fri 2/26/16	
27		📌	Experimental Trials	14.63 days	Mon 2/29/16	Fri 3/18/16	
28		📌	Individual Ethics Memo	4.13 days	Mon 3/14/16	Fri 3/18/16	
29		📌	Team Evaluations	4.13 days	Mon 3/21/16	Fri 3/25/16	
30		📌	End of Quarter Status Report	3.38 days	Mon 3/28/16	Thu 3/31/16	
31							
32		📌?	**SPRING QUARTER 2016**				
33		📌	Continue Trials	14.63 days	Mon 4/4/16	Fri 4/22/16	
34		📌	Compile Data	19.88 days	Mon 4/4/16	Fri 4/29/16	
35		📌	Final Project Report ROUGH	19.88 days	Mon 4/11/16	Fri 5/6/16	
36		📌	Final Project Report FINAL	19.88 days	Fri 5/6/16	Tue 5/31/16	



Project: ESC_GanttChart.mpp
Date: Sun 6/5/16

Task		Milestone	◆	Project Summary	▏▕	Inactive Milestone	◇	Manual Task	▬	Manual Summary Rollup	▬	Start-only	[	External Tasks		Deadline	⬇	Manual Progress	―
Split	⋯⋯	Summary	⊓	Inactive Task		Inactive Summary	▏▕	Duration-only	▬	Manual Summary	⊓	Finish-only	]	External Milestone	◇	Progress	―		

House of Quality for the ESC Efficiency Problem

▲ Larger is Better
◉ Nominal is Best
▼ Smaller is Better

× ○ ○ ◎ □
✱ ◎ △ ▽ ◇

Customer Desciption:
1 = Dr. Westphal
2 = Other Scientists
3 =

Specifications (Hows)

Customer Ratings

Customer Requirements (Whats)	Importance	Insulated	Cycle Time	Life Cycle	Size	Cost	Mass	Movement Time	Temperature Measurement	Weight Measurement	Volume air flow measuremen	Atmospheric pressure measu				Bad				Good
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	1	2	3	4	5
Measures efficiency within 0.5%	60	◎	△			○			○	○	○	○				△				
Compatibility	20	○	○													△				
Cost	10	△		○		◎														△
Compact	10	○			◎	△	△	○												△

△Three Phase Wattmeter (Clayton Green)

Strong -◎
Medium○
Weak -△

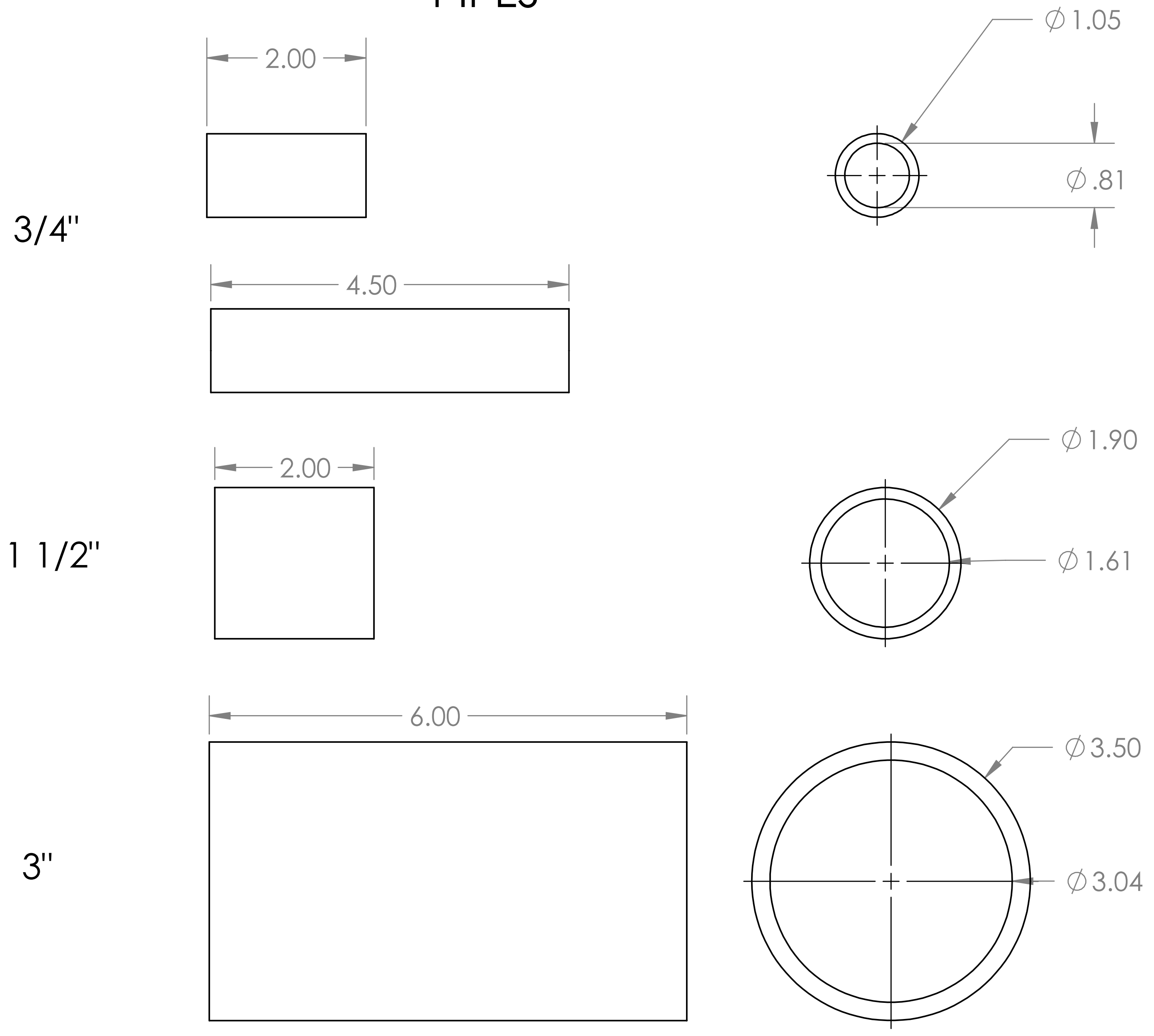
Relationship Strength

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
5				△	△	△	△							
4														
3														
2														
1														
Targets	5-10% heat loss	10 min	< 30 Hours	< One cubic meter	$5,000	< 80 kg	< One hour	±.3°C	±.1g	2% of measurement	±100Pa			
Weighted Importance														
% Importance														

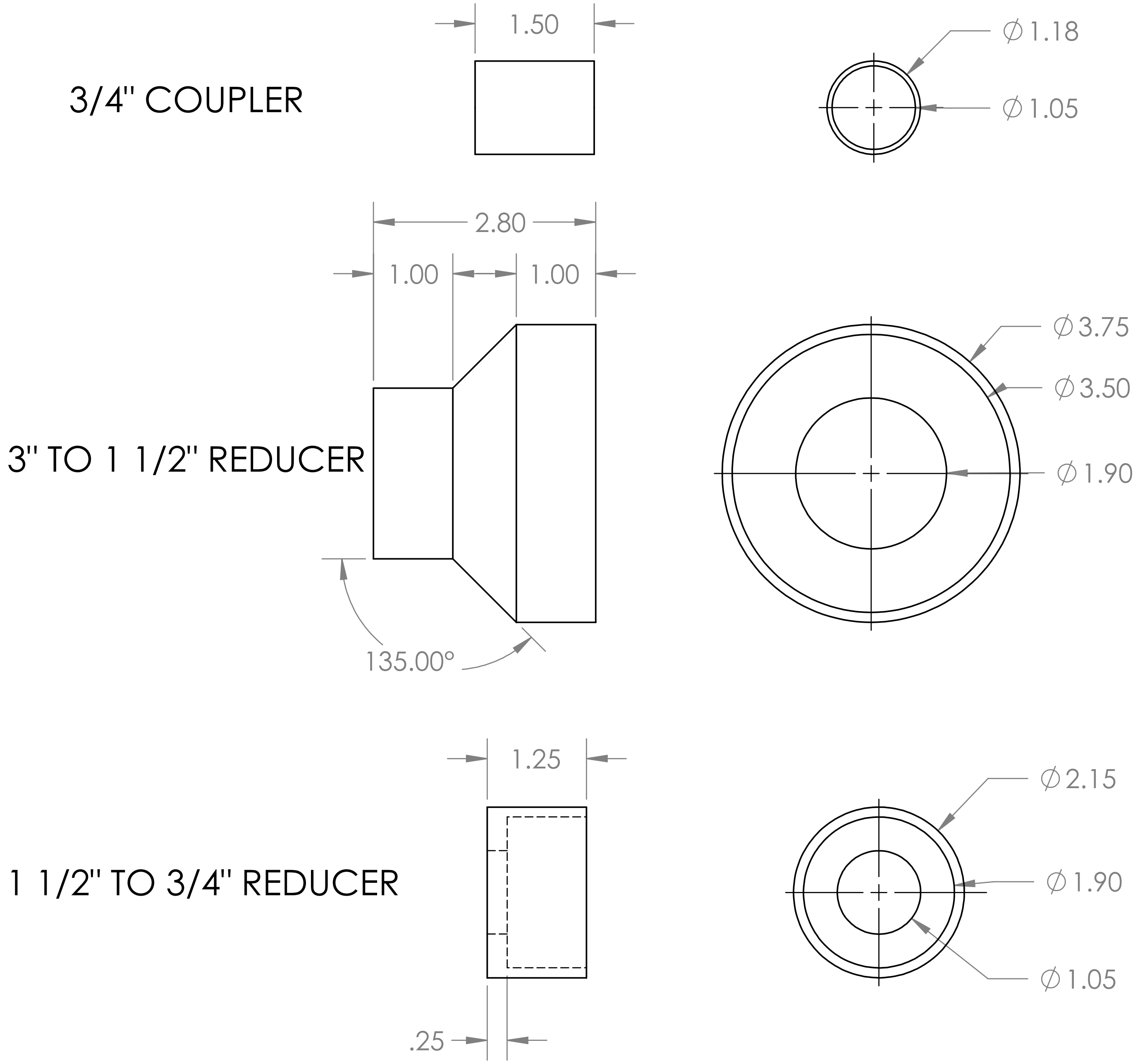
Appendix B - Proof of Concept Data

Trial	Heat Source			Fan		Room Temp. (F)	Atmos. pressue (psi)	Δ T		Air Speed of outlet		Area of Outlet (ft^2)	Volumetric Flowrate, Q			Mass Flow (kg/s)	Power dissapated (Watts)	Percent Loss	Re	Notes
	Voltage (V)	Current (A)	Pout (Watts)	Voltage (V)	Current (A)			(°F)	(°C)	(fpm)	(m/s)		(cfm)	(lit/min)	(lit/sec)					
1	8.6	0.578	4.9708	3	0.03	69.8	14.647	4.4	2.4	170	0.8636	5.45E-03	0.93	26.3	0.438	5.18E-04	1.273	74%	1411	Took 20 mins to reach this equilibrium
2	8.6	0.578	4.9708	3	0.03	69.8	14.647	6.4	3.6	120	0.6096	5.45E-03	0.65	18.5	0.309	3.66E-04	1.307	74%	996	Covered inlet of fan 90% to change air speed, waited __ min to tak temp measurement
3	8.6	0.58	4.988	4	0.033	69.73	14.647	3.8	2.1	250	1.27	5.45E-03	1.36	38.6	0.644	7.62E-04	1.617	68%	2076	increased power of fan, Temperature keeps fluctuating , took ten minutes to measure
4	8.6	0.565	4.859	5.7	0.058	69.57	14.653	3	1.7	350	1.778	5.45E-03	1.91	54.1	0.901	1.07E-03	1.787	63%	2906	Increase voltage of fan, took 4 min
5	12.4	0.835	10.354	5.7	0.057	69.57	14.653	4.8	2.7	350	1.778	5.45E-03	1.91	54.1	0.901	1.07E-03	2.859	72%	2906	Increased voltage of heater
6	12.4	0.836	10.3664	4	0.046	69.82	14.657	6.9	3.8	225	1.143	5.45E-03	1.23	34.8	0.579	6.86E-04	2.642	75%	1868	decreased voltage of fan
7	12.4	0.83	10.292	3	0.028	69.82	14.657	8	4.4	120	0.6096	5.45E-03	0.65	18.5	0.309	3.66E-04	1.634	84%	996	decreased voltage of fan
8	0	0	0	3	0.028	69.82	14.657	1.5	0.8	160	0.8128	5.45E-03	0.87	24.7	0.412	4.88E-04	0.408	N/A	1328	Cold air measurement

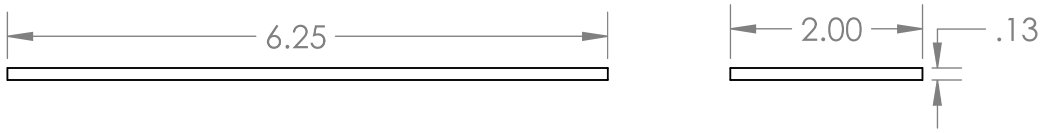
PIPES



FITTINGS



ESC TRAY



NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.05
MATERIAL
FINISH
DO NOT SCALE DRAWING

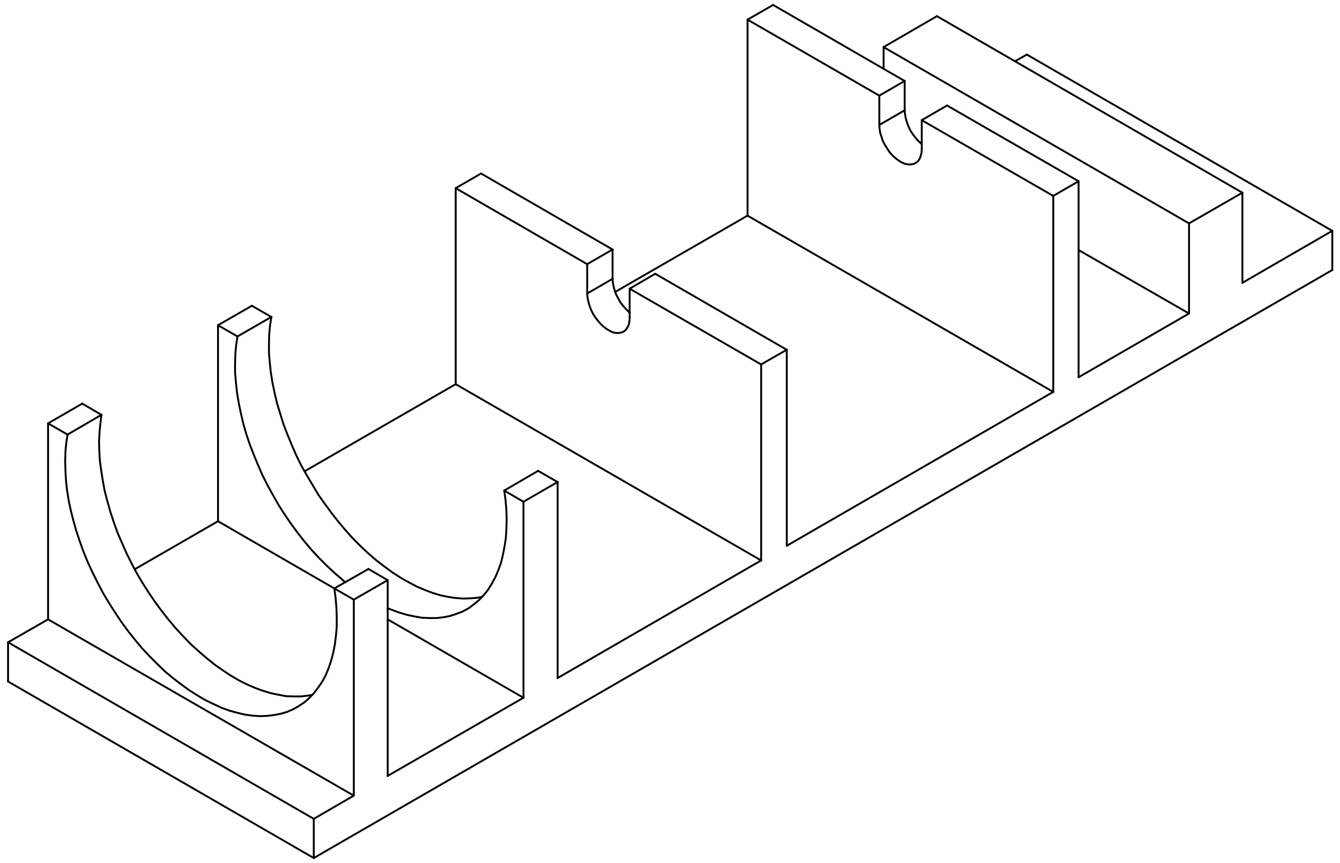
	NAME	DATE
DRAWN	MAP	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

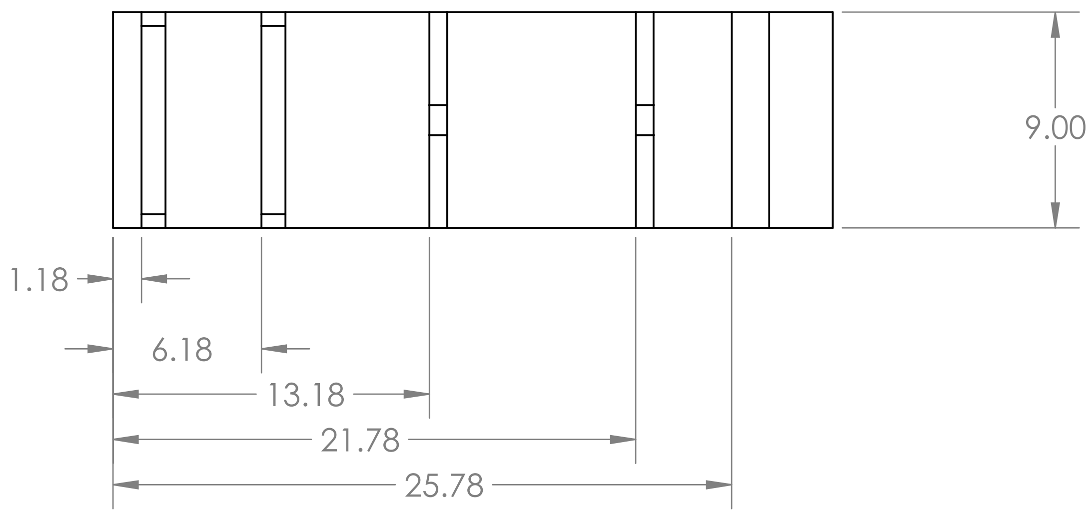
COMMENTS: ALL PIPE LENGTHS AND FITTING DIMENSIONS. INCLUDES DIMENSIONS FOR ESC TREY AS WELL.

