Fuel Cell Air Intake System

Final Report

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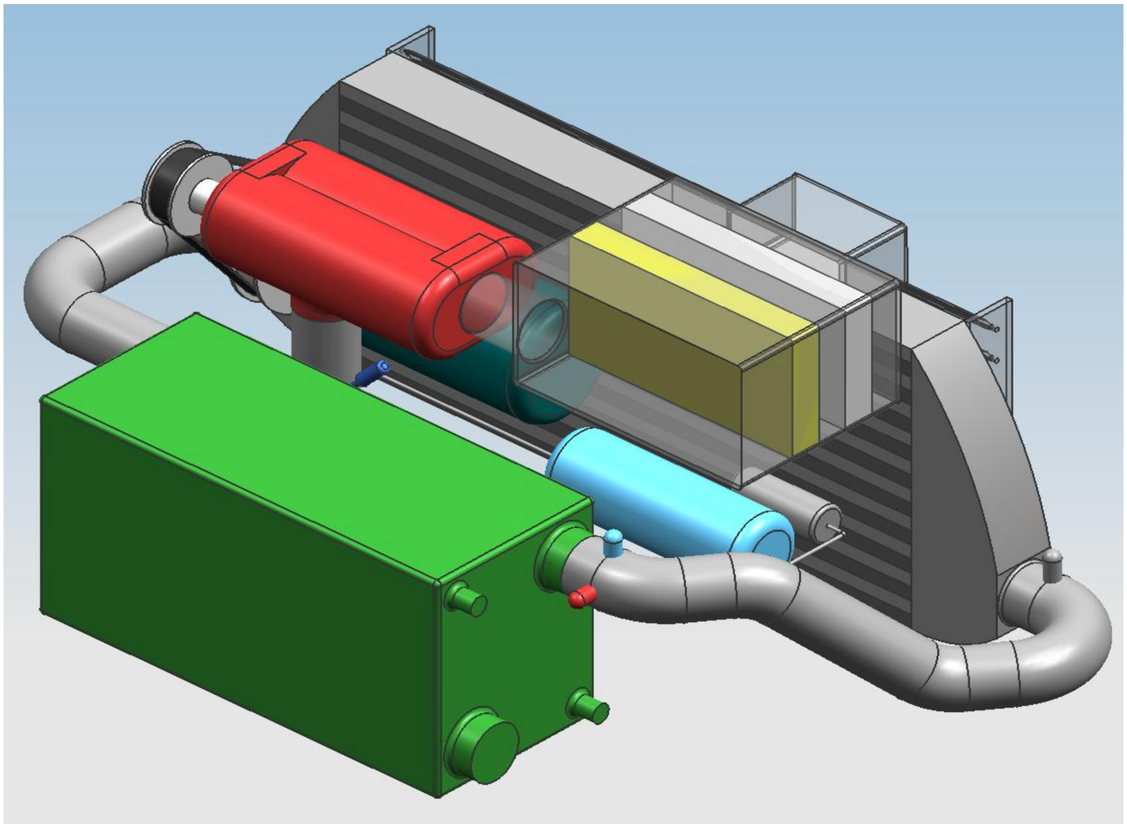

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ABSTRACT

The goal of our project is to research and design an Air Intake System for a proton exchange membrane fuel cell (PEMFC) to be used in automotive applications. Fuel cell technology will allow cars to be powered by hydrogen. The air intake of a PEMFC is critical to its functionality; it supplies air to the cathode side electrode where its oxygen is used in the fuel cell reaction. The important characteristics of an air intake system include: airflow, noise, filtration, humidity, temperature, pressure and packaging. By considering these important aspects, our team has designed an air intake system that allows a fuel cell to function efficiently.

EXECUTIVE SUMMARY

Our project is the fuel cell air intake system for an automotive application and is sponsored by Visteon Corporation. Fuel cells are one of the most popular forms of alternative technology for automotive vehicles. Our sponsor, Visteon, is preparing to be competitive in the upcoming fuel cell vehicle market by supplying intake systems. They have asked us to research and design an air intake system for a Proton Exchange Membrane Fuel Cell (PEMFC) vehicle. The objective of our project is to develop a system that delivers the proper ratio of clean air to hydrogen in the fuel cell membrane and optimize performance.

Specifications that have been determined for our project are relative humidity (100%), temperature (85°C), pressure (2.5 Bar), air purity (removal of dust and chemical compounds), noise (< 65 dBA), and air flow (45 liters/sec for a 100 kW fuel cell stack). As we try to meet these technical specifications, we must also consider our customer's requirements which include packaging (how the system fits inside a medium size vehicle), cost, serviceability, and durability. A quality function deployment (QFD) diagram was executed to analyze tradeoffs and compromises between technical and customer specifications. This tool helps to clarify and quantify the importance of each variable, enabling us to satisfy our specification criteria as much as possible.

To select the best design for the air intake system, we first broke our system into the following components: air intake, filter, compressor, humidifier, and cooler. Then we generated many possible solutions for each component. Each concept was then entered into a Pugh chart for its particular sub-function and then evaluated on its ability to perform the necessary criterion.

For our Final Design, we chose a combination of an activated carbon filter and Visteon dust filter to remover harmful substances, a screw compressor to increase pressure and set the mass flow rate, a liquid injection humidifier to control humidity, and an air-air intercooler to cool the airflow. We also determined that the components listed above and placed in that order will most effectively deliver the proper parameters to the fuel cell.

Our prototype is composed of the same components as our final design except the chemical filter. Our plan was to demonstrate that by using our chosen components, in their particular order, our final design can regulate the pressure, temperature, and humidity of ambient air and deliver it to a fuel cell at pre-specified targets. Our initial targets for our prototype were a relative humidity of 100%, temperature of 40^{o}C, and pressure of 1.35 Bar at the outlet. Our results were a pressure of 1.24 Bar, a temperature increase to 33°C, and an inability to record significant humidity measurements. Failure of our system to reach our initial targets was mostly due to the lack of power supplied to the compressor (small airflow/rotational speed) and an inadequate humidity sensor. However, our team did demonstrate that we could control pressure by regulating the compressor speed and back pressure on the system; control the heat exchange across the intercooler by regulating the cross sectional area of the cross flow, and control the amount of water entering the system by regulating the back pressure of our water tank.

In conclusion, our team has delivered the requested information from Visteon about the specifications necessary for a fuel cell air intake system and has also provided a unique assembly of components to meet these specifications. In the future, more testing should be done to determine the necessary control of our assembly.