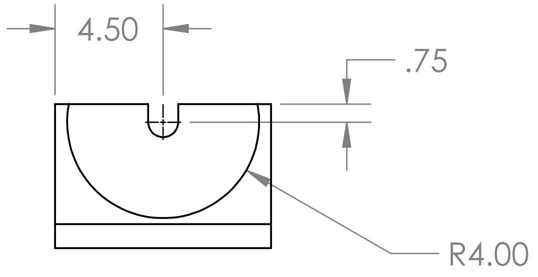
TITLE:
PIPES AND FITTINGS

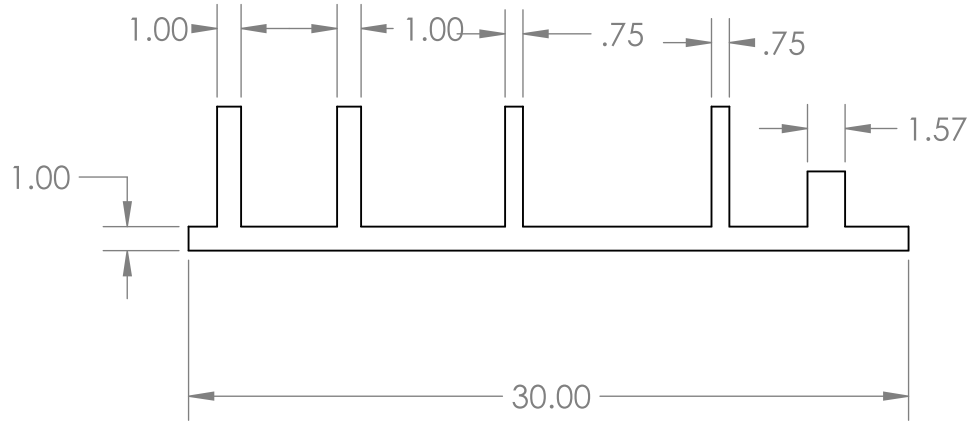
SIZE **B** DWG. NO. 001 REV

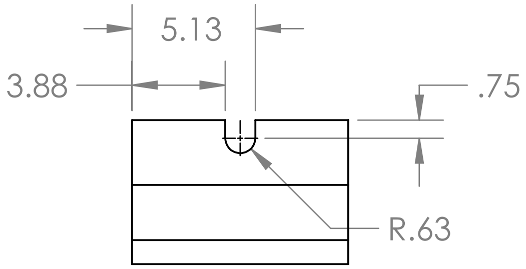
SCALE: 1:1 WEIGHT: SHEET 1 OF 1











PROPRIETARY AND CONFIDENTIAL

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.05
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

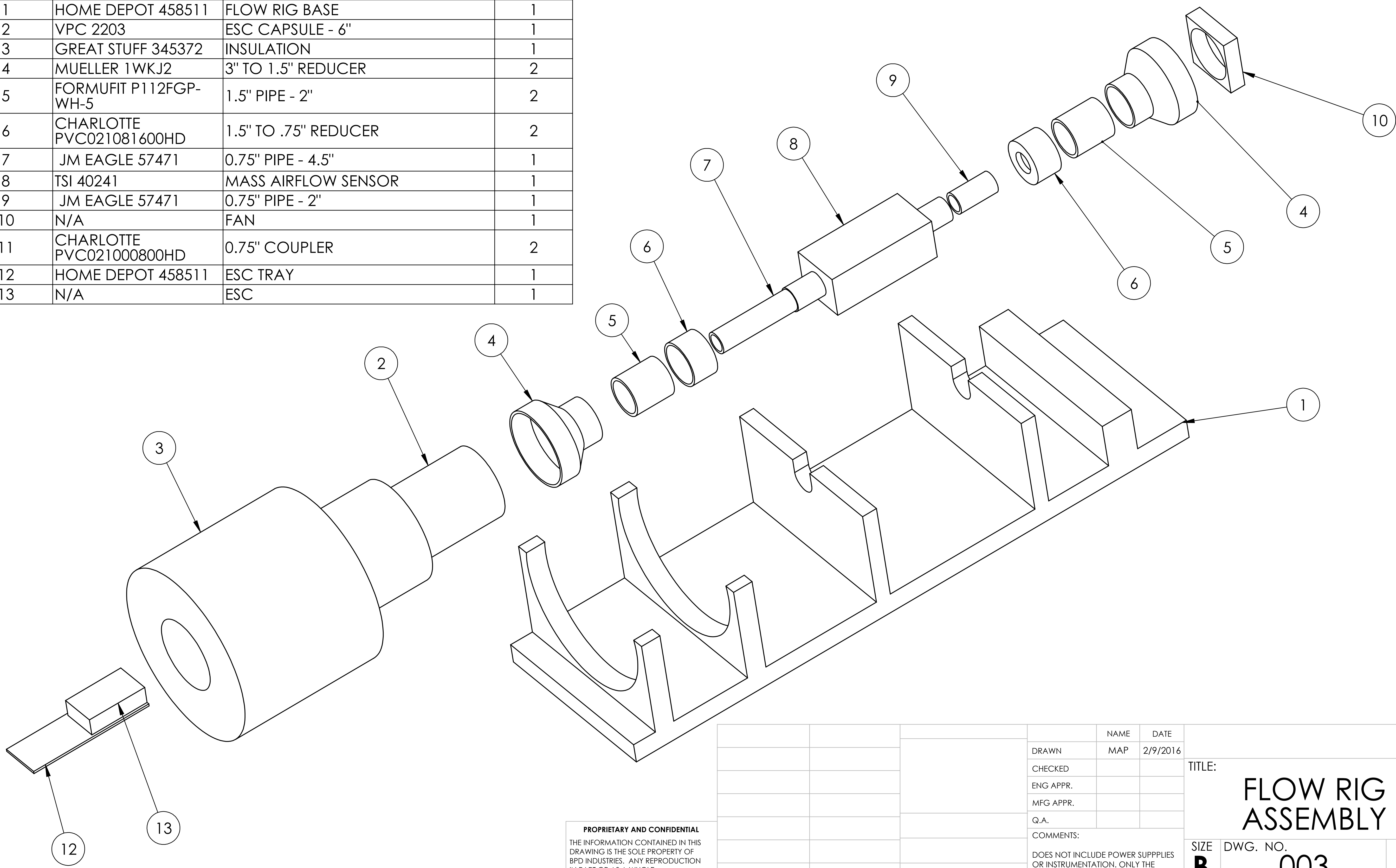
	NAME	DATE
DRAWN	MAP	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS: PART WILL NOT BE COMPLETELY SOLID. ALL VERTICAL STRUCTURES WILL BE CUT OUT SEPARATELY AND ATTACHED IN THIS CONFIGURATION.

TITLE:
FLOW RIG BASE

SIZE **B**
DWG. NO. 002
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	HOME DEPOT 458511	FLOW RIG BASE	1
2	VPC 2203	ESC CAPSULE - 6"	1
3	GREAT STUFF 345372	INSULATION	1
4	MUELLER 1WKJ2	3" TO 1.5" REDUCER	2
5	FORMUFIT P112FGP-WH-5	1.5" PIPE - 2"	2
6	CHARLOTTE PVC021081600HD	1.5" TO .75" REDUCER	2
7	JM EAGLE 57471	0.75" PIPE - 4.5"	1
8	TSI 40241	MASS AIRFLOW SENSOR	1
9	JM EAGLE 57471	0.75" PIPE - 2"	1
10	N/A	FAN	1
11	CHARLOTTE PVC021000800HD	0.75" COUPLER	2
12	HOME DEPOT 458511	ESC TRAY	1
13	N/A	ESC	1



NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MAP	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
DOES NOT INCLUDE POWER SUPPPLIES OR INSTRUMENTATION. ONLY THE PIPIING NETWORK, INSULATION, AND SUPPORTING STRUCTURE.

TITLE:
FLOW RIG ASSEMBLY

SIZE **B**
DWG. NO. 003
REV
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

DIY Projects & Ideas Credit Services Pro Xtra Store Finder Order Status Local Ad

Products and Services What can we help you find? Your Store San Luis Obispo Sign in or Register

Charlotte Pipe | Model # PVC021000800HD | Internet # 203811383 | Store SKU # 188077

3/4 in. PVC Sch. 40 S x S Coupling

★★★★★ | **Write the First Review** | **Ask the first question**

$0.22 /each

IN STOCK AT YOUR SELECTED STORE

San Luis Obispo #1052
San Luis Obispo, CA 93405

52 **In Stock**
Aisle 16, Bay 001
Text Product Location

Open Expanded View Click Image to Zoom

PRODUCT OVERVIEW

Model # PVC021000800HD | Internet # 203811383 | Store SKU # 188077

PVC Sch. 40 fitting are for pressure systems where temperatures will not exceed 140° F. They are highly resilient, with high-tensile and high-impact strength. PVC Sch. 40 has better sound deadening qualities than PVC Sch. 40 DWV Foam Core.

- Conforms to meet Standards: ASTM D 1784, ASTM D 2466, NSF 14 and 61
- White fittings that are used in potable water applications only
- Intended for pressure use
- PVC Sch. 40 pipe and pressure fittings are used in irrigation, underground sprinkler systems, swim pools, outdoor applications and cold water supply lines
- Maximum working temperature of 140 degrees Fahrenheit

SPECIFICATIONS

DIMENSIONS

Fitting 1 size	3/4"	Product Height (in.)	1.344
Fitting 2 size	3/4"	Product Length (in.)	2.125
Product Depth (in.)	2.125	Product Width (in.)	1.344

DETAILS

Compatible Pipe Material	PVC	Pipe or Fitting Product Type	Fittings & Connectors
Connection	Sweat x Sweat	Product Weight (lb.)	0.043 lb
Fitting or Connector Type	Adapter or Coupling	Push to connect	No
Material	PVC	Underground rated	Yes
Maximum working pressure (psi)	480		

WARRANTY / CERTIFICATIONS

Manufacturer Warranty	Charlotte Pipe and Foundry Company (Charlotte Pipe) Products are warranted to be free from manufacturing defects and to conform to currently applicable ASTM standards for a period of five (5) years from date of delivery

MORE PRODUCTS WITH THESE FEATURES

Fitting 1 size: **3/4"**

Price: **$0 - $10**

Brand: **Charlotte Pipe**

SEARCH

DIY Projects & Ideas | Credit Services | Pro Xtra | Store Finder | Order Status | Local Ad

Products and Services

What can we help you find?

Your Store
San Luis Obispo

Sign in
or Register

JM eagle | Model # 57471 | Internet # 202280935 | Store SKU # 193712

3/4 in. x 10 ft. PVC Schedule 40 Plain-End Pipe

★★★★☆ (4) | **Write a Review** | **Questions & Answers (4)**

$2.42 / each | If you buy **10** or more **$2.18** / each

- Solvent-weld joints provide a rigid joint connection
- 140-degree Fahrenheit maximum working temperature
- 480 psi maximum working pressure

Open Expanded View

Click Image to Zoom

PRODUCT OVERVIEW

Model # 57471 | Internet # 202280935 | Store SKU # 193712 | Store SO SKU # 136293

This 3/4 in. x 10 ft. PVC Sch. 40 Plain-End Pipe is perfect for DWV and water-supply applications. This pipe is easy to load, transport and handle and offers excellent corrosion resistance.

- Sch. 40 PVC construction
- Retains a smooth interior
- Easy to load, transport and handle
- Can be cut with a power saw or ordinary handsaw (not included)
- Resistant to tuberculation, corrosive soil or water conditions and electrolytic or galvanic corrosion
- For DWV and water-supply applications
- Connects directly to most plumbing and IPS fixtures and into CIOD fittings with adapters or transition gaskets (not included)
- For use underground and in partial support systems aboveground
- Install in accordance with JM publication TR-407B solvent-weld pipe installation guide and TR-410A pressure pipe tapping guide
- Meets ASTM D1785 and D2665 specifications
- NSF listed
- Corrosion resistance: Solvent weld PVC is unaffected by electrolytic or galvanic corrosion, or any known corrosive soil or water condition
- Meets ASTM D1785 and D2665
- Note: Product may vary by store.

SPECIFICATIONS

DIMENSIONS

Actual inside diameter (in.)	0.81	Product Height (in.)	1.05
Actual outside diameter (in.)	1.05	Product Length (ft.)	10 ft
Pipe Size	3/4"	Product Width (in.)	1.05
Product Depth (in.)	120		

DETAILS

Coiled	No	Pipe or Fitting Product Type	Pipe & Tubing
Material	PVC	Product Weight (lb.)	2.183 lb
Maximum Working Temperature (F)	140	Rating	Schedule 40
Maximum working pressure (psi)	480	Recommended function	DWV and Water Supply
Minimum working temperature (F)	0	Wrapped	No
Pipe & Tubing Product Type	PVC Schedule 40		

WARRANTY / CERTIFICATIONS

Certifications and Listings	IAPMO Certified,NSF Listed	Manufacturer Warranty	1 year

MORE PRODUCTS WITH THESE FEATURES

Price: **$0 - $10**

Pipe Size: **3/4"**

Review Rating: **4 & Up**

SEARCH

DIY Projects & Ideas Credit Services Pro Xtra Store Finder Order Status Local Ad

Products and Services What can we help you find? Your Store San Luis Obispo Sign in or Register

Formufit | Model # P112FGP-WH-5 | Internet # 205171546

1-1/2 in. x 5 ft. Furniture Grade Sch. 40 PVC Pipe in White

★★★★★ (5) | **Write a Review** | **Questions & Answers (3)**

$10.86 **/each**

PRODUCT NOT SOLD IN STORES

Open Expanded View Click Image to Zoom

PRODUCT OVERVIEW

Model # P112FGP-WH-5 | Internet # 205171546

Make your PVC projects beautiful and last for years longer with Formufit Furniture Grade PVC Sch. 40 PVC pipe. Furniture Grade PVC is UV resistant, impact proof non-toxic and is vibrant in color and gloss.

- Made from ultra-strong, UV-resistant furniture grade PVC material
- Unmarked, glossy surface finish gives a clean, professional appearance
- Works with 1-1/2 in. Sch. 40 PVC fittings
- Join by solvent welding or by press-to-fit
- Non-toxic and safe, does not contain heavy metals or phthalates
- Note: not NSF rated, should not be used for plumbing applications

SPECIFICATIONS

DIMENSIONS

Actual inside diameter (in.)	1.610	Product Height (in.)	1.9
Actual outside diameter (in.)	1.900	Product Length (ft.)	5
Pipe Size	1-1/2"	Product Width (in.)	1.9
Product Depth (in.)	60		

DETAILS

Coiled	No	Pipe or Fitting Product Type	Pipe & Tubing
Material	PVC	Product Weight (lb.)	2.75 lb
Maximum Working Temperature (F)	170	Rating	Furniture Grade - Not Rated
Maximum working pressure (psi)	0	Recommended function	Structural Buidling - Furniture
Minimum working temperature (F)	-20	Returnable	90-Day
Pipe & Tubing Product Type	Specialty	Wrapped	No

WARRANTY / CERTIFICATIONS

Certifications and Listings	No Certifications or Listings	Manufacturer Warranty	1 Year Product Replacement under general product use conditions

MORE PRODUCTS WITH THESE FEATURES

Price: **$10 - $20**

Brand: **Formufit**

Pipe Size: **1-1/2"**

Review Rating: **4 & Up**

SEARCH

DIY Projects & Ideas Credit Services Pro Xtra Store Finder Order Status Local Ad

Products and Services What can we help you find? Your Store San Luis Obispo Sign in or Register

Charlotte Pipe | Model # PVC021081600HD | Internet # 203811562 | Store SKU # 536636

1-1/2 in. x 3/4 in. PVC Sch. 40 Reducer Bushing

★★★★★ | **Write the First Review** | **Ask the first question**

Open Expanded View Click Image to Zoom

$1.62 **/each**

IN STOCK AT YOUR SELECTED STORE

San Luis Obispo #1052
San Luis Obispo, CA 93405

16 **In Stock**
Aisle 16, Bay 003
Text Product Location

PRODUCT OVERVIEW

Model # PVC021081600HD | Internet # 203811562 | Store SKU # 536636

PVC Sch. 40 fitting that is for pressure systems where temperatures will not exceed 140° F. They are highly resilient, with high-tensile and high-impact strength. PVC Sch. 40 has better sound deadening qualities than PVC Sch. 40 DWV Foam Core.
California residents: see Proposition 65 information↗

- Conforms to meet Standards: ASTM D 1784, ASTM D 2466, NSF 14 and 61
- White fittings that are used in potable water applications only
- Intended for pressure use
- PVC schedule 40 pipe and pressure fittings are used in irrigation, underground sprinkler systems, swimming pools, outdoor applications and cold water supply lines
- Maximum working temperature of 140 degrees Fahrenheit

SPECIFICATIONS

DIMENSIONS

Fitting 1 size	3/4"	Product Height (in.)	1.140
Fitting 2 size	1-1/2"	Product Length (in.)	1.25
Product Depth (in.)	2.04	Product Width (in.)	1.140

DETAILS

Compatible Pipe Material	PVC	Pipe or Fitting Product Type	Fittings & Connectors
Connection	Spigot x FIP	Product Weight (lb.)	.030 lb
Fitting or Connector Type	Bushing	Push to connect	No
Material	PVC	Underground rated	Yes
Maximum working pressure (psi)	185		

WARRANTY / CERTIFICATIONS

Manufacturer Warranty	Charlotte Pipe and Foundry Company (Charlotte Pipe) Products are warranted to be free from manufacturing defects and to conform to currently applicable ASTM standards for a period of five (5) years from date of delivery

MORE PRODUCTS WITH THESE FEATURES

Price: **$0 - $10**

Brand: **Charlotte Pipe**

SEARCH

DIY Projects & Ideas | Credit Services | Pro Xtra | Store Finder | Order Status | Local Ad

Products and Services | What can we help you find? | Your Store San Luis Obispo | Sign in or Register

VPC | Model # 2203 | Internet # 205706641 | Store SKU # 503826

3 in. x 2 ft. PVC Sch. 40 Pipe

★★★★★ | **Write the First Review** | **Questions & Answers** (1)

Open Expanded View Click Image to Zoom

$9.99 **/piece**

NEARBY STORES MAY HAVE THIS ITEM

Check Nearby Stores

PRODUCT OVERVIEW

Model # 2203 | Internet # 205706641 | Store SKU # 503826

This VPC 3 in. x 2 ft. PVC Sch. 40 Pipe is made from PVC and can be used where systems will not exceed 140°F. This pipe can withstand a working pressure up to 260 psi for flexible use in underground DWV systems. 3 in. I.D. pipe size.

- Made from PVC
- For use where systems will not exceed 140°F
- Maximum working pressure of 260 psi
- Can be used in underground DWV systems
- 1 year warranty
- Durable construction and built to last
- Note: product may vary by store

SPECIFICATIONS

DIMENSIONS

Actual inside diameter (in.)	3.042	Product Height (in.)	24
Actual outside diameter (in.)	3.5	Product Length (ft.)	2 ft
Pipe Size	3"	Product Width (in.)	3.5

Product Depth (in.)	3.042		

DETAILS

Coiled	No	Product Weight (lb.)	2.98 lb
Material	PVC	Rating	DWV
Maximum Working Temperature (F)	140	Recommended function	DWV
Minimum working temperature (F)	33	Returnable	90-Day
Pipe & Tubing Product Type	PVC DWV	Wrapped	No
Pipe or Fitting Product Type	Pipe & Tubing		

WARRANTY / CERTIFICATIONS

Certifications and Listings	IAPMO Certified,NSF Listed	Manufacturer Warranty	30 Days

MORE PRODUCTS WITH THESE FEATURES

Brand: **VPC**

Pipe Size: **3"**

SEARCH

How can we improve our **Product Images**?

☐ **Compare**

MUELLER INDUSTRIES

Pipe Reducer or Increaser, PVC, 3x1 1/2 In

Price
$6.98 / each

● **Deliver one time only**

○ **Auto-Reorder Every** 1 Month ▼

1 Add to Cart

+ Add to List

Confirm ZIP Code to determine availability.

ZIP Code

93401 Save

☆☆☆☆☆ **Be the first to write a review** | **Ask & Answer**

Item # **1WKJ2** Mfr. Model # **1WKJ2** UNSPSC # **40142321**

Catalog Page # **3496** Shipping Weight **0.41 lbs.**

Country of Origin **USA** | *Country of Origin is subject to change.*

Note: Product availability is real-time updated and adjusted continuously. The product will be reserved for you when you complete your order. More

Technical Specs

Item	**Reducer**	Connection Type	**Hub**
Body Material	**PVC**	Color	**White**
Schedule	**DWV**	Max. Temp.	**140 Degrees F**
Pipe Size	**3" x 1-1/2"**	Standards	**Cell Class 12454, ASTM D1784**

McMASTER-CARR® OVER 555,000 PRODUCTS
(562) 692-5911
(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

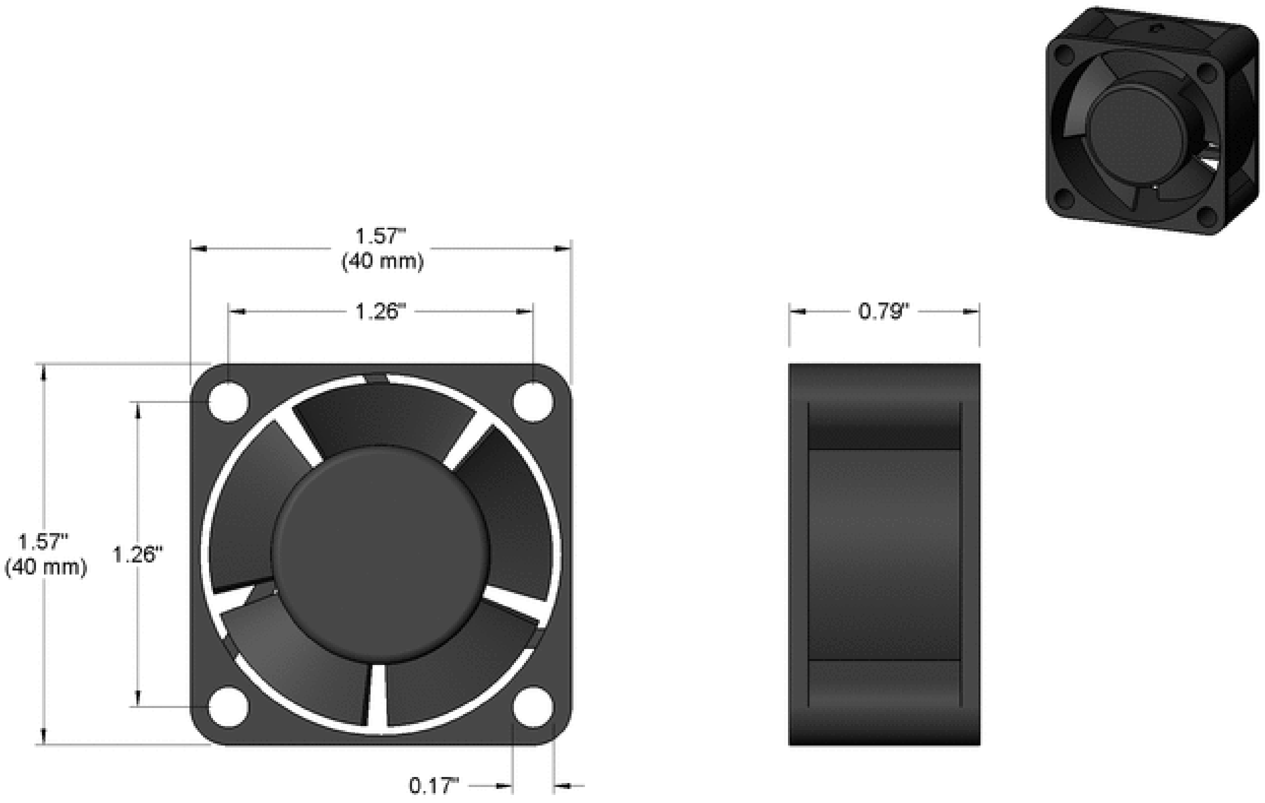
DC Equipment Cooling Fan

1.57" Square x 0.79" Depth, 7 CFM, 24 VDC

In stock
$25.98 Each
1939K22

Size	1.57" (40 mm)
Depth	0.79"
Connections	Wire Leads
Airflow	7 cfm
Volume	29 dB
Mounting Holes	0.17"
Material	
Frame	Plastic
Blade	Plastic
Amps	0.07
Additional Specifications	24 Volt DC Fans Square

Quiet and compact, these fans are the most popular choice for cooling heat-sensitive equipment. They're also known as muffin fans. All have UL recognized components and are CSA certified. Fasteners not included. For fan guards, filters, and thermostats, see Equipment-Cooling Fan Accessories.



McMASTER-CARR CAD

http://www.mcmaster.com

PART NUMBER **1939K22**

Equipment-Cooling Fan

The information in this 3-D model is provided for reference only.

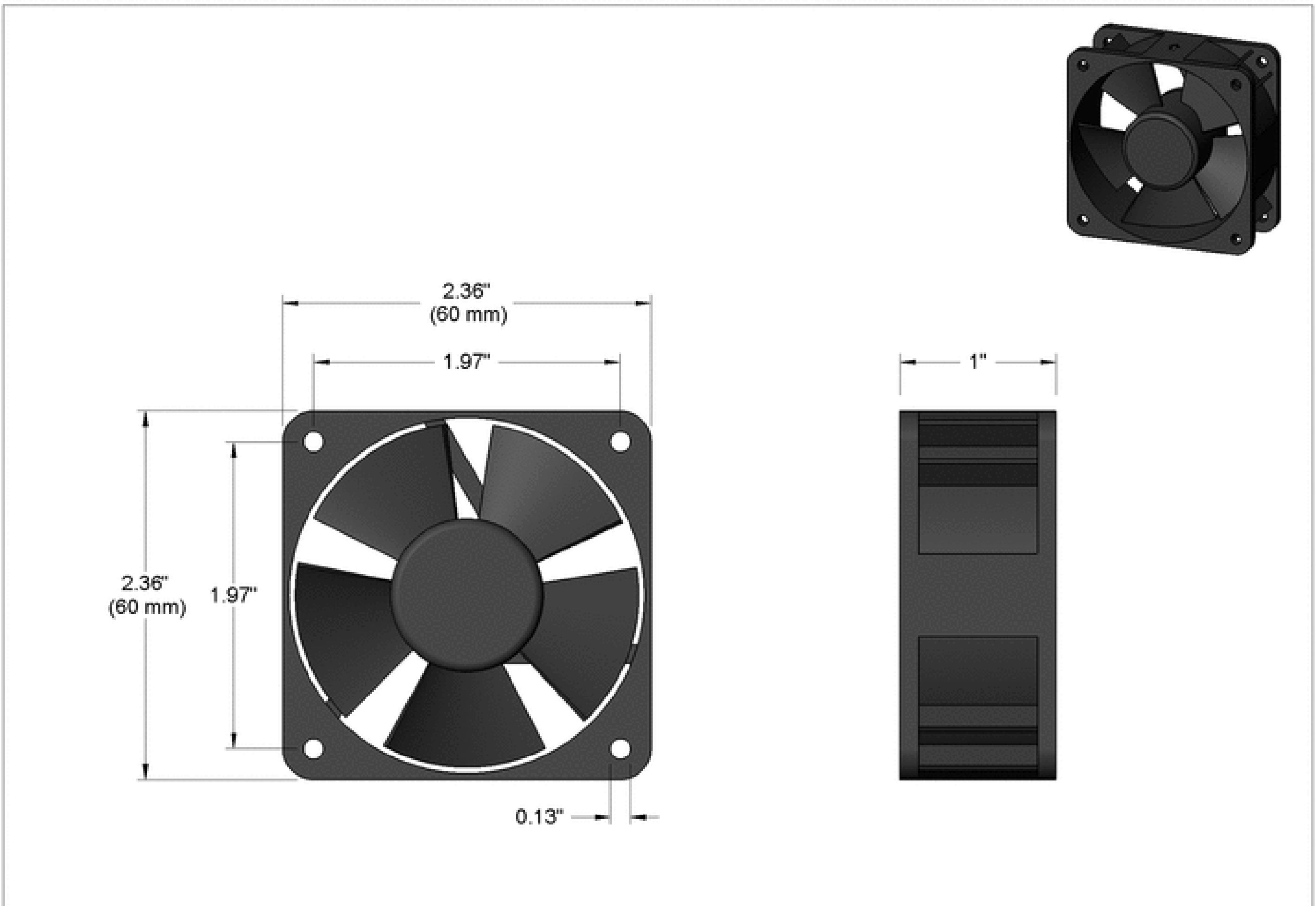
DC Equipment Cooling Fan

2.36" Square x 1" Depth, 20 CFM, 24 VDC

In stock
$23.75 Each
1939K57

Size	2.36" (60 mm)
Depth	1"
Connections	Wire Leads
Airflow	20 cfm
Volume	30 dB
Mounting Holes	0.13"
Material	
Frame	Plastic
Blade	Plastic
Amps	0.06
Additional Specifications	24 Volt DC Fans Square

Quiet and compact, these fans are the most popular choice for cooling heat-sensitive equipment. They're also known as muffin fans. All have UL recognized components and are CSA certified. Fasteners not included. For fan guards, filters, and thermostats, see Equipment-Cooling Fan Accessories.



McMASTER-CARR CAD

PART NUMBER **1939K57**

http://www.mcmaster.com

Equipment-Cooling
Fan

The information in this 3-D model is provided for reference only.

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(562) 695-2323 (fax)
la.sales@mcmaster.com
Text 75930

Alligator Clip

Crimp/Screw-Down Connection, Nickel Plated Steel

In stock
$0.58 Each
7236K55

Jaw Style	Alligator
Wire Connection	Crimp, Screw-Down
Clip Material	Nickel-Plated Steel
Insulation Style	Noninsulated
For Wire Gauge	20, 19, 18, 17, 16
Jaw Opening	5/16"
Tooth Style	Toothed
Current	5 A
Length	1 11/16"
Spring Material	Zinc-Plated Steel
Screw Material	Zinc-Plated Steel
Rivet Material	Zinc-Plated Steel
Related Products	Optional Black Vinyl Sleeves Optional Red Vinyl Sleeves

Spring-loaded clips create a secure temporary electrical connection for hands-free testing.

Toothed clips have a stronger grip but make less overall contact than toothless clips.

Minco Websites: Components Solutions

MINCO Components.com
YOUR ONLINE SOURCE FOR STANDARD MINCO COMPONENTS

Cart (0) | Si

Literature

Search

Shop by Product Engineering Tools Part # Search

Home > Heaters > Silicone Rubber Heaters > HR6926

Actual product may not be shown

Silicone Rubber Heaters: HR6926

ADD TO CART

Price: $49.80

Product Details

● English

Provides heat where it’s needed to reduce operating costs.