PROBLEM DESCRIPTION

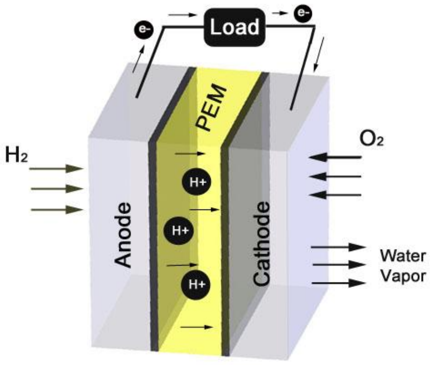
As more research and development is spent on fuel cell technologies, their large-scale implementation in automobiles becomes more promising. Visteon Corporation is a large automotive supplier which manufactures a wide range of parts including electronic products, climate control systems, and interior products. As they foresee the proton exchange membrane fuel cell (PEMFC) vehicle emerging in the automotive market, they are taking the necessary steps to be first in providing their customers with a suitable air intake system. As our sponsor, Visteon will be working with our team in designing and developing this system for small to mid-size vehicles. The goal is to produce an intake system design which supplies air at the proper flow-rate, humidity, temperature, pressure, and purity to achieve the optimum performance and efficiency from a PEMFC stack. This design must also meet cost, manufacturability, packaging, serviceability, durability, and noise requirements. The final output of our project will be a scaled-down prototype to demonstrate our system design in operation.

INFORMATION SOURCES

To educate ourselves as much as possible on fuel cell technology and to obtain engineering specifications for optimum performance, our team has gathered information from a variety of sources. These sources include our sponsor, published research books, scientific journal articles, and interviews with professors, patent searches, and other online sources.

The Proton Exchange Membrane Fuel Cell

The underlying principle for hydrogen fuel cells is to combine hydrogen and oxygen molecules to form water while forcing electrons through a separate path to produce current, as shown in Figure 1 below.



http://www.ultracellpower.com/gfx/tech_fuel_dgrm.jpg

Figure 1: A simple diagram of how a PEMFC works.

In proton exchange membrane fuel cells (PEMFC), there is a solid polymeric proton conducting membrane which separates the anode from the cathode [1]. This type of fuel cell may also be called a polymer electrolyte membrane fuel cell (PEMFC), and remarkably they share the same acronym. As seen from Figure 1, hydrogen is supplied to the anode while oxygen is supplied to the cathode. The membrane allows only positively charged hydrogen ions (H^+), or protons, through. The electrons are forced to travel a separate path from anode to cathode thus generating a current. At the cathode, the reactants combine to form water. Equation 1 below describes the reactions which take place in a PEMFC [2].

Anode: $H_2 \longrightarrow 2H^+ + 2e^-$

Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$ (Eq. 1)

Overall Reaction: $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$

The most common membrane used in PEMFCs is Nafion®, a sulphonated fluoropolymer invented by DuPont in the 1960's. This material has essentially become an "industry standard" as it is the electrolyte against which others are judged [3].

PEM type fuel cells are favored over other types for many reasons. They have attained the highest performance levels and longest lifetimes of all types of fuel cells [1]. Figure 2 illustrates the general performance characteristics between different leading fuel cell types; it is clear that PEMFCs are one of the top choices in fuel cell technology.

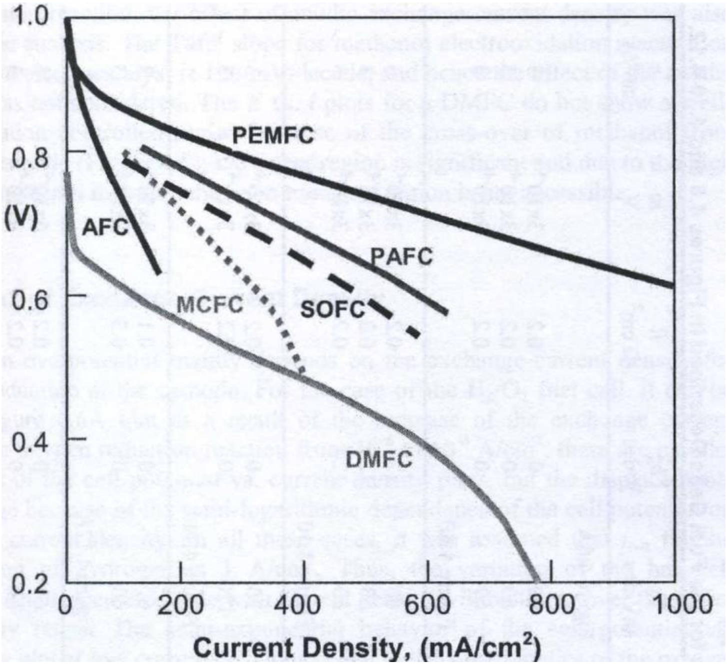


Figure 2: PEMFC performance capabilities are higher than other leading fuel cell types

PEMFCs have attracted much interest and received much developmental research. Because of this, it is easy to understand Visteon Corporation's anticipation for this technology's implementation in automobiles. Their concern, and consequently our project, focuses on the cathode side of the PEMFC. Here, ambient air will serve as the reactant gas and supply the necessary oxygen. The conditions of the air entering the fuel cell stack can greatly influence its performance. To produce optimal power output while preventing damage to the fuel cell, the following variables must be carefully considered. They are: airflow, humidity, temperature, pressure, and purity. Studying these aspects and their impact on PEMFC performance will guide the engineering specifications of the air intake system design.

Airflow

Control of the mass flow rate of air across the cathode electrode is very important to the fuel cell's operation. Based on Equation 1, we can determine the theoretical amount of hydrogen and oxygen required to generate a specified current. However, we are particularly interested in the amount of air rather than the amount of oxygen. Using the assumption that generally 20% of air is composed of oxygen, an equation has been derived which calculates the theoretical amount of air required for a certain power output [3]. This is shown by Equation 2 below,

$$AirUsage = \left(3.57x10^{-7}\right)\times\left(\lambda\right)\times\left(\frac{P_e}{V_C}\right) \quad \text{in kg/s} \qquad \text{(Eq. 2)}$$

where λ is the stoichiometric multiple, P_e is the power output of the fuel cell stack in watts, and V_c is the average voltage of each cell. Using $\lambda = 1$ provides the exact amount of air necessary to react with all the hydrogen, which means the air will be depleted of oxygen at the outlet of the fuel cell stack. To ensure all reactive sites are utilized, it has been found to use at least $\lambda=2$ [1,3]. Another purpose for faster airflow rates is to aid in the removal of excess water created by the reaction within the PEMFC [3].