Fast and efficient thermal transfer. Uniform thermal performance by custom profiling. Customized options for turnkey thermal solutions.

Custom options:
- Factory vulcanization and high temperature capability allows higher wattage levels
- Optional custom profiled heat density creates a uniform heat sink temperature which can improve processing yields
- High temperature capability to 235°C (455°F)
- Custom shapes and sizes to 22" x 90" (560 x 2285 mm)
- Custom resistance to 200 Ω/in² (31 Ω/cm²)
- Heaters can include thermostats, temperature sensors and cutouts, wiring harnesses, connectors, and controllers
- RoHS compliance
- Temperature range: -45 to 235°C (-50 to 455°F). With UL component recognition: -45 to 220°C (-50 to 428°F)
- Resistance tolerance: ±10% or ±0.5 Ω , whichever is greater
- Dielectric strength: 1000 VRMS
- Minimum bend radius: 0.125" (3.2 mm)

Attributes

Mounting	Acrylic Adhesive (PSA)
Thickness (in)	0.060
Min Temp (°F)	-26
Max Temp (°F)	212
Weight (oz)	0.22
Style	Etched Silicone Rubber
X dim (in)	2.00
Y dim (in)	3.00
R (Ω)	14.75
AWG	24
Area (in2)	5.3140
Volt	28.00
Watt	53.1
Availability	In Stock
Watt Density (w/in²)	10.00

Documentation

Product Drawing	HR6926.pdf

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www.minco.com

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General Purpose Duct Tape

2" Width x 20 Yards Length, Silver

In stock
1-53 Rolls $5.57
54 or more $4.14
76135A48

Width	2"
Length	20 yds.
Color	Silver
Case Quantity	54

You'll get water resistance with excellent adhesion from this flexible, multipurpose tape. It has a shiny polyethylene coating and rubber adhesive, except for conformable and easy-tear vinyl tape, which have a matte vinyl coating, and transparent tape, which has an acrylic adhesive.

General Purpose—Use to secure fiberglass insulation, as a condensation barrier in refrigeration assemblies, and in short-term ductwork sealing. Tape is 0.01" thick. Temperature range is 40° to 160° F.

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Electrical Tape

3/4" Width x 20 Yards Long, Black

In stock
1-9 Rolls $1.06
10 or more $0.95
7619A11

Width	3/4"
Length	20 yds.
Color	Black
Case Quantity	10
Additional Specifications	SDS
RoHS	Compliant

Insulate wire and cable splices up to 600 volts. Tape is also great for harnessing wire and cable and as jacketing for cable splices and repairs. It is resistant to moisture, weather, abrasion, chemicals, and copper corrosion. Made of 0.007" thick PVC with rubber adhesive. Temperature range is 35° to 175° F. UL listed.

MASS FLOWMETERS FOR GASES

UNDERSTANDING, ACCELERATED

MEASURE FLOW, PRESSURE, AND TEMPERATURE... ALL IN ONE INSTRUMENT!

Designed for Performance

TSI thermal mass flowmeters incorporate a proprietary platinum film sensor design for measuring gas flows in applications demanding fast response and high accuracy over a wide flow range. TSI flowmeters have turn-down ratios greater than 1000:1 due to our thermal flow sensing technology and extensive gas calibration process. The TSI 4000 Series was designed for ultra-low pressure loss to minimize any undesirable effects the flowmeter can have on the readings when installed in-circuit.

Industries

+ Medical
  - Ventilators
  - Anesthesia
  - CPAP
+ Environmental
+ Analytical
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Applications

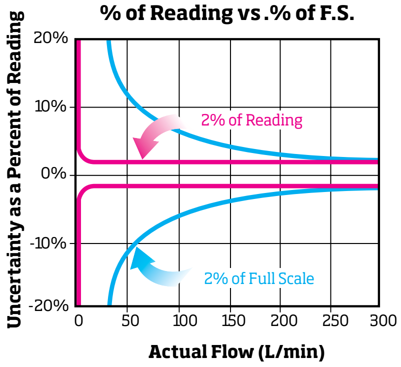
+ Product Development
+ Manufacturing
+ Research
+ Field Service
+ Quality Assurance

Features

+ 4 millisecond flow response
+ High accuracy ±2% of reading
+ High turndown ratio
+ Low pressure drop
+ Convenient analog output of flow rate
+ Versatile digital output of flow rate, volume, pressure, temperature
+ Built-in temperature and pressure compensation
+ NIST-traceable calibration certificate included at no additional cost

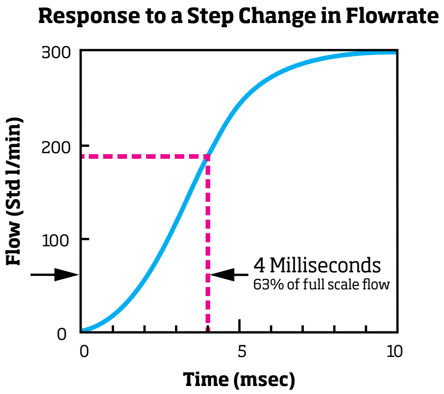
RS232 Interface For Digital Outputs and Configurable Device Options

+ Set analog output zero and scaling
+ Specify start/stop trigger levels for volume measurement
+ Set update rate for LCD display
+ Set sampling rate for analog and digital outputs
+ Select gas calibration
+ Select either standard or volumetric flow measurement
+ Set display units for Model 4140/4143 to L/min or cm^3/min
+ Compute volume



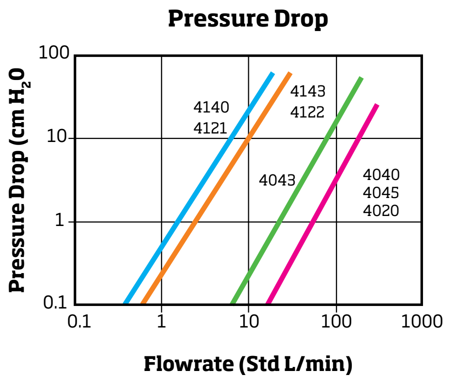
Accurate

A flowmeter specified as ±2% of full scale is most accurate at full scale. If full scale is 300 L/min, then the uncertainty for all readings is ±6 L/min. TSI flowmeters are specified as ±2% of reading and have an uncertainty of ±2% of the actual reading from full scale all the way down to a specified lower limit. TSI flowmeters, therefore, provide dependable accuracy over a wide range of flow rates. One TSI flowmeter covers the same range as three or more "percent of full scale" devices...with better accuracy at all points!



Fast

Fast 4 millisecond response ensures accuracy in fluctuating flows. This fast response is ideal for closed-loop control systems and integrated volume measurements. Pressure and temperature measurements are also extremely fast.



Low Pressure Drop

Low pressure drop minimizes flow circuit back pressure and its impact on the system under test.

SPECIFICATIONS – DIGITAL DISPLAY MODELS

		Low Flow - 4140 Series				High Flow - 4040 Series		
Model		4140	41403	4143	41433	4040	4043	4045
Gas Calibration		Air, O_2, N_2	Air, O_2, N_2, N_2O	Air, O_2, N_2	Air, O_2, N_2, N_2O	Air, O_2, N_2, Air/O_2 Mixture		
Inlet/Outlet Diameter		0.25" (6.4 mm)		0.375" (9.53 mm)		22 mm ISO tapered	0.50" (12.7 mm)	0.75" (19.1 mm)
Flow Measurement	Range	0.01-20 Std L/min				0-300 Std L/min	0-200 Std L/min	0-300 Std L/min
	Accuracy – Air and O_2	±2% of reading or 0.005 Std L/min, whichever is greater				±2% of reading or 0.05 Std L/min, whichever is greater		
	Accuracy – N_2	±3% of reading or 0.010 Std L/min, whichever is greater				±3% of reading or 0.1 Std L/min, whichever is greater		
	Accuracy – Air and O_2 mixture	N/A				±3% of reading or 0.1 Std L/min, whichever is greater		
	Accuracy – N_2O	N/A	±3% of reading or 0.010 Std L/min, whichever is greater	N/A	±3% of reading or 0.010 Std L/min, whichever is greater	N/A		
	Response	4 ms to 63% of full scale flow				4 ms to 63% of full scale flow		
LCD Display Units		L/min, Std L/min, cm^3/min, Std cm^3/min				L/min, Std L/min		
Overall Dimensions		5" x 2" x 1.25" (127 mm x 49 mm x 32 mm)				7.2" x 2.5" x 2.1" (182 x 63 x 53 mm)		
Volume* Measurement	Range	0.01 - 99.9 liters				0.01 - 99.9 liters		
	Accuracy	±2% of reading (see Operator's Manual for additional details)				±2% of reading (see Operator's Manual for additional details)		
Pressure Measurement	Range	50-199 kPa absolute				50-199 kPa absolute		
	Accuracy	±1 kPa				±1 kPa		
	Response	<4 ms to 63% of final value for step charge				<4 ms to 63% of final value for step charge		
Temperature Measurement	Range	0-50°C				0-50°C		
	Accuracy	±1°C at flow greater than 1 Std L/min				±1°C at flow greater than 1 Std L/min		
	Response	<75 ms to 63% of final value for step change				<75 ms to 63% of final value for step change		
Outputs	Analog	0-10 VDC flow only, zero and span adjustable via RS232				0-10 VDC flow only, zero and span adjustable via RS232		
	Digital	RS232				RS232		
DC Power Input		7.5 VDC ±1.5 V, 300 mA max				7.5 VDC ±1.5 V, 300 mA max		

Accessories	Description	TSI Part Number
Supplied	Power Supply	P/N 8918-NA (North America)
		P/N 8918-EC (Continental Europe)
		P/N 8918-GB (United Kingdom)
		P/N 8918-AT (Australia)
	Computer Cable (mini-DIN to 9-Pin D-Sub)	P/N 1303583
	Analog Cable (mini-Din to tinned-wire)	P/N 1303584
	RS232 Serial Command Set Manual	P/N 1980340
	Operator's Manual	P/N 1980339 (404x Series)
		P/N 1980383 (414x Series)
	Calibration Certificate	No P/N assigned
	Inlet Filter	P/N 1602292 [Model 4040 (22mm ISO-Taper)]
		P/N 1602300 [Models 4043, 4045 (0.375" FNPT, HEPA)]
		P/N 1602317 [Models 4140, 41403 (0.25" tube, 6mm)]
		P/N 1602342 [Models 4143, 41433 (0.375" tube, 9mm)]
Optional	Battery Pack/Stand for all Models	P/N 4199 (includes six AA-size batteries)
	Hard-side Carrying Case	P/N 1319176 (404x Series)
		P/N 1319201 (414x Series)
	Filter, Low Pressure Drop, 0.375" FNPT, HEPA Grade	P/N 1602345 (Models 4043, 4045)

*Supplied through RS232 port only.
Specifications subject to change without notice.
See Operator's Manual for full listing.

Shown with optional
Carrying Case

Shown with Optional
Battery Pack/Stand

SPECIFICATIONS – NON-DISPLAY MODELS

		Low Flow - 4120 Series						High Flow - 4020 Series				
Model		4121 Series			4122 Series			4021 Series		4024 Series		
		41211	41212	41216	41221	41222	41226	40211	40212	40241	40242	40246
Gas Calibration		Air	O_2	N_2	Air	O_2	N_2	Air	O_2	Air	O_2	N_2
Inlet/Outlet Diameter		0.25" (6.4 mm)			0.375" (9.53 mm)			22 mm ISO tapered		0.75" (19.1 mm)		
Flow Measurement	Range	0.01-20 Std L/min						0-300 Std L/min				
	Accuracy – Air and O_2	±2% of reading or 0.005 Std L/min, whichever is greater						±2% of reading or 0.05 Std L/min, whichever is greater				
	Accuracy – N_2	±3% of reading or 0.010 Std L/min, whichever is greater						±3% of reading or 0.1 Std L/min, whichever is greater				
	Response	4 ms to 63% of full scale flow						4 ms to 63% of full scale flow				
Overall Dimensions		5" x 2" x 1.1" (127 mm x 49 mm x 29 mm)						7.2" x 2.5" x 1.5" (182 x 63 x 38 mm)				
Pressure Measurement		N/A						N/A				
Temperature Measurement	Range	0-50°C						0-50°C				
	Accuracy	±1°C at flow greater than 1 Std L/min						±1°C at flow greater than 1 Std L/min				
	Response	<75 ms to 63% of final value for step change						<75 ms to 63% of final value for step change				
Outputs	Analog	0-4 VDC flow only, zero and span adjustable via RS232						0-4 VDC flow only, zero and span adjustable via RS232				
	Digital	RS232						RS232				
DC Power Input (User Supplied)		5.0 VDC ±0.25 V, 300 mA max						5.0 VDC ±0.25 V, 300 mA max				
Recommended Filtration		HEPA-grade						HEPA-grade				

Accessories	Description	TSI Part Number
Supplied	Analog and Digital Cable (mini-DIN to tinned wire)	P/N 1303584
Optional	Inlet Filter, 22mm ISO Taper	P/N 1602292 (Models 40211, 40212)
	Inlet Filter, 0.25" tube, 6mm	P/N 1602317 (Models 41211, 41212, 41216)
	Inlet Filter, 0.375" tube, 9mm	P/N 1602342 (Models 41221, 41222, 41226)

Specifications subject to change without notice. See Operator's Manual for full listing.

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Home / Heat Sinks

Heatsink, 14 X 14mm X 6mm, Adhesive Backed

Stock No: 31973 HK

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Availibilty: **In Stock** Units: **529**

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Detailed Description

Mini natural aluminum heatsinks for D-PAC, flatpac components.Peel-n-stick adhesive backing.
Surface area:~1.2sq/in
Sq: 14mm **H:** 6mm **WT:** .004

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Stanley Fixed-Blade Utility Knife

Manufacturer Model Number 10-209

In stock
$7.03 Each
3678A11

For Cutting	Gaskets, Rope, Sheets, Twine, Webbing, Wire Cloth
For Use On	Cardboard, Cork, Fabric, Leather, Paper, Plastic, Rubber
Manufacturer	Stanley
Manufacturer Model Number	10-209
Blade Type	Fixed
Blade	
Length	2 1/2"
Width	3/4"
Thickness	0.024"
Material	Steel
Edge	Straight
Blades Replaceable	Yes
Blade Position	Blade Fully Extended
Number of Blades Included	3
Blade Storage Location	Handle
Overall Length	5 1/2"
Handle	
Material	Metal
Color	Gray
Type	Straight
Grip Texture	Knurled

View our offering of replacement blades.

CE

User's Guide

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It is the policy of OMEGA to comply with all worldwide safety and EMC/EMI regulations that apply. OMEGA is constantly pursuing certification of its products to the European New Approach Directives. OMEGA will add the CE mark to every appropriate device upon certification.

GENERAL INFORMATION

This manual provides information on the use of three digital handheld thermometers. Functional features both common and unique to each model are described.

All three models are microprocessor based, and provide accurate and reliable operation. They function with the most popular thermocouples; types K, J, and T. A variety of features in these projects enhance their versatility, while simplifying operation.

It is recommended that you read this manual thoroughly, especially the sections on safety, prior to operating these instruments.

SPECIFICATIONS

THERMOCOUPLE INPUTS: 2 (T1, T2) miniature TC connectors.
Accepts male miniature and subminiature TC connectors.

THERMOCOUPLE TYPES: K, J, T

READOUT: T1, T2, T1-T2, and SCAN (T1, T2, T1-T2).

ACCURACY: (18°C to 28°C ambient, 2 years, excludes thermocouple error).

TC Type	Range	Resolution	Accuracy (T1, T2)	Accuracy (T1-T2)	Extended Temp. Range Acc'y (T1, T2), Typ.
K	–200°C to 1372°C –328°F to 2502°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	–200°C to –250°C, ±(3°C) –328°F to –418°F, ±(5°F)
J	–210°C to 760°C –346°F to 1400°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	— —
T	–200°C to 400°C –328°F to 752°F	0.1/1°C 0.1/1°F	±(0.1% rdg + 0.6°C) ±(0.1% rdg + 1.0°F)	Acc'y (T1) + Acc'y (T2) Acc'y (T1) + Acc'y (T2)	–200°C to –250°C, ±(3°C) –328°F to –418°F, ±(5°F)

REPEATABILITY: ±0.2°C typical for 1 week at constant ambient temperature.

TEMPERATURE COEFFICIENT: 18°C to 28°C; included in accuracy specification. From 0°C to 18°C, and 28°C to 50°C; less than ±(0.02% rdg + 0.1°C)/°C.

ENVIRONMENTAL LIMITS FOR OPERATING: 0°C to 50°C, less than 80% relative humidity (R.H.) up to 35°C; reduce R.H. limit by 3%/°C from 35°C to 50°C.

ENVIRONMENTAL LIMITS FOR STORAGE: –35°C to 60°C, less than 90% relative humidity (R.H.) up to 35°C; reduce R.H. limit by 3%/°C from 35°C to 60°C.

INPUT CURRENT: 50 nA typical.

READING RATE: (T1, T2, T1-T2); 1 reading/second typical, all parameters.

MAXIMUM COMMON MODE VOLTAGE: 42V peak to earth.

POWER: 9 volt transistor battery (NEDA 1604).

BATTERY LIFE, CONTINUOUS: 50 hrs typical, carbon-zinc; 100 hrs typical, alkaline; 200 hrs typical, lithium; 15 hrs typical, Ni-Cd (rechargeable).

BATTERY INDICATOR: Display indicates BAT when less than 10% of life remains.

DISPLAY: 5 digit LCD, 0.4" height. Polarity indication, and decimal point.

Annunciators

- Readout Parameter: T1, T2, T1-T2, SCAN
- Record Parameter: MIN or MAX (when viewing recorded data).
- Readout Scale: °F, °C
- TC Type: K, J, T
- Hold (when activated)
- Reading Trend: up-arrow for increasing readings, down-arrow for decreasing readings. Both arrows on for stable reading.
- Record MIN/MAX readings for T1, T2, and/or T1-T2; Flashing annunciator indicates data being collected. Steady annunciator indicates data available, but not being up-dated.

KEYPAD: 9 momentary switches with tactile feedback select;

- Power ON/OFF
- Readout: T1, T2, T1-T2, or SCAN
- TC type: K, J, T
- Readout scale: °F/°C
- Resolution: 0.1°/1°
- Display Hold
- Record MIN/MAX
- View MIN/MAX
- Stop recording MIN/MAX (first keystroke), clear recorded MIN/MAX (second keystroke)

POWER OFF CONFIGURATION RETENTION: Instrument retains last selected;

- Readout: T1, T2, T1-T2, SCAN
- TC type: K, J, T
- Resolution: 0.1°/1°
- Scale: °F/°C

DIAGNOSTICS: Display codes indicate the following conditions:

- Low Battery: ‘BAT’
- Open Thermocouple(s): ‘OPEN’
- Invalid Keypad Entry: Momentary ‘E-1’
- Temperature Reading exceeds TC Rating: ‘E-2’
- Internal Hardware Fault: ‘E-3’ (consult factory)
- LCD Test: During power-up, all segments/annunciators turned on momentarily.

ELECTROMAGNETIC COMPATIBILITY: Add ±0.5% of range to accuracy specifictions for RF fields up to 1 volt/meter. Accuracy not specified for fields greater than 1 volt/meter.

DIMENSIONS, WEIGHT: 7.0" x 2.9" x 1.1". Net weight 10 oz.

DIFFERENCE SPECIFICATIONS

MODEL HH-21:

THERMOCOUPLE INPUTS: 1

DISPLAY: 5 digit LCD, 0.4" height. Polarity indication, and decimal point.

Annunciators
- Readout Scale: °F, °C
- TC Type: K, J, T
- Hold (when activated)

KEYPAD: 5 momentary switches with tactile feedback select;
- Power ON/OFF
- TC type: K, J, T
- Readout scale: °F/°C
- Resolution: 0.1°/1°
- Display Hold

POWER OFF CONFIGURATION RETENTION: Instrument retains last selected;
- TC type: K, J, T
- Resolution: 0.1°/1°
- Scale: °F/°C

MODEL HH-22:

THERMOCOUPLE TYPES: K, J

Thermocouple Wire

Duplex Insulated

"SLE" Special Limits of Error Available

ANSI color code shown

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K

Duplex Insulated
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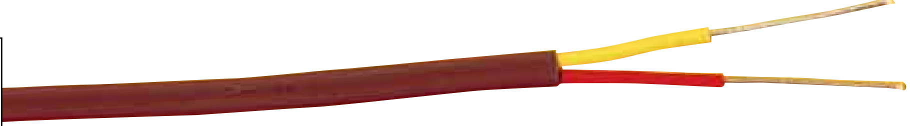
Duplex ANSI Type K



ANSI Color Code: Positive Wire, Yellow; Negative Wire, Red; Overall, Brown

OMEGA Engineering does not use reprocessed PFA or PVC in manufacturing thermocouple wire

Insulation	AWG No.	Model Number	Type Wire	Insulation		Max. Temp		Nominal Size	Wt.† kg/300 m (lb/1000')
				Conductor	Overall	°C	°F	mm (inch)	
Ceramic*	14	**XC-K-14**	Solid	Nextel Ceramic	Nextel Ceramic	1090	2000	3.6 x 5.0 (0.140 x 0.200)	18 (38)
	20	**XC-K-20**	Solid			980	1800	3.4 x 4.8 (0.135 x 0.190)	8 (16)
	20	**XT-K-20**	Solid			980	1800	2.7 x 3.9 (0.105 x 0.155)	7 (15)
	20	**XL-K-20**	Solid			980	1800	2.4 x 3.4 (0.095 x 0.135)	7 (14)
	24	**XC-K-24**	Solid			870	1600	2.9 x 4.4 (0.115 x 0.175)	6 (12)
	24	**XT-K-24**	Solid			870	1600	2.2 x 3.4 (0.088 x 0.132)	5 (11)
	24	**XL-K-24**	Solid			870	1600	2.0 x 3.0 (0.078 x 0.116)	5 (10)
Vitreous Silica*	20	**XR-K-20**	Solid	Refrasil	Refrasil	870	1600	2.9 x 4.6 (0.115 x 0.180)	6 (14)
Silica*	14	**XS-K-14**	Solid	Silica	Silica	1090	2000	3.6 x 5.0 (0.140 x 0.200)	16 (35)
	20	**XS-K-20**	Solid			980	1800	2.7 x 3.9 (0.105 x 0.155)	6 (12)
	24	**XS-K-24**	Solid			870	1600	2.2 x 3.4 (0.088 x 0.132)	5 (10)
High Temp. Glass**	20	**HH-K-20**	Solid	High Temp Glass	High Temp Glass	871	1600	1.5 x 2.7 (0.060 x 0.105)	4 (9)
	24	**HH-K-24**	Solid			871	1600	1.4 x 2.3 (0.055 x 0.090)	3 (5)
Glass	20	**GG-K-20**	Solid	Glass Braid	Glass Braid	482	900	1.5 x 2.1 (0.060 x 0.095)	4 (9)
	20S	**GG-K-20S**	7 x 28	Glass Braid		482	900	1.5 x 2.5 (0.060 x 0.100)	4 (9)
	24	**GG-K-24**	Solid	Glass Braid		482	900	1.3 x 2.0 (0.050 x 0.080)	3 (5)
	24S	**GG-K-24S**	7 x 32	Glass Braid		482	900	1.3 x 2.2 (0.050 x 0.085)	3 (5)
	26	**GG-K-26**	Solid	Glass Wrap		482	900	1.1 x 1.9 (0.045 x 0.075)	2 (4)
	28	**GG-K-28**	Solid	Glass Wrap		482	900	1.0 x 1.4 (0.040 x 0.055)	2 (3)
	30	**GG-K-30**	Solid	Glass Wrap		482	900	0.9 x 1.3 (0.037 x 0.050)	2 (3)
	36	**GG-K-36**	Solid	Glass Wrap		482	900	0.8 x 1.1 (0.033 x 0.045)	1 (2)
Glass with Stainless Steel Overbraid	20	**GG-K-20-SB**	Solid	Glass	Stainless Steel Braid over Glass	482	900	2.3 x 3.0 (0.090 x 0.120)	6 (14)
	20S	**GG-K-20S-SB**	7 x 28			482	900	2.3 x 3.2 (0.090 x 0.127)	7 (15)
	24	**GG-K-24-SB**	Solid			482	900	2.2 x 3.0 (0.085 x 0.117)	5 (11)
	24S	**GG-K-24S-SB**	7 x 32			482	900	2.0 x 2.8 (0.080 x 0.110)	5 (11)
Kapton Fused Polymide Tape	20	**KK-K-20**	Solid	Fused Polymide Tape	Fused Polymide Tape	260	500	1.5 x 2.5 (0.060 x 0.100)	5 (11)
	20S	**KK-K-20S**	7 x 28			260	500	1.5 x 2.7 (0.060 x 0.105)	5 (11)
	24	**KK-K-24**	Solid			260	500	1.3 x 1.9 (0.050 x 0.075)	3 (6)
	24S	**KK-K-24S**	7 x 32			260	500	1.3 x 2.2 (0.050 x 0.085)	3 (6)
	30	**KK-K-30**	Solid			260	500	1.0 x 1.4 (0.040 x 0.055)	3 (5)
PFA Glass	30	**TG-K-30**	Solid	PFA	Glass Braid	260	500	0.9 x 1.2 (0.034 x 0.047)	1 (2)
	36	**TG-K-36**	Solid			260	500	0.7 x 1.0 (0.028 x 0.038)	1 (2)
	40	**TG-K-40**	Solid			260	500	0.7 x 0.9 (0.026 x 0.035)	1 (2)
Neoflon PFA (High Performance)	20	**TT-K-20**	Solid	PFA	PFA	260	500	1.7 x 3.0 (0.068 x 0.116)	5 (11)
	20	**TT-K-20S**	7 x 28			260	500	1.9 x 3.2 (0.073 x 0.126)	5 (11)
	22	**TT-K-22S**	7 x 30			260	500	1.7 x 3.4 (0.065 x 0.133)	4 (9)
	24	**TT-K-24**	Solid			260	500	1.4 x 2.4 (0.056 x 0.093)	3 (6)
	24	**TT-K-24S**	7 x 32			260	500	1.6 x 2.6 (0.063 x 0.102)	3 (6)
	30	**TT-K-30††**	Solid			260	500	0.6 x 1.0 (0.024 x 0.040)	1 (2)
	36	**TT-K-36††**	Solid			260	500	0.5 x 0.8 (0.019 x 0.030)	1 (2)
	40	**TT-K-40††**	Solid			260	500	0.4 x 0.7 (0.017 x 0.026)	1 (2)
PFA Polymer w/Twisted and Shielded Conductors	20	**TT-K-20-TWSH**	Solid	PFA Polymer	PFA Polymer and Shielding	260	500	3.7 (0.15)	9 (20)
	20S	**TT-K-20S-TWSH**	7 x 28			260	500	3.8 (0.15)	9 (20)
	24	**TT-K-24-TWSH**	Solid			260	500	2.7 (0.11)	4 (9)
	24S	**TT-K-24S-TWSH**	7 x 32			260	500	2.9 (0.12)	4 (9)
Neoflon FEP	20	**FF-K-20**	Solid	FEP	FEP	200	392	1.7 x 3.0 (0.068 x 0.116)	5 (11)
	24	**FF-K-24**	Solid			200	392	1.7 x 3.0 (0.056 x 0.092)	3 (6)
FEP Polymer w/Twisted and Shielded Conductors	20	**FF-K-20-TWSH**	Solid	FEP Polymer	FEP Polymer and Shielding	200	392	3.7 (0.15)	9 (20)
	20S	**FF-K-20S-TWSH**	7 x 28			200	392	3.8 (0.15)	9 (20)
	24	**FF-K-24-TWSH**	Solid			200	392	2.7 (0.11)	4 (9)
	24S	**FF-K-24S-TWSH**	7 x 32			200	392	2.9 (0.12)	4 (9)
TFE Tape Polymer	20	**TFE-K-20**	Solid	TFE Tape Polymer	Fused TFE Tape Polymer	260	500	1.5 x 2.5 (0.060 x 0.100)	5 (11)
	20S	**TFE-K-20S**	7 x 28			260	500	1.5 x 2.7 (0.060 x 0.105)	5 (11)
	24	**TFE-K-24**	Solid			260	500	1.3 x 1.9 (0.050 x 0.075)	3 (6)
	24S	**TFE-K-24S**	7 x 32			260	500	1.3 x 2.2 (0.050 x 0.085)	3 (6)
Polyvinyl	24	**PR-K-24**	Solid	Polyvinyl	(Rip Cord)***	105	221	1.4 x 2.3 (0.050 x 0.086)	3 (5)
	24	**PP-K-24S**	7 x 32		(Polyvinyl)	105	221	2.0 x 3.4 (0.082 x 0.134)	3 (5)

† Weight of spool and wire rounded to the next highest kg (lb) (does not include packing material). *†† Overall color clear.*
*††† To order special limits of error wire, add **"-SLE"** to model number before spool length.* ** Has color tracers on jacket and conductors.*
*** HH Wire has trace thread in positive leg, negative leg is red, overall has trace thread.* **** Two insulated leads bonded together, but with no overwrap.*
Additional Type K insulated wires are available. See Fused Tape Insulated TFE-K and KK-K Series.
***Ordering Example: XC-K-20-SLE-1000,** 1000' (300 m) of Type K duplex insulated special limits of error thermocouple wire.*

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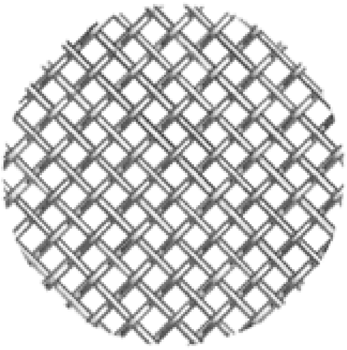
Corrosion-Resistant 304 Stainless Steel Wire Cloth Disc

9317T81

Medium Diameter, 20 x 20 Mesh, .016" Wire Diameter



Mesh Size	20 × 20
Opening Size	0.034"
Open Area	46%
Wire Diameter	0.016"
Diameter	2 1/2", 2 1/4", 2 3/8", 2 9/16", 2", 3 9/16", 3", 4 9/16", 4"
Additional Specifications	Package quantity is 10 for 4" Diameter and 4 9/16" Diameter

A convenient solution for inline filtering, discs are die cut for an exact diameter with smooth edges for use in tube, pipe, and duct. They're made from our popular Type 304 stainless steel wire cloth, which has good corrosion and abrasion resistance. Discs are often used as replacement screens in plastic extruders.

2 Lb. Polyurethane Mix and Pour Foam

Part # - 24/25

For Floatation, Sculpting, and Cavity Filling

Our #24/25 is a two-part, equal mix, self-rising, 2lb/ cu. ft. density closed-cell foam system. Foaming begins within 45 seconds after the two liquids are mixed and continues for several more minutes. The foam expands approximately 30 times its liquid volume before curing, and will fill any shape cavity. It does not react with oil or gasoline and it will not absorb water. #24/25 is ideal for floatation applications and provides 60 pounds of floatation per cubic foot of foam. Unlike polyester foams, polyurethane foam is compatible with both polyester and epoxy resins. This foam is designed to meet USCG Title 33, Chapter 1, Part 183.

Properties of "#25" SIDE	
Appearance	Dark brown liquid
Odor	Slight Amine
Density, @ 77° F	10.2 lbs / gal
Viscosity, @ 77° F	200 cps
Flash Point	>400° F
Vapor Pressure, at 20° C	0.00016 mm Hg

Properties of "#24" SIDE	
Appearance	Amber liquid
Odor	Amine
Density, @ 55° F	9.1 lbs / gal
Viscosity, @ 73° F	450 cps
Flash Point, ASTM 3278-89	>200° F
HFC-245fa, % Resin	7.6 %

Application	
Mix Ratio: Parts by Weight	89 ñ#24òSide / 100 ñ#25òSide

Foam Reactivity & Density	**Hand mix**	**High-Pressure**
Jiffy Mixer RPM	1720	--
Component Pressures, ñ#24òSide / ñ#25òSide	--	1500 psi / 1500 psi
Component Temps, ñ#24òSide / ñ#25òSide	55° F / 70° F	70° F / 70° F
Mix time, seconds	20	--
Cream time, seconds	34	10
Gel time, seconds	180	55
Tack Free time, seconds	220	120
Free Rise Density, #10 Cup, lb/ft^3	2.0	2.0

Typical Physical Properties		**ASTM**
Molded Panel		
Core Density, pcf	3.0	D-1622
Compressive Strength, psi	34	D-1621
Perpendicular:		
Compressive Strength @10% deflection, psi	28	D-1621
Compressive Modulus, psi	669	D-1621
Tensile Strength, psi	52	D-1623
Moisture Vapor Transmission	11	D-1623
Water absorption, lbs./sq ft	0.06	D-2842
Closed Cells, %	94	NCFI TM-300
K Factor, BTU-IN / HR-FT2-°F		
Aged	0.21	C-518
UL® 94 Flame Class (File E112987)	HBF	

Dimensional Stability, % Volume Change		**ASTM**
158° F/ 100% RH		
28 Days	-1.0	D-2126
200° F		
28 Days	-1.0	D-2126
-20° F		
28 Days	-0.5	D-2126

Certification:

U.S. Coast Guard: (CGD 75- 168) Flotation Material

Rigid polyurethane samples prepared from this foam have been tested at an independent laboratory. Molded samples have passed the U.S. Coast Guard immersion test (CGD 75-168), and meet or exceed performance criteria set out in D.O.T. ï Coast Guard ï Flotation Materials, Par. 183.144, Federal Regulations Volume 43, No. 233, 1/5/2005

U.S. Coast Guard: (CITE: 33CFG183.516) Encase Fuel Tanks.