As seen in Appendix E, we have found that the power requirements for small to mid-size fuel cell vehicles fall within the range of 50-100 kW. We will use the upper limit, 100 kW, for P_e so as to design a system that is fully capable for this vehicle classification. V_c will depend on the efficiency of the fuel cell stack used. While this may vary slightly between manufacturers, a value of 0.65 volts can be used with good approximation [3]. Now, we can use Equation 2 to find the mass flow rate of air required, approximately 0.11 kg/s.

To convert this mass flow rate of air to volumetric flow rate, we must first find the density of air. Dry air density cannot be used since density is a function of both pressure and humidity. We discuss in following sections the reasoning behind the pressure and humidity chosen; they are 2.5 bar and 100% relative humidity respectively. Equation 3 below can be used to find the density of air when taking into account these variables [4].

$$\rho_{humidair} = \frac{p_d}{R_d \cdot T} + \frac{p_v}{R_v \cdot T} \quad \text{in kg/m}^3 \qquad \text{(Eq. 3)}$$

Where p_d is the partial pressure of dry air in pascals, R_d is the specific gas constant of dry air (287 J/kg·K), p_v is the water vapor pressure in pascals, R_v is the specific gas constant for water vapor (461.5 J/kg·K), and T is the temperature of the resulting mixture in Kelvin. The partial pressures p_d and p_v must add up to the total pressure of the mixture, or 2.5 bar.

The water vapor pressure (p_v) can be calculated from the relative humidity (ϕ in fraction) and the saturation pressure (p_{sat}) as shown in Equation 4 below [4].

$$p_v = \phi(p_{sat}) \qquad \text{(Eq. 4)}$$

The saturation pressure (p_{sat}) is the vapor pressure at 100% relative humidity. It is a function of temperature and can be found from Equation 5 below [4].

$$p_{sat} = 6.1078x10^{\left(\frac{7.5T-2048625}{T-35.85}\right)} \quad \text{in mbar} \qquad \text{[Eq. 5]}$$

We have determined, and will explain in a following section, that the temperature of air desired at the inlet of the fuel cell stack is 85ºC, or 358K. Therefore, Equation 5 finds p_{sat} at this temperature to be 57700 Pa. With 100% relative humidity, Equation 4 is used to find p_v equal to p_{sat}. Since $p_v + p_d$ must equal 2.5 bar (250,000 Pa), p_d must be 192300 Pa. Finally, we find from Equation 3 the density of humid air at our specified conditions to be 2.20 kg/m^3.

Combining the results of density and mass flow rate from Equations 3 and 2 respectively, we find that the volumetric flow rate of air required to the fuel cell is 0.05 m^3/s, or roughly 50 liters/sec.

Humidity

Water management is a crucial topic for PEMFCs due to the nature of the Nafion® membrane. If it is well hydrated, the H^+ ions can move freely within the material and it will be a good proton conductor. On the other hand, if there is insufficient water in the membrane, then proton conductivity will decrease dramatically [1,3,5]. Since water is produced at the membrane as a byproduct of the operating fuel cell, we questioned the need for externally supplying moisture. It has been found that when a fuel cell runs at temperatures over 60ºC, dry airflow will dry out the electrodes faster than water is produced by the H_2/O_2 reaction [3]. In the next section, we conclude that the fuel cell's target operating temperature is 80ºC. Therefore, there is a need to supply extra moisture to the fuel cell membrane.

One method to provide this moisture involves humidification of the reactant gases. Water can diffuse through the membrane, and so in some cases, humidification of the air alone can be sufficient to hydrate the entire membrane [3]. However, a potential problem with this method involves "electro-osmotic drag" where protons can "drag" water molecules along as they travel from the anode to the cathode. Because of this, the anode side of the membrane can become dry even though the cathode side is completely hydrated [3]. This is an issue which must be analyzed thoroughly and will require counter-measures beyond those capable through the operation of an air intake system.

For our project, we will focus on the humidity of the incoming air at the cathode side. The air supplied to the fuel cell stack will need to be humidified to at least 90% relative humidity [1], with the goal near 100% [5]. Another potential problem which must be controlled through the intake system is flooding of the electrode. When the electrode becomes flooded, the path lengths increase for the reactant gas to reach catalyst sites [1]. This may occur if the air entering the fuel cell is over humidified, above 100% relative humidity. In essence, the air stream will contain condensed water droplets which can collect on the electrode and hinder performance [3]. Therefore, a delicate balance of water content in the air is vital and must be regulated as close to

100% relative humidity as possible. A complete understanding of air humidity and its relationship between temperature and pressure is therefore necessary for proper regulation.

Temperature

Increasing temperatures of the reactant gases enhances the kinetics of the reactions at the anode and the cathode. Higher operating temperatures for PEMFCs also reduce ohmic resistances due to higher conductivity of the electrolyte. Furthermore, diffusion coefficients of reactants increase with increasing temperature; thus, higher current densities are achievable before mass transport limitations occur. These effects of increasing temperature on PEMFC performance can be seen from Figure 3 below [1, P.462].

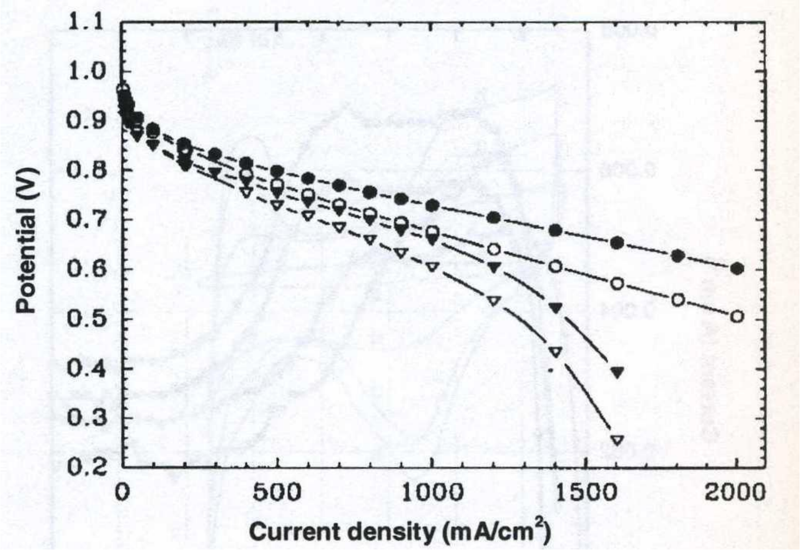


Figure 3: Effect of temperature on PEMFC performance.
(●) = 95ºC Oxygen
(○) = 50ºC Oxygen
(▼) = 95ºC Air
(∇) = 50ºC Air

Another favorable effect of higher operating temperatures is the minimizing of CO poisoning as shown in Figure 4 below [1, P.452].