Rigid polyurethane foam samples have been tested by an independent laboratory. Molded samples have passed the ASTM D-471 and Military specification MIL P-21929B sections of 33CFG183.516. 12/23/2005.

Linear D.C. Power Supply

The GPS-Series is single output, 54W to 90W, linear DC power supplies. The GPS-Series includes both analog and digital display meters with varying power outputs. The GPS-Series features overload and reverse polarity protection as well as high regulation and low ripple/noise that are maintained at 0.01% and < 1mVrms, respectively. Continuous or dynamic internal load selection accommodates applications such as pulsed current. Remote control terminals offer programming and operation from an external device.

GPS-1830D/1850D/3030D

CE

GPS-1850/3030

CE

GPS-3030DD

CE

SPECIFICATIONS	
CONSTANT VOLTAGE OPERATION	
Regulation	Line regulation≤0.01% + 3mV Load regulation≤0.01% + 3mV (rating current≤3A) ≤0.01% + 5mV (rating current>3A)
Ripple & Noise	≤0.5mVrms 5Hz ~ 1MHz (rating current≤3A) ≤1mVrms 5Hz ~ 1MHz (rating current>3A)
Recovery Time	≤100µS (50% load change, minimum load 0.5A)
Temp. Coefficient	≤300 ppm /°C
Output Range	0 to rating voltage continuously adjustable
CONSTANT CURRENT OPERATION	
Regulation	Line regulation≤0.2% + 3mA Load regulation≤0.2% + 3mA
Ripple Current	≤3mArms
Output Range	0 to rating current continuously adjustable (Hi / Lo range switchable)
METER	
Analog	V-meter and I-meter 2.5 class Dimensions 50 x 50 mm
Digital	3½ digits 0.5" LED display (GPS-1830D/1850D/3030D) 3½ digits 0.39" LED display (GPS-3030DD) Accuracy±(0.5% of rdg + 2 digits)
INSULATION	
Chassis and Terminal	20MΩ or above (DC 500V)
Chassis and AC Cord	30MΩ or above (DC 500V)
POWER SOURCE	
AC 100V/120V/220V/240V±10%, 50/60Hz	
DIMENSIONS	
128(W) x 145(H) x 285(D) mm	

FEATURES

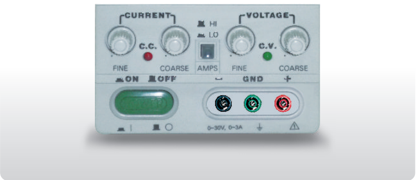
- ✲ Light and Compact Design
- ✲ 0.01% High Regulation
- ✲ Constant Voltage and Constant Current Operation
- ✲ Remote Control for External Programmability
- ✲ Internal Select for Continuous or Dynamic Load
- ✲ Low Ripple and Noise
- ✲ Overload and Reverse Polarity Protection
- ✲ Series or Parallel Operation
- ✲ Optional European Type Jack Terminal for GPS-3030/GPS-3030D/GPS-3030DD

ORDERING INFORMATION

Model		Output Volts(V)	Output Amps(A)	Weight (kg)
GPS-1850	90W D.C. Power Supply	0 ~ 18	0 ~ 5	5.5
GPS-3030	90W D.C. Power Supply	0 ~ 30	0 ~ 3	5
GPS-1830D	54W D.C. Power Supply	0 ~ 18	0 ~ 3	4
GPS-1850D	90W D.C. Power Supply	0 ~ 18	0 ~ 5	5
GPS-3030D	90W D.C. Power Supply	0 ~ 30	0 ~ 3	5
GPS-3030DD	90W D.C. Power Supply	0 ~ 30	0 ~ 3	5

ACCESSORIES :
User manual x 1 , Power cord x 1
Test lead GTL-105A x 1 (≤3A) or GTL-104A x 1 (≤10A)
European test lead GTL-203A x 1 (≤ 3A)or GTL-204A x 1 (≤10A)

European Type Jack Terminal



DIY Projects & Ideas   Credit Services   Pro Xtra   Store Finder   Order Status   Local Ad

Products and Services   What can we help you find?   Your Store San Luis Obispo   Sign in or Register

Oatey | Model # 310133 | Internet # 100345577 | Store SKU # 187100

8 oz. PVC Cement

★★★★★ (10) | **Write a Review** | **Questions & Answers (3)**

$4.94 /each

IN STOCK AT YOUR SELECTED STORE

San Luis Obispo #1052
San Luis Obispo, CA 93405

30 **In Stock**
Aisle 16, Bay 005
Text Product Location

Open Expanded View   Click Image to Zoom

PRODUCT OVERVIEW

Model # 310133 | Internet # 100345577 | Store SKU # 187100 | Store SO SKU # 125490

The Oatey 8 oz. PVC Cement is specially formulated to bond PVC pipe and fittings up to 6 in. Dia with interference fit. The solvent cement works by softening pipe and fitting surfaces to create a strong bond. Includes a dauber stem for easy application.

- Regular-bodied clear cement for use on all schedules and classes of PVC pipe and fittings up to 4 in. for Sch. 40 and up to 2 in. for Sch. 80
- Lo-V.O.C. solvent cement meets California South Coast Air Quality Management District (SCAQMD) 1168/316A or BAAQMD method 40 and various environmental requirements
- Recommended for potable water, pressure pipe, conduit and DWV
- Recommended application temperature 40Â°F to 110Â°F / 4Â°C to 43Â°C
- Meets ASTM D-2564

SPECIFICATIONS

DIMENSIONS

Product Depth (in.)	1	Product Width (in.)	1
Product Height (in.)	1		

DETAILS

Applicator in lid	Yes	Pipe Material/Type	PVC
Colored	Yes	Quantity (oz.)	8
Maintenance, Repair & Supplies Product Type	Pipe Cement, Primer & Cleaner	Returnable	90-Day

WARRANTY / CERTIFICATIONS

Manufacturer Warranty	2 years

MORE PRODUCTS WITH THESE FEATURES

Price: **$0 - $10**

Brand: **Oatey**

Review Rating: **4 & Up**

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Feedback

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Lightweight Scissors

8" Overall Length

In stock
$11.72 Each
7091A11

For Cutting	Gaskets, Rope, Sheets, Strapping, Twine, Webbing, Wire Cloth
For Use On	Cardboard, Fabric, Leather, Paper, Plastic, Rubber
Overall Length	8"
Cut Length	3"
Blade Material	Uncoated Stainless Steel
Handle Material	Plastic
Handle Type	Straight
Opening Style	Manual
Handedness	Right
Blade Tip Shape	Pointed
Blade Edge	Straight/Straight

These stainless steel scissors are corrosion-resistant.

DIY Projects & Ideas Credit Services Pro Xtra Store Finder Order Status Local Ad

Products and Services What can we help you find? Your Store San Luis Obispo Sign in or Register

GREAT STUFF | Model # 345372 | Internet # 202023037 | Store SKU # 574958

16 oz. Fireblock Insulating Foam Sealant

★★★★☆ (59) | **Write a Review** | **Questions & Answers** (19)

Open Expanded View Click Image to Zoom

$6.98 **/each**

- Save money and time by using this fire code approved formula
- Air-sealing and insulating saves up to 20% on home energy costs
- 16 oz. Fireblock Insulating Foam Sealant

IN STOCK AT YOUR SELECTED STORE

San Luis Obispo #1052
San Luis Obispo, CA 93405

51 **In Stock**
Aisle BW, Bay 035
Text Product Location

PRODUCT OVERVIEW

Model # 345372 | Internet # 202023037 | Store SKU # 574958

GREAT STUFF Fireblock Insulating Foam Sealant can save much more than energy costs. By sealing the pipe, cable and duct penetrations, you minimize airflow. During a fire, that means flames, harmful gasses and toxic smoke cannot spread as quickly. And in an emergency, that could make all the difference. The fact that it helps you conserve energy, reduce drafts and save on heating and cooling costs is great too.

- Impedes spread of fire and smoke through service penetrations
- Recognized as an alternate fireblocking material for residential construction; tested according to ASTM E84, ASTM E814 (Modified), UL 1715
- Seals service penetrations between floors and electrical runs through wall studs
- Airtight, water-resistant and has exceptional adhesion to building materials
- Tack free in 6 minutes; trims in 30 minutes; cures rigid in 8 hours
- Bright orange colored foam for easy code identification
- All-direction dispensing

SPECIFICATIONS

DIMENSIONS

Product Depth (in.)	3	Product Width (in.)	3
Product Height (in.)	9.5		

DETAILS

Insulation R-Value	2	Product Weight (oz.)	16 oz
Insulation Type	Spray Foam	Returnable	90-Day
Paintable / Stainable	Paintable/Stainable	Two Part	No

WARRANTY / CERTIFICATIONS

ENERGY STAR Certified	Yes	Warranty Information	NA
Fire Block Rated	Yes		

MORE PRODUCTS WITH THESE FEATURES

Insulation Type: **Spray Foam**

Insulation R-Value: **2**

Brand: **GREAT STUFF**

Price: **$0 - $10**

Review Rating: **4 & Up**

SEARCH

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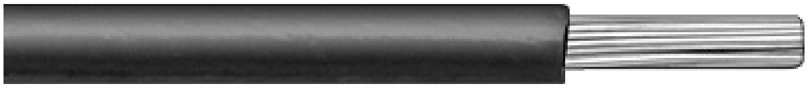
Stranded Wire

8054T17

300V AC, 14 Gauge



Wire Gauge	14
Amps @ 86° F	33
OD	0.11"
Color	Black, Blue, Brown, Gray, Green, Green/Yellow, Orange, Purple, Red, White, Yellow
Length	25 ft., 50 ft., 100 ft., 200 ft., 500 ft.
Temperature Range	-40° to 220° F
Insulation	PVC
Additional Specifications	Stranded Wire—300V AC Stranded Wire: Flexible; Solid Wire: Bend and stay
RoHS	Compliant

Also known as hook-up wire, this general purpose wire is for internal wiring of electrical panels and electronics. Flame rated VW-1. UL recognized and CSA certified.

300V AC—Meets UL 1007/1569.

Appendix E - Example Calculations

Error

The heat transfer equation used for our model is:

$$q = \dot{m} c_p \Delta \mathrm{T}$$

Where:

q= heat lost from the ESC (J/s)

$\dot{m}$= mass flow rate of air (kg/s)

c_p= specific heat capacity of air (J/kg K)

ΔT= differential temperature between inlet and outlet (˚C)

Table 1. The values considered for error in the equation above along with the instrument errors.

Parameter	**Value based on Trial 7 of POC exp.**	**Instrument**	**Accuracy**		**Resolution Error**	**Total error (RSS)**
			Percent	**Actual**		
$\dot{V}$	18.5 L/min	TSI Thermal Mass Flowmeter Model 4045	±2%	±0.37 L/min	±0.005 L/min	±0.37 L/min
ΔT	4.4 ˚C	Omega RTD Thermometer Model HH804	±0.1% +0.6 ˚C	±0.6044 ˚C	±0.05 ˚C	±0.6˚C
		Thermocouple wire Duplex Insulated Type K	N/A		N/A	
c_p	1.005 kJ/kg K	Table, @ 25 ˚C	N/A		±0.0005 kJ/kg K	±0.0005 kJ/kg K

First the heat loss is calculated, based on the values from **Table 1**. These measured values come from the Proof of Concept (POC) experiment completed on January 24, 2016. In this experiment, Trial 7 had the highest temperature change which allows for the lowest error associated with the RTD thermometer and sensor. In the POC experiment, thermocouples were used instead of the RTD thermometer, and an anemometer was used instead of the TSI mass flowmeter. However, this will not affect the calculations of error predicted for the actual experiment using the desired instruments above.

1) Convert volumetric flowrate to mass flowrate:

$$\dot{m} = \dot{V} \rho$$

$$\dot{m} = \left(18.5 \, \frac{L}{\mathrm{min}}\right)\left(1.205 \frac{kg}{m^3}\right)\left(\frac{1 \, m^3}{1000 \, L}\right)\left(\frac{min}{60\mathrm{sec}}\right)$$

$$\dot{m} = 0.00037 \frac{kg}{s}$$

2) Calculate heat:

$$q = \dot{m} c_p \Delta \mathrm{T}$$

$$q = (0.00037 \frac{kg}{s})(1.005 \frac{kJ}{kg \, K})(4.4 \, K)$$

$$q = 1.64 \, Watts$$

Next, the propagation of error due to multiplication, is calculated, where *dx* represents total error of each instrument, found in **Table 1** and *x* represents the measured value:

$$\frac{dq}{q} = \sqrt{\left(\frac{d\dot{V}}{\dot{V}}\right)^2 + \left(\frac{\mathrm{d}(\Delta \mathrm{T})}{\Delta T}\right)^2 + \left(\frac{dc_p}{c_p}\right)^2}$$

$$\frac{dq}{q} = \sqrt{\left(\frac{0.37}{18.5}\right)^2 + \left(\frac{0.6}{4.4}\right)^2 + \left(\frac{0.0005}{1.005}\right)^2}$$

$$\frac{dq}{q} = 0.14$$

$$\boldsymbol{error} = \mathbf{14\%}$$

Therefore, in the case of Trial 7 of our POC experiement:

$$q = 1.64 \pm 0.23\ Watts$$

We expect less error in future runs because the temperature difference will be greater, giving us less error.

Heat Loss through Conduction

The flow rig involves a pipe that would contain the ESC (heat source), through which air would flow. This pipe will be insulated to minimize heat loss. If the cylinder were modeled to have a uniform inner surface temperature equal to the expected outlet temperature, we could use the below formula to calculate heat loss.

$$q = \frac{2\,\pi k\,(T_i - T_0)l}{\ln\left(\frac{r_o}{r_i}\right)}$$

Where:
q = heat transferred per unit time (W)
k = thermal conductivity (W/mK)
T_i = temperature inside pipe (°C)
T_o = temperature outside pipe (°C)
r_o = outer radius (m)
r_i = inner radius (m)
l = length of pipe

The assumption of uniform surface temperature being equal to the outlet temperature represents a worst-case scenario. In reality the inlet air would be room temperature until it had been heated by the ESC. Real operation of the flow rig would result in a lower amount of heat loss. An example calculation with reasonable operating parameters is shown below:

k = 0.03 W/mK for insulating foam
T_i = 30°C
T_o = 20°C
r_o = 0.1 m
r_i = 0.04 m
l = 0.15

$$q = \frac{2\,\pi\left(0.03\,\frac{W}{mK}\right)\,(30\text{°C} - 20\text{°C})(0.15m)}{\ln\left(\frac{0.1m}{0.04m}\right)}$$

$$\boldsymbol{q_{loss} = 0.31\,Watts}$$

As a percentage of our expected 5W output, this yields a 6.2% heat loss**.** It is important to note that the values used in this calculation does not reflect the same values used in the error calculations because we expect the heat loss to be ‘better’ than the POC experiment in which a large Styrofoam box was used to contain the ESC.

Heat Loss through Radiation

The Stefan-Boltzmann equation below shows us how much heat will be emitted as radiation from our ESC.

$$q = \epsilon\sigma A\left(T_a^4 - T_b^4\right)$$

Where:

q = heat transferred per unit time (W)

ϵ = emissivity, assumed for Aluminum Commercial Sheet material

σ = 5.67*10^{-8} W/(m^2K), the Stefan-Boltzmann Constant

T_a = temperature of the ESC (K)

T_b = temperature of surroundings (K)

A = surface area of the object

$$q = (0.09) * (5.67 * 10^{-8}\,W/mK) * (0.00827m^2) * (323K^4 - 300K^4) = 0.11W$$

This represents about 2% of the total heat loss of the ESC. Much of this radiative heat can be retained with a reflective coating on the inside of the flow pipe.