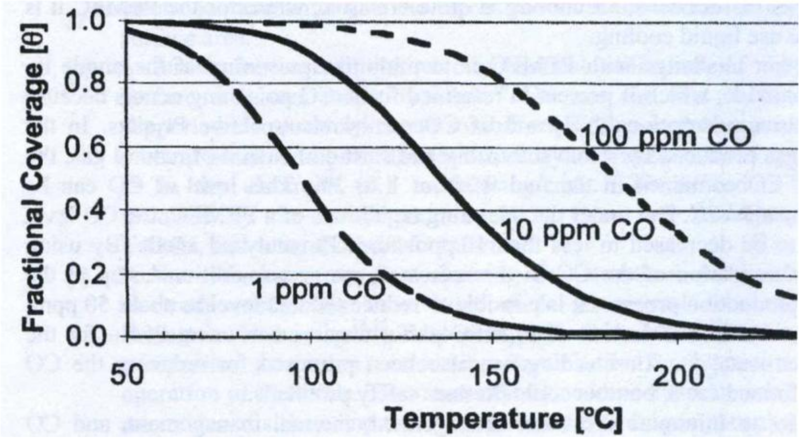


Figure 4: Higher operating temperatures increases CO tolerance in PEMFCs

From these facts, the inclination would be to choose as high a temperature as possible to operate a PEMFC.

However, determining the PEMFC operating temperature relies upon many factors. First, a temperature limit is drawn based on the thermal stability and conductivity of the electrolyte membrane. With Nafion® this limit should be around 85ºC [6]. At low pressures (≤ 3 bar), the operating temperature is further limited to 80ºC due to the rapid increase of water vapor pressure with temperature.

According to work at Los Alamos National Lab (LANL), Texas A&M University (TAMU), and other laboratories, the ideal operating temperature for PEMFCs is 80ºC [1]. Their studies also indicate that humidification temperatures of the oxygen should be 5ºC hotter [1]. Therefore, we have determined that the air intake system should provide air at a temperature of around 85ºC for optimal conditions.

Pressure
Increasing pressure has similar effects as increasing temperature on the performance of a PEMFC. The rates of diffusion are enhanced at higher operating pressures [1], and activation over potential is reduced by increasing catalyst site occupancy [3]. Figure 5 below illustrates the better performance of a PEMFC due to higher pressures of the reactant gases.

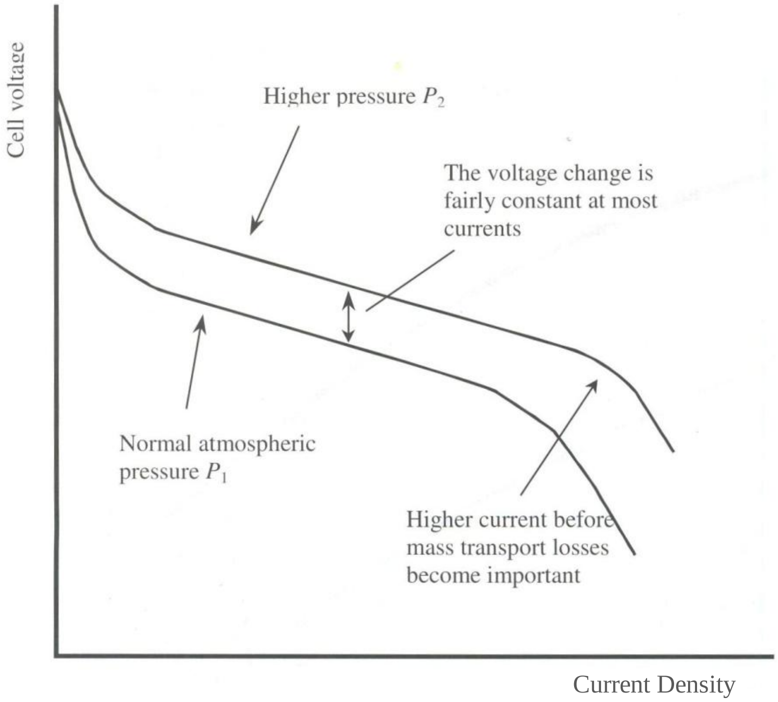


Figure 5: Higher reactant gas pressures result in performance improvements for PEMFCs

Of course, increasing the pressure requires the use of some compression device. This compressor must take in some form of energy to operate. If driven by an electric motor, which is almost always the case, there is a parasitic loss to the entire system; a portion of the power output is lost just for operation. A relationship between voltage gained and increasing pressures is shown in Equation 6 below. An estimate for the parasitic loss to drive the compressor is found by combining Equation 2 with compressor efficiency; this is shown in Equation 7 [3].

$$\Delta \mathrm{V}_{\mathrm{gain}} = C \ln\left(\frac{P_2}{P_1}\right) \qquad \text{[Eq. 6]}$$

$$\Delta \mathrm{V}_{\mathrm{loss}} = 3.57x10^{-7} x \left[\frac{T_1}{\eta_m \eta_c}\right]\left[\left(\frac{P_2}{P_1}\right)^{0.286} - 1\right]\lambda \qquad \text{[Eq. 7]}$$

Where C is a constant, T_1 is the ambient air temperature, η_{m} is the motor efficiency, η_{c} is the compressor efficiency, P_1 is the ambient air pressure, and P_2 is the compressor outlet pressure. The net change in voltage, $\Delta V_{\mathrm{gain}} - \Delta V_{\mathrm{loss}}$, has been plotted with pressure rise ratio, P_2/P_1, for two conditions as shown in Figure 6 below. The values for each variable used in the two models are listed in Table 1.

Table 1: Values used for the models in Figure 6 [3]

Variable	Realistic Model	Optimistic Model
C	0.06 V	0.10 V
T_1	15ºC	15ºC
η_m	0.9	0.95
η_c	0.7	0.75
Λ	2	1.75

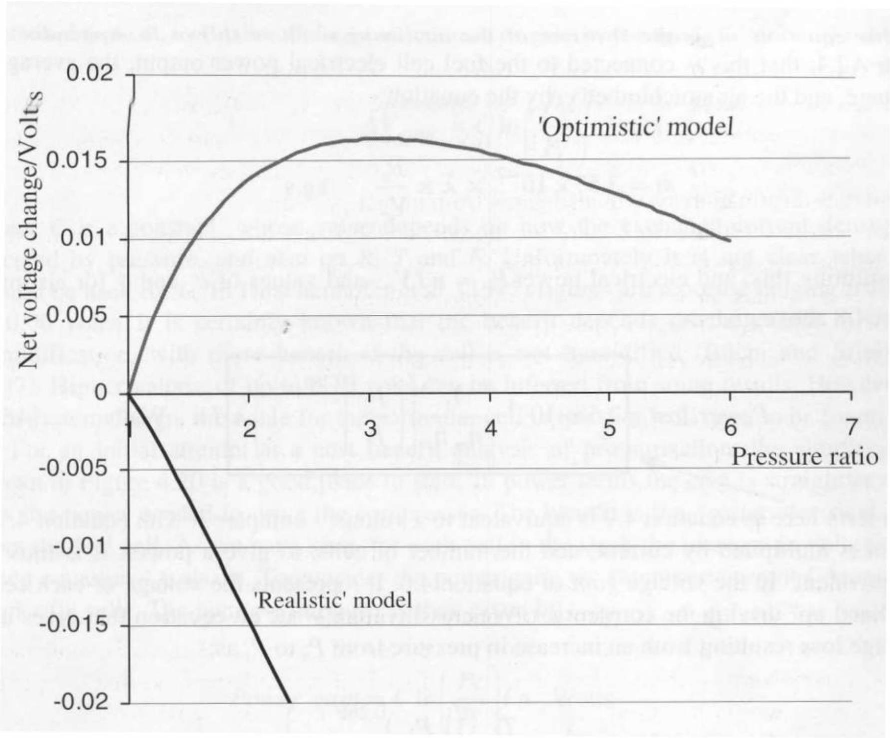


Figure 6: Pressure maximizes PEMFC performance at 3 bar [3]

While Figure 6 above shows an optimal operating pressure for the ‘optimistic’ case of around 3 bar. It also shows that there is never a net gain in the ‘realistic’ model. In other words, the power required to run a compressor is always greater than the power gained by increasing pressure. This “realistic” model is geared more towards small fuel cells with relatively low power output to begin with. Such little power may not be sufficient to drive even the smallest of compressors. Therefore, it is clear why no benefit can be seen with the inclusion of a compressor.

In our system’s application, the automotive fuel cell stack will output power ranging between 50 and 100 kW as mentioned earlier. In practice, it has been found that compressors will draw roughly 25% of the power produced [24]. Even at 50 kW, there will be 12 kW available to drive a compressor when assuming this 25% parasitic loss. It can now be seen how pressurizing a fuel cell is more practical for larger, more powerful stacks.

Operating a fuel cell without pressurizing the air is not even an option for our project. It is clear that a compressor will be required to move this air, especially at idle or low vehicle speeds. Supplying the airflow mentioned above will require an increase in pressure. The optimal operating pressure has been found at 2.5 bar through experiments [23]. This agrees with the theoretical rough estimate shown in Figure 6 [3]. Therefore, we have set our engineering specification for pressure to 2.5 bar.

Purity

There are certain contaminants which have negative effects on the fuel cell. They must be filtered out of the incoming air in order to prevent damage and performance loss of the fuel cell. Like the internal combustion engine, dust must be filtered out since the intake system, as well as the fuel cell, is composed of many components that are sensitive to this impurity. Aside from dust and other particulates, some harmful chemical substances must also be removed.

The common chemical contaminants to fuel cells found in air include sulfur compounds, nitrogen compounds, carbon monoxide and other volatile organic compounds [7,8]. Of these, sulfur compounds are most damaging to the fuel cell because they adsorb onto the Pt catalyst and reduce the number of available reactivity sites for the oxygen reduction reaction [7]. Other chemicals which have serious negative effects on PEMFCs include chemical warfare agents such as cyanogen chloride, hydrogen cyanide, sulfur mustard, and saran [9]. However, because these are very uncommon in normal atmospheric air composition, we will not consider them in our project. We will focus only on the common contaminants listed above.

The PEMFC's tolerance levels to contaminants vary from one to another, and the filter performance for allowable concentrations must be determined accordingly. For example, the effects of carbon monoxide are temporary and fully recoverable with only a 4% drop in power output under concentrations of 20 ppm [8]. On the contrary, only 1ppm of NO_2 causes a 10% drop and 1ppm SO_2 a massive 35%. Performance losses from sulfur compounds are only partially recoverable at best [10], meaning that these substances cause permanent damage to the fuel cell. The effects of NO_2 and SO_2 on PEMFC performance can be seen in Figures 7 and 8, shown below [11].