Appendix F - Cost Analysis

ESC Efficiency Rig Project Total Spending

Item	Vendor	Model #	Description	Qty	Price	Ship/Tax	Total
TSI Mass Flowmeter	tsi.com	40241	Measures mass flow	1	$ 926.25	$ 74.10	$1,000.35
16 oz. GREAT STUFF Fireblock Spray Foam	Home Depot	345372	Polyurethane spray foam	2	$ 6.98	$ -	$ 13.96
2 Lb. Polyurethane Mix and Pour Foam	Fibre Glast	24/25-A	Pourable polyurethane foam, two-part kit	1	$ 34.95	$ 9.95	$ 44.90
1"x12"x6' Common Board	Home Depot	N/A	Supports rig	1	$ 11.97	$ -	$ 11.97
Omega Handheld Microprocessor Digital Thermometer	N/A	HH-23	Displays the temperature	1	$ -	$ -	$ -
Thermocouple Wire Duplex Insulated Type K	N/A	PR-K-24	Detects temperature change	1	$ -	$ -	$ -
DC Equipment Cooling Fan, 20 CFM	McMaster-Carr	1939K57	Creates flow for rig	1	$23.75	$ -	$ 23.75
DC Equipment Cooling Fan, 7 CFM	McMaster-Carr	1939K22	Creates flow for rig	1	$ 25.98	$ -	$ 25.98
Silicone Rubber Heater	Minco Components.com	HR6926	Validation Heater, 2"x3", 14.75 ohm	2	$ 49.80	$ 9.95	$ 109.55
GW Laboratory DC Power Supply	N/A	GPS-3030D	Provides power for all electronic devices	3	$ -	$ -	$ -
8 oz. Oatley PCV Cement	Home Depot	310133	Connects PVC piping	1	$ 4.94	$ -	$ 4.94
14 x 14mm x 6mm Heatsink	Marlin P. Jones & Assoc.	31973 HK	Apply to heater	12	$ 0.25	$ -	$ 3.00
3" x 2 ft VPC PCV Sch. 40 pipe	Home Depot	2203	Will contain the ESC	1	$9.99	$ -	$ 9.99
3 in. x 1-1/2 in. PVC DWV Reducing Coupling	Home Depot	C4801HD3112	Pipe reducer for rig	6	$ 4.41	$ -	$ 26.46
1-1/2in x 5 ft Formufit Furniture Grade Sch. 40 PVC Pipe in White	Home Depot	P112FGP-WH-5	pipe for rig	1	$ 10.86	$ -	$ 10.86
1-1/2 in x 3/4 in Charlotte Pipe PVC Sch. 40 Reducer Bushing	Home Depot	PVC021081600 HD	Pipe reducer for rig	6	$1.62	$ -	$ 9.72
3/4 in x 10 ft JM eagle PVC Schedule 40 Plain-End Pipe	Home Depot	57471	pipe for rig	1	$ 2.42	$ -	$ 2.42
3/4 in . Charlotte Pipe PVC Sch. 40 S x S Coupling	Home Depot	PVC021000800 HD	Pipe reducer for rig	6	$ 0.22	$ -	$ 1.32
Sioux Chief, 1 in. x 3/4 in. Vinyl Braided Tubing, 10 ft length	Home Depot	900-02306C00101	Tube to connect to flow meter	1	$ 21.32	$ -	$ 21.32
SAKRETE 8 in. x 48 in. Concrete Form Tube	Home Depot	65470075	Tube mold for foam	1	$ 6.92	$ -	$ 6.92
General Purpose Duct Tape	McMaster-Carr	76135A48	Tape to bind fans and seal junctions	2	$ 5.57	$ -	$ 11.14
Electrical Tape, 20 Yards	McMaster-Carr	7619A11	Tape for sealing junctions and wires	2	$ 1.06	$ -	$ 2.12
Stanley Fixed-Blade Utility Knife	McMaster-Carr	3678A11	Tool for cutting	1	$ 7.03	$ -	$ 7.03
Scissors	McMaster-Carr	7091A11	Tool for cutting	1	$ 11.72	$ -	$ 11.72
Aligator Clips	McMaster-Carr	7236K55	Connects wires to power supply	16	$ 0.58	$ -	$ 9.28
Stranded Wire - 300V AC, 14 Gauge, Green/Yellow, 50 ft	McMaster-Carr	8054T17	Connect fans and heater to power supplys	1	$ 21.54	$ -	$ 21.54
Stainless Steel Wire Cloth Discs	McMaster-Carr	9317T81	Mesh for mixing flow	1	$ 9.84	$ -	$ 9.84
Polyester Mesh Discs	McMaster-Carr	93185T21	Mesh for mixing flow	1	$ 1.67	$ -	$ 1.67
						TOTAL	$1,401.75

Individual ESC Efficiency Rig Cost

Item	Vendor	Model #	Description	Qty	Price	Ship/Tax	Total
TSI Mass Flowmeter	tsi.com	40241	Measures mass flow	1	$ 926.25	$ 74.10	$1,000.35
2 Lb. Polyurethane Mix and Pour Foam	Fibre Glast	24/25-A	Pourable polyurethane foam, two-part kit	1	$ 34.95	$ 9.95	$ 44.90
1"x12"x6' Common Board	Home Depot	N/A	Supports rig	1	$ 11.97	$ -	$ 11.97
Omega Handheld Microprocessor Digital Thermometer	N/A	HH-23	Displays the temperature	1	***$ 225.00***	$ -	***$ 225.00***
Thermocouple Wire Duplex Insulated Type K	N/A	PR-K-24	Detects temperature change	1	***$ 28.00***	$ -	***$ 28.00***
DC Equipment Cooling Fan, 20 CFM	McMaster-Carr	1939K57	Creates flow for rig	1	$23.75	$ -	$ 23.75
DC Equipment Cooling Fan, 7 CFM	McMaster-Carr	1939K22	Creates flow for rig	1	$ 25.98	$ -	$ 25.98
Silicone Rubber Heater	Minco Components.com	HR6926	Validation Heater, 2"x3", 14.75 ohm	1	$ 49.80	$ 9.95	$ 59.75
GW Laboratory DC Power Supply	N/A	GPS-3030D	Provides power for all electronic devices	3	***$ 175.00***	$ -	***$ 525.00***
8 oz. Oatley PCV Cement	Home Depot	310133	Connects PVC piping	1	$ 4.94	$ -	$ 4.94
14 x 14mm x 6mm Heatsink	Marlin P. Jones & Assoc.	31973 HK	Apply to heater	12	$ 0.25	$ -	$ 3.00
3" x 2 ft VPC PCV Sch. 40 pipe	Home Depot	2203	Will contain the ESC	1	$9.99	$ -	$ 9.99
3 in. x 1-1/2 in. PVC DWV Reducing Coupling	Home Depot	C4801HD3112	Pipe reducer for rig	3	$ 4.41	$ -	$ 13.23
1-1/2in x 5 ft Formufit Furniture Grade Sch. 40 PVC Pipe in White	Home Depot	P112FGP-WH-5	pipe for rig	1	$ 10.86	$ -	$ 10.86
1-1/2 in x 3/4 in Charlotte Pipe PVC Sch. 40 Reducer Bushing	Home Depot	PVC021081600 HD	Pipe reducer for rig	2	$1.62	$ -	$ 3.24
3/4 in x 10 ft JM eagle PVC Schedule 40 Plain-End Pipe	Home Depot	57471	pipe for rig	1	$ 2.42	$ -	$ 2.42
3/4 in . Charlotte Pipe PVC Sch. 40 S x S Coupling	Home Depot	PVC021000800 HD	Pipe reducer for rig	6	$ 0.22	$ -	$ 1.32
Sioux Chief, 1 in. x 3/4 in. Vinyl Braided Tubing, 10 ft length	Home Depot	900-02306C00101	Tube to connect to flow meter	1	$ 21.32	$ -	$ 21.32
SAKRETE 8 in. x 48 in. Concrete Form Tube	Home Depot	65470075	Tube mold for foam	1	$ 6.92	$ -	$ 6.92
General Purpose Duct Tape	McMaster-Carr	76135A48	Tape to bind fans and seal junctions	2	$ 5.57	$ -	$ 11.14
Electrical Tape, 20 Yards	McMaster-Carr	7619A11	Tape for sealing junctions and wires	2	$ 1.06	$ -	$ 2.12
Aligator Clips	McMaster-Carr	7236K55	Connects wires to power supply	2	$ 0.58	$ -	$ 1.16
Stranded Wire - 300V AC, 14 Gauge, Green/Yellow, 50 ft	McMaster-Carr	8054T17	Connect fans and heater to power supplys	1	$ 21.54	$ -	$ 21.54
						TOTAL	$2,057.90

Appendix G - Experimental Procedure Plan

1. **Introduction/Description**

   The final goal of the ESC Efficiency Senior Project is to measure the efficiency of an Electronic Speed Controller (ESC) by building a flow rig that can detect the heat rising from a small heater similar to an ESC. This rig will use a fan to blow air over the top of the heated electronic while thermocouples at the beginning and end of the flow will measure the change in temperature. A mass flow meter will also be used to measure the mass flow. These measurements will be used to solve for the heat transfer rate, which will be used to find the power lost from an ESC as it converts DC power to three-phase AC power.

2. **Approval**

   Approved By:
   Team Members—Grace Cowell, Matthew Hudson, and Marcus Pereira
   Advisor—Dr. Mello
   Sponsor—Dr. Westphal

3. **Test Strategy**
   a. *What we will test:*
      i. Temperature change between inlet and outlet in °C
      ii. Mass flow in L/min
   b. *Other values we must record*
      i. Amperage and voltage of heat source to compare with measure heat
      ii. Amperage and voltage of fan as it relates to fan speed
      iii. Room temperature/ humidity/atmospheric pressure
   c. *Equipment/materials:*
      i. Two K-type thermocouples welded together to measure change in temperature between two locations
      ii. Omega Handheld Microprocessor Digital Thermometer
      iii. Pipe and tray flow rig as designed in final report
      iv. TSI Mass Flowmeter
      v. Small computer fan from Dr. Westphal
      vi. Heat source—Minco heater
         1. Must be same size as ESC and have same amount of heat range
      vii. Three power supplies—One will power the computer fan, the other will power the heater, and the other will power flow meter
      viii. Bananas plugs

d. Set up:

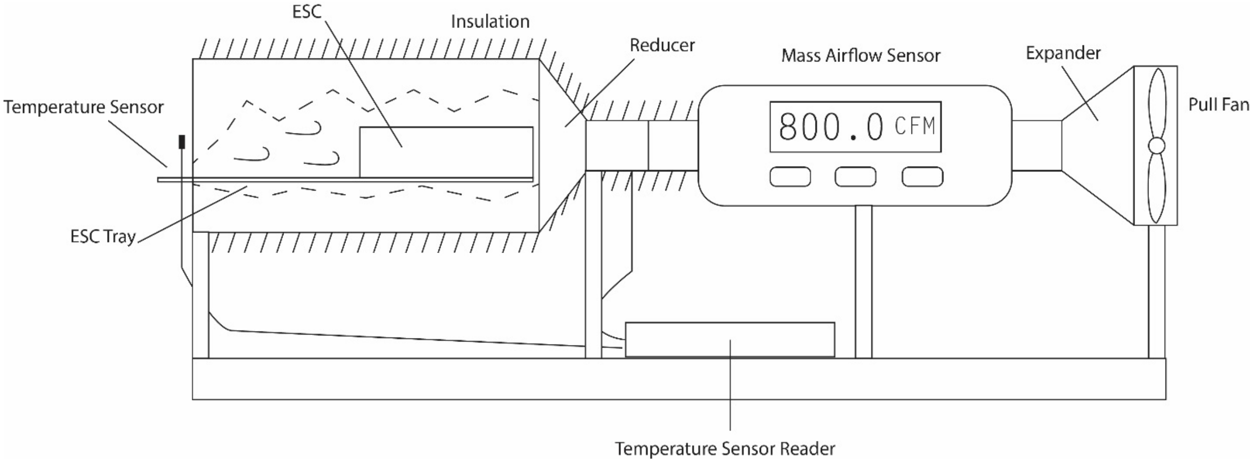


Figure 1. Diagram of flow rig experiment set up.

e. Procedure:

1)Wire fan and heater to their respective power supplies.
2)Arrange equipment as seen in Figure 1.
3)Set fan voltage and amp based on trial and error
4)Set heater voltage and amp based on trial and error
5)Record power settings
6)Turn on all equipment and wait to allow system to reach equilibrium state.
7)Record temperature change and air speed.

Test 1:

8)Increase fan speed in increments, wait for system to reach equilibrium, and record new temperatures and air speeds.

Test 2:

9)Increase heater power in increments, while keeping fan speed the same, and repeat step 7.

f. Responsibilities

All team members will work together in setting up this preliminary experiment and recording results. This is only a mock-up of the future test, which will require more specific individual responsibilities.

g. Safety/Risks/Items of concern

i. Ensure all equipment is unplugged when wiring setup
ii. Make sure Styrofoam seams are sealed so as not to let air flow out other than the inlet and exit
iii. Keep thermocouple ends away from fan propeller

Table H1. The three analyzed data sets with respect to their individual errors for the thermocouples and flowmeter.