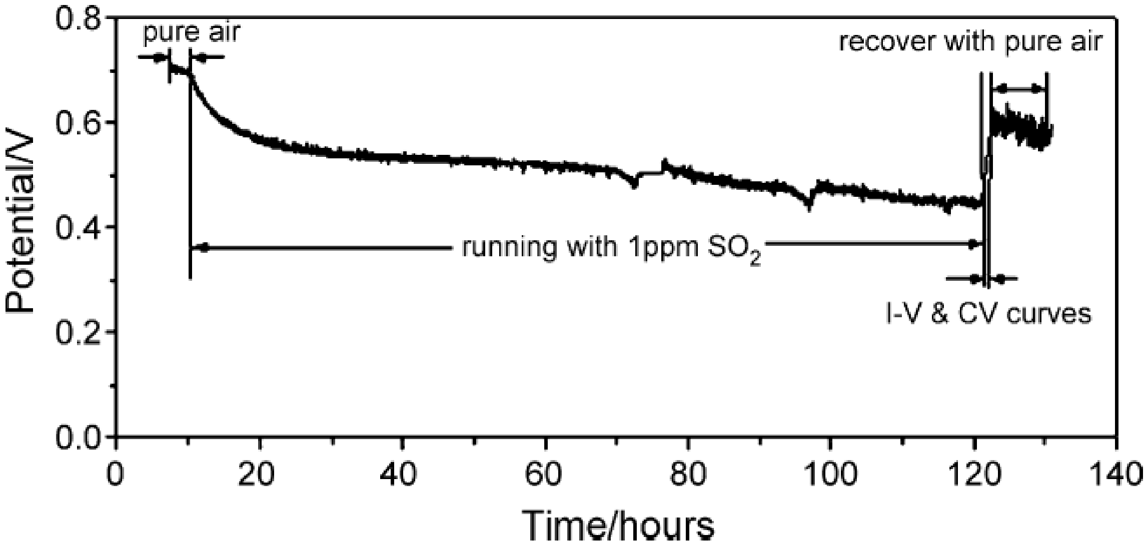


Figure 7: Effect of 1ppm SO_2 on PEMFC performance

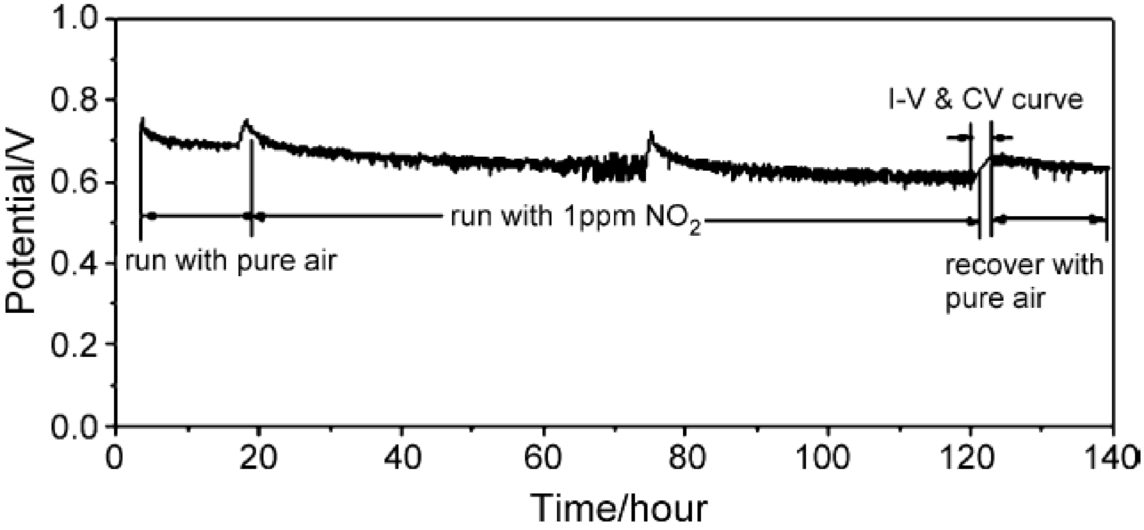


Figure 8: Effect of 1ppm NO_2 on PEMFC performance

Nitrogen compounds found in the air are mainly composed of NO_2 (80%) and NO (20%) [11]. As for sulfur compounds, SO_2 and H_2S are the major contaminants of concern in the air. [7]. The sulfur compounds should be most strictly filtered. Since even 1ppm concentration of SO_2 can decrease power output by as much as 35%, we decided that chemical filters must be effective to a point where < 100 ppb of sulfur compounds are allowed. The next most important chemicals to filter out are the nitrogen compounds. We have determined that chemical filters must be effective to a point where < 500 ppb is allowed. The least important of the harmful chemicals that require filtering is carbon monoxide. We determined concentrations < 20 ppm acceptable. In areas of high pollution created by industrialization, SO_2 concentrations as high as 300-400 ppb have been recorded [12]. H_2S concentrations lie in the ppt ranges and may not present much of an issue. Nitrogen compounds range up to 500 ppb [12] and therefore may also not be an issue. Carbon monoxide levels have been known to be recorded at the 40 to 200 ppb range with a strong downward trend of the concentration in North America [12]. Considering that the allowable amount of carbon monoxide concentration is in the 20 ppm range, this will also not be a problem to the fuel cell.

Noise

We have determined our target for noise generation to be below 65 dBA [34]. Initially, we benchmarked our system against an internal combustion engine vehicle. Visteon informed us that their current target for such a system is between 60-70 dBA. After conducting research, we found an article stating that their chosen compressor met the requirements of generating noise below 65 dBA [24]. From this and the fact that the compressor is the loudest component of the air intake system, we have set a target of 65 dBA for our entire system. To achieve this target, we plan on using Hemholtz resonators to attenuate any frequencies exceeding this threshold. The frequency being attenuated can be calculated based on Equation 8 below.

$$f_H = \frac{v}{2\pi}\sqrt{\frac{A}{V_o L}} \qquad \text{[Eq 8]}$$

where f_H = frequency being attentuated v = speed of sound in a gas A =
Cross sectional area of the neck V_o = Volume of the cavity L = Length of the neck

Another tool we will use to attenuate high dBA frequencies is a quarter-wave resonator. Quarter-wave resonators work by use of the principal of destructive interference. Destructive interference is the canceling out of a sound wave by interaction with another wave that is "out of phase". A sound wave enters the quarter-wave resonator, reflects off the back surface, and exits the resonator cavity with a half-period shift. The exiting sound wave causes destructive interference with the original wave.

Packaging

Our team was not given a specific car to model our design for but instead, we were told that the design should be made for use in a "small to mid-size vehicle". As a result, our team has made assumptions about the packaging and size of our design. In the United States, a mid-size vehicle today has an average wheelbase between 2.667-2.794 meters [13]. Since there is no mention on width of mid-size vehicles in US classification, we used Japan's system which defines an average width of about 1.7 meters for mid-size vehicles [13]. Since our team is concerned with the distance from the front of the car to the fuel cell stack, our team also needed an overall length of mid-size vehicles. Our team chose the Toyota Camry, a commonly purchased mid-size vehicle in the US, as a typical model for the length. The Toyota Camry has a vehicle length of 4.81 meters [14]. Our team has assumed that the fuel cell stack will be exactly in the middle of the car based on our knowledge of current fuel cell vehicles' packaging [15]. Our assumed length between the front of the car and the fuel cell stack is 2.4 meters.

To determine the current packaging of the components for an air intake system of a fuel cell vehicle, our team has looked at a variety of current vehicles. One such vehicle is the Honda FCX Clarity. As seen in Figure 9 the air enters the scoop located under the hood, moves to the filter and then the compressor. Figure 10 shows a composite fuel cell vehicle where air enters the scoop located at the front right, goes through an air filter and compressor, cycles back to the front through an intercooler, and then goes through the humidifier near the center of the car before reaching the fuel cell stack.