							Thermo Error								Flow Meter Error			
		Start time	Time of recording	Description	delta T (°C)	Normalized delta T	Resolution Error (±°C)	Instrument error (±°C)	Thermo-couple error (±°C)	Total (±°C)	Flowmeter T (°C)	Average temp (°C)	Flowmeter P (kPA)	Flow (SLPM)	Resolution Error (±SLPM)	Instrument Error (±SLPM)	Total (±SLPM)	Mass Flow (kg/s)
5/19/2016	Trial 1		2:01	Cold test	1.5		0.05	0.600	1	1.167	21.7	22	100.2	10.08	0.005	0.202	0.202	2.02E-04
	Trial 2	2:03	2:04		1.1		0.05	0.600	1	1.167	21.6	22	100.2	20.38	0.005	0.408	0.408	4.09E-04
	Trial 3	2:06	2:07		1		0.05	0.600	1	1.167	21.3	21	100.2	30.17	0.005	0.603	0.603	6.05E-04
	Trial 4	2:13	2:32	2.5W, 10 LPM	6.1	4.85	0.05	0.605	1	1.170	26.5	24	100.2	10.02	0.005	0.200	0.200	1.98E-04
	Trial 5	2:33	2:43	2.5W, 20 LPM	5.1	3.85	0.05	0.604	1	1.169	25.3	23	100.2	20.54	0.005	0.411	0.411	4.05E-04
	Trial 6	2:44	2:50	2.5W, 30LPM	4.4	3.15	0.05	0.603	1	1.169	24.5	23	100.2	30.04	0.005	0.601	0.601	5.93E-04
	Trial 7	2:52	3:18	5W, 10 LPM	14.7	13.45	0.05	0.613	1	1.174	33.8	27	100.2	10.04	0.005	0.201	0.201	1.95E-04
	Trial 8	3:19	3:27	5W, 20 LPM	11.6	10.35	0.05	0.610	1	1.173	--	--	100.2	20.37	0.005	0.407	0.407	3.96E-04
	Trial 9	3:28	3:37	5 W, 30 LPM	9.1	7.85	0.05	0.608	1	1.171	28.9	25	100.2	29.87	0.005	0.597	0.597	5.89E-04
	Trial 10	3:39	4:32	10 W, 10 LPM	32.7	31.45	0.05	0.631	1	1.184	49.2	33	100.2	10.32	0.005	0.206	0.206	2.00E-04
	Trial 11	4:33	4:48	10 W, 20 LPM	24.4	23.15	0.05	0.623	1	1.179	43.4	32	100.2	20.28	0.005	0.406	0.406	3.94E-04
	Trial 12	4:50	5:06	10 W, 30 LPM	17.6	16.35	0.05	0.616	1	1.176	37.1	29	100.2	29.93	0.005	0.599	0.599	5.81E-04
5/21/2016	Trial 1	2:25	2:29	Cold test, no flow	0		0.05	0.600	1	1.167	23.7	24	100.7	0.00	0.005	0.000	0.005	0.00E+00
	Trial 2	2:30	2:33	Cold test, 10 LPM	0.2		0.05	0.600	1	1.167	20.8	21	100.7	10.14	0.005	0.203	0.203	2.03E-04
	Trial 3	2:35	2:38	Cold test 20 LPM	0.5		0.05	0.600	1	1.167	20.7	21	100.6	20.64	0.005	0.413	0.413	4.14E-04
	Trial 4	2:39	2:42	Cold test, 30LPM	0.3		0.05	0.600	1	1.167	20.6	21	100.6	30.10	0.005	0.602	0.602	6.04E-04
	Trial 5	2:48	3:06	2.5W, 10 LPM	5	4.7	0.05	0.605	1	1.170	25	23	100.7	10.03	0.005	0.201	0.201	2.01E-04
	Trial 6	3:06	3:15	2.5W, 20 LPM	4.6	4.3	0.05	0.604	1	1.169	24.8	23	100.6	20.55	0.005	0.411	0.411	4.12E-04
	Trial 7	3:16	3:25	2.5W, 30LPM	3.7	3.4	0.05	0.603	1	1.169	23.8	22	100.6	30.15	0.005	0.603	0.603	6.05E-04
	Trial 8	3:28	3:50	5W, 10 LPM	13	12.7	0.05	0.613	1	1.174	31.3	25	100.7	10.19	0.005	0.204	0.204	2.01E-04
	Trial 9	3:51	4:05	5W, 20 LPM	10.7	10.4	0.05	0.610	1	1.173	29.7	25	100.7	20.47	0.005	0.409	0.409	4.04E-04
	Trial 10	4:06	4:19	5 W, 30 LPM	8.3	8	0.05	0.608	1	1.171	28.1	24	100.6	29.98	0.005	0.600	0.600	5.92E-04
	Trial 11	4:23	5:15	10 W, 10 LPM	30.6	30.3	0.05	0.630	1	1.183	46.4	31	100.7	10.32	0.005	0.206	0.206	2.00E-04
	Trial 12	5:17	5:32	10 W, 20 LPM	23.8	23.5	0.05	0.624	1	1.180	42.6	31	100.7	20.10	0.005	0.402	0.402	3.90E-04
	Trial 13	5:34	5:59	10 W, 30 LPM	17.7	17.4	0.05	0.617	1	1.176	35.4	27	100.7	30.10	0.005	0.602	0.602	5.84E-04
5/25/2016	Trial 1			Cold test, no flow	0.4		0.05	0.600	1	1.167	20.4	20	101	0.00	0.005	0.000	0.005	0.00E+00
	Trial 2			Cold test, 10 LPM	0.3		0.05	0.600	1	1.167	20.2	20	101	10.00	0.005	0.200	0.200	2.01E-04
	Trial 3			Cold test 20 LPM	0.3		0.05	0.600	1	1.167	20.1	20	101	19.94	0.005	0.399	0.399	4.00E-04
	Trial 4			Cold test, 30LPM	0.3		0.05	0.600	1	1.167	20.1	20	100.9	30.02	0.005	0.600	0.600	6.02E-04
	Trial 5			2.5W, 10 LPM	6.8	6.5	0.05	0.607	1	1.171	26.8	24	101	9.95	0.005	0.199	0.199	1.96E-04
	Trial 6			2.5W, 20 LPM	4.5	4.2	0.05	0.604	1	1.169	25.7	24	101	20.23	0.005	0.405	0.405	3.99E-04
	Trial 7			2.5W, 30LPM	3.6	3.3	0.05	0.603	1	1.169	24.3	23	100.9	30.23	0.005	0.605	0.605	5.97E-04
	Trial 8			5W, 10 LPM	14.3	14	0.05	0.614	1	1.175	33	26	101	9.91	0.005	0.198	0.198	1.96E-04
	Trial 9			5W, 20 LPM	10	9.7	0.05	0.610	1	1.172	30.3	25	101	19.61	0.005	0.392	0.392	3.87E-04
	Trial 10			5 W, 30 LPM	7.9	7.6	0.05	0.608	1	1.171	27.4	24	100.9	30.07	0.005	0.601	0.601	5.93E-04
	Trial 11			10 W, 10 LPM	32.3	32	0.05	0.632	1	1.184	47.7	32	101	10.18	0.005	0.204	0.204	1.98E-04
	Trial 12			10 W, 20 LPM	20.5	20.2	0.05	0.620	1	1.178	39.7	30	101	20.10	0.005	0.402	0.402	3.90E-04
	Trial 13			10 W, 30 LPM	15.7	15.4	0.05	0.615	1	1.175	34.7	27	101	29.87	0.005	0.597	0.597	5.80E-04

Table H2. The three analyzed data sets with respect to their fan and heater outputs, total error, and percentage of captured power.

	Description	Fan voltage (V)	Fan amp (A)	Heater voltage (V)	Heater amp (A)	Actual Power Out (W)	Calculated Power Out (W)	% Error	% of Power out
5/19/2016	Cold test	13.0	0.07	0	0	0.00	0.30	0%	-
		16.8	0.12	0	0	0.00	0.45	0%	-
		24.4	0.17	0	0	0.00	0.61	0%	-
	2.5W, 10 LPM	13.0	0.07	6.1	0.409	2.49	0.96	24%	39%
	2.5W, 20 LPM	16.8	0.12	6.1	0.411	2.51	1.57	30%	63%
	2.5W, 30LPM	24.4	0.17	6.1	0.411	2.51	1.88	37%	75%
	5W, 10 LPM	13.0	0.07	8.7	0.583	5.07	2.64	9%	52%
	5W, 20 LPM	16.8	0.12	8.7	0.583	5.07	4.11	12%	81%
	5 W, 30 LPM	24.4	0.17	8.7	0.583	5.07	4.65	15%	92%
	10 W, 10 LPM	13.0	0.07	12.2	0.819	9.99	6.33	4%	63%
	10 W, 20 LPM	16.8	0.12	12.2	0.816	9.96	9.16	5%	92%
	10 W, 30 LPM	24.9	0.17	12.2	0.816	9.96	9.55	7%	96%
5/21/2016	Cold test, no flow	0.0	0.00	0	0	0.00	0.00	0%	-
	Cold test, 10 LPM	13.2	0.07	0	0	0.00	0.00	0%	-
	Cold test 20 LPM	16.9	0.12	0	0	0.00	0.00	0%	-
	Cold test, 30LPM	24.3	0.17	0	0	0.00	0.00	0%	-
	2.5W, 10 LPM	13.0	0.07	6.1	0.409	2.49	0.95	25%	38%
	2.5W, 20 LPM	16.8	0.12	6.1	0.408	2.49	1.78	27%	72%
	2.5W, 30LPM	24.4	0.17	6.1	0.408	2.49	2.07	34%	83%
	5W, 10 LPM	13.1	0.06	8.7	0.584	5.08	2.57	9%	51%
	5W, 20 LPM	16.8	0.12	8.7	0.583	5.07	4.22	11%	83%
	5 W, 30 LPM	24.4	0.17	8.7	0.583	5.07	4.76	15%	94%
	10 W, 10 LPM	13.1	0.07	12.2	0.816	9.96	6.10	4%	61%
	10 W, 20 LPM	16.7	0.12	12.2	0.813	9.92	9.22	5%	93%
	10 W, 30 LPM	24.8	0.17	12.2	0.814	9.93	10.22	7%	103%
5/25/2016	Cold test, no flow	0.0	0.00	0	0	0.00	0.00	0%	-
	Cold test, 10 LPM	12.9	0.07	0	0	0.00	0.00	0%	-
	Cold test 20 LPM	16.6	0.11	0	0	0.00	0.00	0%	-
	Cold test, 30LPM	24.4	0.16	0	0	0.00	0.00	0%	-
	2.5W, 10 LPM	12.9	0.07	6.1	0.407	2.48	1.28	18%	52%
	2.5W, 20 LPM	16.9	0.12	6.1	0.405	2.47	1.69	28%	68%
	2.5W, 30LPM	24.8	0.17	6.1	0.405	2.47	1.98	35%	80%
	5W, 10 LPM	12.9	0.07	8.7	0.584	5.08	2.75	9%	54%
	5W, 20 LPM	16.6	0.11	8.7	0.584	5.08	3.77	12%	74%
	5 W, 30 LPM	24.8	0.17	8.7	0.584	5.08	4.53	16%	89%
	10 W, 10 LPM	13.0	0.07	12.2	0.816	9.96	6.46	4%	65%
	10 W, 20 LPM	16.7	0.11	12.2	0.816	9.96	8.05	6%	81%
	10 W, 30 LPM	24.8	0.17	12.2	0.816	9.96	9.12	8%	92%

Table H3. Averages of the three analyzed data sets for their respective expected power levels and flowrates.

				Thermo Error								**Flow Meter Error**										
	Description	**delta T (°C)**	**Normalized delta T (°C)**	**Resolution Error (±°C)**	**Instrument error (±°C)**	**Thermo-couple error (±°C)**	**Standard Deviation (±°C)**	**Total (±°C)**	**Flowmeter T (°C)**	**Flowmeter P (kPA)**	**Flow (SLPM)**	**Resolution Error (±SLPM)**	**Instrument Error (±SLPM)**	**Standard Deviation (±SLPM)**	**Total (±SLPM)**	**Mass Flow (kg/s)**	**Heater voltage**	**Heater amp**	**Actual Power Out**	**Calculated Power Out**	**% Error**	**% of Power out**
Average of three tests	2.5W, 10 LPM	6.0	5.4	0.05	0.605	1	0.999	1.538	26.10	100.63	10.00	0.005	0.200	0.044	0.205	1.98E-04	6.1	0.408	2.49	1.07	29%	43%
	2.5W, 20 LPM	4.7	4.1	0.05	0.604	1	0.236	1.193	25.27	100.60	20.44	0.005	0.409	0.182	0.447	4.06E-04	6.1	0.408	2.49	1.68	29%	67%
	2.5W, 30LPM	3.9	3.3	0.05	0.603	1	0.126	1.176	24.20	100.57	30.14	0.005	0.603	0.095	0.610	5.98E-04	6.1	0.408	2.49	1.97	36%	79%
	5W, 10 LPM	14.0	13.4	0.05	0.613	1	0.653	1.343	32.70	100.63	10.05	0.005	0.201	0.140	0.245	1.97E-04	8.7	0.584	5.08	2.65	10%	52%
	5W, 20 LPM	10.8	10.2	0.05	0.610	1	0.391	1.236	30.00	100.63	20.15	0.005	0.403	0.470	0.619	3.95E-04	8.7	0.583	5.08	4.03	13%	79%
	5 W, 30 LPM	8.4	7.8	0.05	0.608	1	0.202	1.189	28.13	100.57	29.97	0.005	0.599	0.100	0.608	5.91E-04	8.7	0.583	5.08	4.65	15%	92%
	10 W, 10 LPM	31.9	31.3	0.05	0.631	1	0.867	1.467	47.77	100.63	10.27	0.005	0.205	0.081	0.221	1.99E-04	12.2	0.817	9.97	6.26	5%	63%
	10 W, 20 LPM	22.9	22.3	0.05	0.622	1	1.813	2.162	41.90	100.63	20.16	0.005	0.403	0.104	0.416	3.91E-04	12.2	0.815	9.94	8.77	10%	88%
	10 W, 30 LPM	17.0	16.4	0.05	0.616	1	1.000	1.544	35.73	100.63	29.97	0.005	0.599	0.119	0.611	5.82E-04	12.2	0.815	9.95	9.58	10%	96%

Table H4. Data from the fourth trial that was eliminated due to residual heat issues.

		Description	delta T (°C)	Normalized delta T	Flowmeter T (°C)	Flowmeter P (kPA)	Flow (SLPM)	Mass Flow (kg/s)	Fan voltage (V)	Fan amp (A)	Heater voltage (V)	Heater amp (A)	Actual Power Out (W)	Calculated Power Out (W)	% of Power out
Eliminated Test: 5/22/2016	Trial 1	Cold test, no flow	0	-	22.7	100.8	0.00	0.00E+00	0.0	0.00	0	0	0.00		
	Trial 2	Cold test, 10 LPM	-0.2	-	20.4	100.8	10.10	1.99E-04	13.0	0.07	0	0	0.00		
	Trial 3	Cold test 20 LPM	-0.1	-	20.3	100.8	20.42	4.03E-04	16.8	0.11	0	0	0.00		
	Trial 4	Cold test, 30LPM	-0.1	-	20.3	100.8	29.91	5.90E-04	24.0	0.17	0	0	0.00		
	Trial 5	2.5W, 10 LPM	9.7	9.57	28.6	100.8	10.00	1.97E-04	13.2	0.07	6	0.408	2.49	1.90	76%
	Trial 6	2.5W, 20 LPM	7.1	6.97	27.2	100.8	20.10	3.97E-04	17.0	0.12	6	0.41	2.50	2.78	111%
	Trial 7	2.5W, 30LPM	5.2	5.07	25	100.8	30.00	5.92E-04	24.0	0.17	6	0.41	2.50	3.02	121%
	Trial 8	5W, 10 LPM	20.3	20.17	38.1	100.8	10.30	2.03E-04	13.2	0.07	9	0.582	5.06	4.12	81%
	Trial 9	5W, 20 LPM	12.3	12.17	31.5	100.7	20.20	3.99E-04	16.8	0.12	9	0.582	5.06	4.88	96%
	Trial 10	5 W, 30 LPM	9.7	9.57	29.3	100.7	30.10	5.94E-04	24.8	0.17	9	0.582	5.06	5.71	113%
	Trial 11	10 W, 10 LPM	31.7	31.57	48.2	100.8	10.10	1.99E-04	13.0	0.07	12	0.813	9.92	6.32	64%
	Trial 12	10 W, 20 LPM	24	23.87	42.4	100.8	20.10	3.97E-04	16.8	0.12	12	0.814	9.93	9.52	96%
	Trial 13	10 W, 30 LPM	17.7	17.57	36.4	100.7	30.00	5.92E-04	24.8	0.17	12	0.814	9.93	10.45	105%
	Trial 14	10 W, 30 LPM	16.5	16.37	36.4	100.7	30.00	5.92E-04	24.8	0.17	12	0.814	9.93	9.74	98%

Table H5. Data from flow mixing trials under various conditions.

	Temperature (˚C)							
Location	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trail 6**	**Trial 7**	**Average within location**
1	24.7	25.7	25.1	26.0	22.7	25.2	26.0	25.17
2	25.8	25.7	25.8	23.7	22.7	25.1	26.5	25.77
3	21.6	25.2	25.3	23.0	22.6	25.2	23.6	24.03
4	24.6	26.6	25.1	26.7	22.8	25.6	25.5	25.43
5	21.7	23.8	26.4	26.0	23.2	24.7	24.3	23.97
6	21.4	23.8	25.5	23.3	22.6	24.7	22.7	23.57
7	22.4	25.6	24.5	26.5	22.7	25.4	22.2	24.17
8	21.2	23.2	24.9	22.9	22.8	23.7	21.6	23.10
9	21.4	22.7	24.3	23.0	22.6	23.9	22.0	22.80
Average	22.76	24.70	25.21	24.57	22.74	24.83	23.82	
Standard Deviation	1.67	1.27	0.61	1.58	0.18	0.62	1.74	
% SD	7.34	5.15	2.41	6.43	0.78	2.49	7.29	

	Description
Trial 1	1 1/2" Diam exit (Before reduced diam)
Trial 2	3/4"Diam exit
Trial 3	3/4" Diam, 3" away from exit
Trial 4	3/4" Diam exit with baffling
Trial 5	hole in paper
Trial 6	deep inside 1" pipe
Trial 7	redo of trial 1

Appendix I - Hazard Identification Checklist

ME428/429/430 Senior Design Project 2015-2016

SENIOR PROJECT CRITICAL DESIGN HAZARD IDENTIFICATION CHECKLIST

Team: BPD Industries, ESC Efficiency project Advisor: Dr. Mello

Y	N	
☐	☑	Do any parts of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points adequately guarded?
☐	☑	Does any part of the design undergo high accelerations/decelerations that are exposed to the user?
☐	☑	Does the system have any large moving masses or large forces that can contact the user?
☐	☑	Does the system produce a projectile?
☐	☑	Can the system to fall under gravity creating injury?
☐	☑	Is the user exposed to overhanging weights as part of the design?
☐	☑	Does the system have any sharp edges exposed?
☑	☐	Are there any ungrounded electrical systems in the design?
☑	☐	Are there any large capacity batteries or is there electrical voltage in the system above 40 V either AC or DC?
☐	☑	Is there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids when the system is either on or off?
☐	☑	Are there any explosive or flammable liquids, gases, dust, or fuel in the system?
☐	☑	Is the user of the design required to exert any abnormal effort and/or assume a an abnormal physical posture during the use of the design?
☐	☑	Are there any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☑	Will the system generate high levels of noise?
☑	☐	Will the product be subjected to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc. that could create an unsafe condition?
☐	☑	Is it easy to use the system unsafely?
☐	☑	Are there any other potential hazards not listed above? If yes, please explain on the back of this checklist.

For any “Y” responses, add a complete description on the reverse side. DO NOT fill in the corrective actions or dates until you meet with the mechanical and electrical technicians.

Hazard Identification Checklist notes:

-There are ungrounded fan motors in the system, with low voltage.

-The laptop and DC power supplies will be plugged into 120 V AC household plugs.

-The DC heater can reach temperatures high enough to burn the human skin.