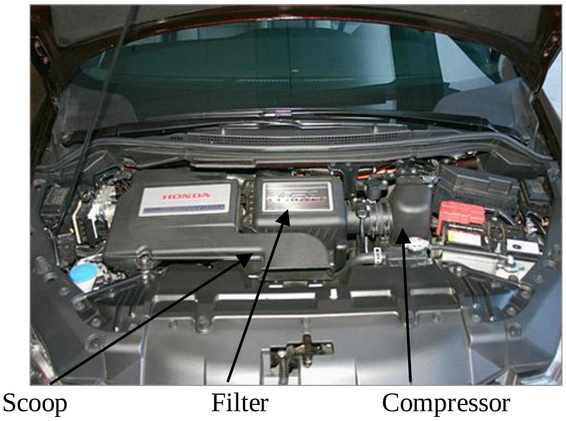


Figure 9: Honda FCX Clarity [16]

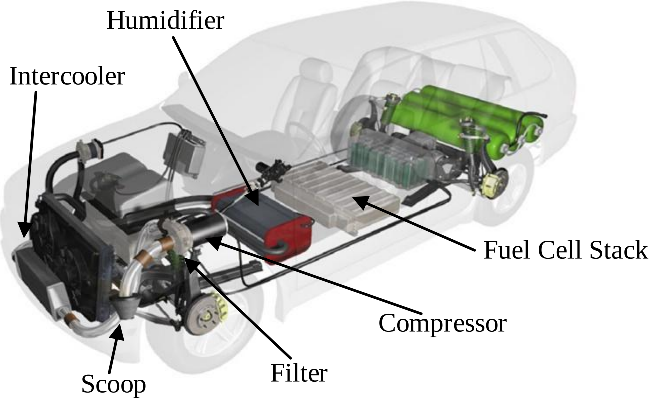


Figure 10: Composite Fuel Cell Arrangement [15]

Customer Requirements

The customer requirements are at the heart of any design. The most amazing design is worthless if it does not achieve the desires of the customer. When we think about our customer, it is important to not only design towards the desires of our sponsor (Visteon), but to also meet the desires of the end customer (drivers).

The best way to determine Visteon's requirements was to personally ask them. A meeting was set to discuss their expectations for the air intake system. Our sponsor's top requirements in order of most important to least important are: product serviceability, cost, quietness, performance, and durability. Although not specifically mentioned as a top priority, our team believes that there are some additional important requirements for our sponsor. These include: ease of manufacture, packaging, and weight.

End customer requirements were more difficult to determine; however, as drivers, we had a good idea of what might be important. We speculate that the driver's top priorities are: performance, cost, quietness, durability, and serviceability.

ENGINEERING SPECIFICATIONS

The first step in meeting our customer requirements is to understand the PEMFC and identify the engineering specifications needed for an air intake system. Through literature review and research, we were able to accomplish this. As described in the previous section, the airflow characteristics necessary for the fuel cell to operate at peak performance include airflow rate, humidity, temperature, pressure, and air purity. Aside from airflow characteristics, the intake system must also have engineering specifications set for its noise levels and packaging. Table 2 summarizes the engineering specifications determined for the air intake system of a mid-size fuel cell vehicle.

Table 2: Fuel Cell Air Intake Engineering Specifications

	Characteristic	Specification
1	Airflow Rate	50 L / sec
2	Humidity	100% R.H.
3	Temperature	85ºC
4	Pressure	2.5 Bar
5	SO_2 Filtration	<100 ppb
6	H_2S Filtration	<100 ppb
7	CO Filtration	<20 ppm
8	NO_2 Filtration	<500 ppb
9	NO Filtration	<500 ppb
10	Dust Filtration	> 9
11	Noise	< 65 dBA
12	Lifetime	> 4000 hours
13	Packaging	1 m^3

A quality function deployment was constructed and can be seen in Appendix D. This was used to determine the engineering specifications hierarchy when they are considered in design.

Quality Function Deployment

Having determined the engineering specifications of the intake system, we needed to analyze the interactions between them as well as how each correlates with customer requirements. A quality function deployment (QFD) diagram was used for this analysis. Our completed QFD can be seen in Appendix D. Assigning weights to each customer requirement was necessary. The QFD aids in determining a hierarchy of importance for our engineering specifications. This acts as a tool for discerning judgment when tradeoffs between one specification and another must be considered. The top 5 are, in order of most important to least: pressure, temperature, humidity, lifetime, and filtration.

Customer Requirement Weights

We divided the customer requirements into a hierarchy with three levels. The top of the hierarchy includes a long lifetime for the fuel cell, a long lifetime of the air intake system, a cost efficient intake system, and high performance from the fuel cell. The second tier of this hierarchy includes noise generation, ease of maintenance, eco-friendliness, packaging, and ease of manufacturing. The customer requirements with the lowest priority include the aesthetics and weight of the air intake system.

We determined the relative importance of the customer requirements by taking into account the order of their importance to our customer and how many of our customers are affected by the requirement. We discussed in an earlier section how customer requirements were determined. For our customer Visteon, we were fortunate enough to be able to ask them what their requirements were and in what order. For the drivers, we used our own ranking as drivers ourselves. If a requirement impacted only one of our two customers and ranked low on their hierarchy, it received a relative weight of one. If a customer requirement was moderate to one customer or was a requirement of both of our customers, it received a weight of three. If a customer requirement was a high priority of either customer or of moderate importance to both customers, it received a weight of nine.

CONCEPT GENERATION

From the literature review, we now have a general idea of the system requirements. Of course, these requirements and engineering specifications will continually be developed and updated with ongoing research. However, they allow us to take the next step towards reaching our goal of creating the best tangible system design and materializing a working prototype. This step is known as concept generation and involves the brainstorming of all possible ideas. At this stage, no ideas are to be rejected; criticism and evaluation are unwelcome. The goal here is to avoid narrow-mindedness and to branch out and explore every possibility. Creativity and imagination may spark designs and ideas which otherwise would never have been considered. However, the methodology we followed was neither random nor without reason.

We began by analyzing the engineering specifications gathered through research to break down the air intake system into its individual functions. This allowed us to simplify our concept generation by focusing on individual categories rather than the system as a whole. The functional decomposition revealed five categories for which concepts were generated. These are: intake inlet scoop, filtration, compression, humidification, and temperature control.

Component order was also a subject which required concept generation. A detailed list of all concepts generated and pictures of some of these concepts can be seen in Appendix F and Appendix G.

Functional Decomposition

From the engineering specifications, we determined the important functions which must be performed by the air intake system. Figure 11 shows the functional decomposition.

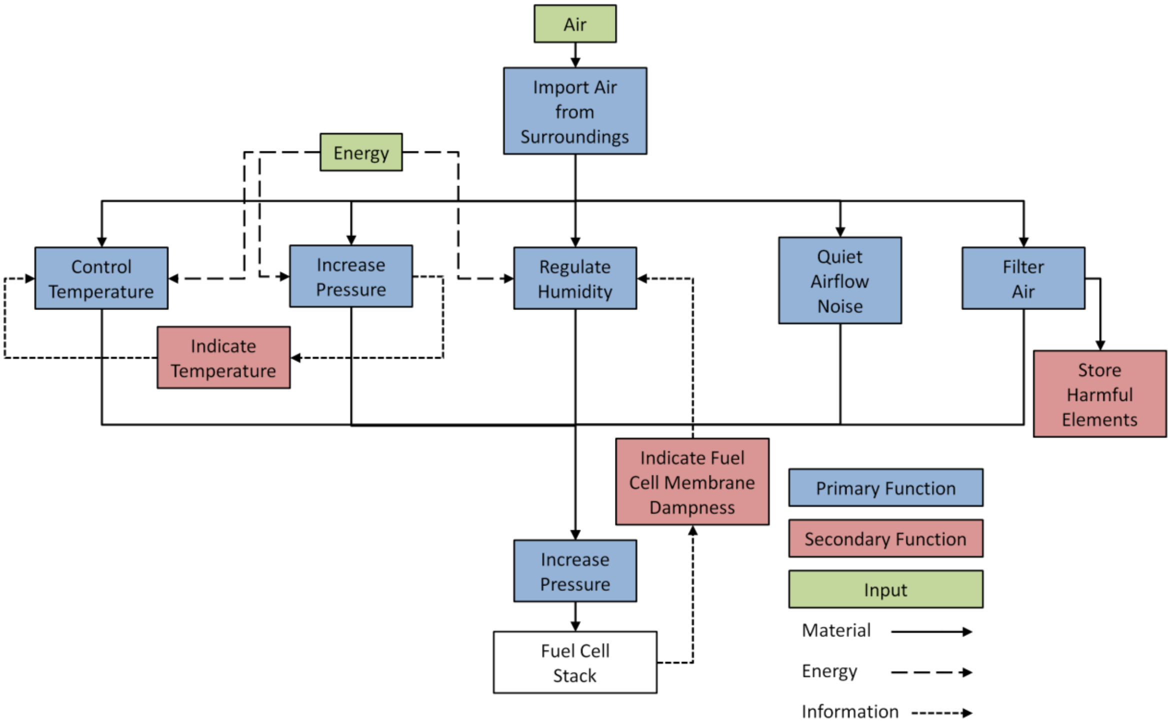


Figure 11: Functional Decomposition of the Air Intake System

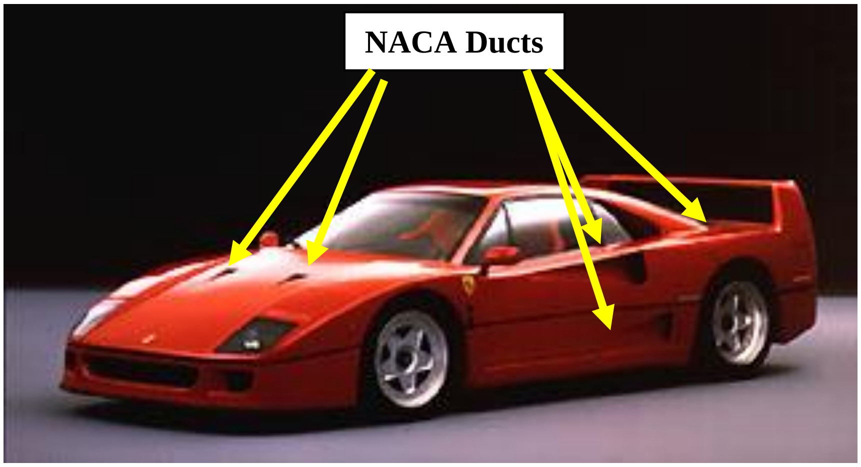
Since our design project is the air intake system of a fuel cell vehicle, the most important component for our system is the incoming air. The primary functions of our system include: taking in air from the ambient, filtering harmful substances out, quieting the noise of the airflow below 65 dBA, regulating the temperature to 85°C, achieving a humidity of 100%, increasing pressure to 2.5 bar, and guiding the air to the fuel cell stack. Inputs to the system include the air and the energy needed to achieve the desired temperature, humidity, and pressure.
Importing air into the system includes directing the air in from the ambient, ensuring a flow rate of 50 L/sec, and eventually directing it to the fuel cell. Filtering involves the removal of dust and harmful chemicals (primarily SO_2) from the air and storing those elements. The important aspects of pressurizing the air include increasing the pressure to 2.5 bar, minimizing pressure ripples, and minimizing energy usage. Temperature control involves regulating the temperature of the air to 85°C by applying the proper amount of heating/cooling and then making sure heat losses are minimal between the controller and the fuel cell. Controlling the humidity requires a system that can adjust the humidity of the air at the intake to 100% and then monitor the dampness of the fuel cell membrane to prevent it from becoming soaked. Lastly, noise must not exceed 65 dBA.

Intake Inlet Scoop

The purpose of the inlet scoop is to direct air from a specified location towards the air intake system. Some of the major concepts for this intake inlet design are described in detail below.

The "Whale Mouth" idea originates from observing a whale or a manta ray with a large mouth opening. This allows the creature to be able to take in large amounts of water. We found this concept inspiring because our system requires large amounts of airflow (about 50 L/s). This design would consist of a large cross-sectional area scoop which leads to the ducting.

The idea of NACA Ducts came from the many NACA ducts seen on the Ferrari F40. Upon some research, these ducts were developed from what is now NASA and were designed for low drag on flight applications. The NACA duct design is a submerged scoop along the surface of a vehicle's body as shown in Figure 12 below. These ducts will allow air to enter while minimizing disturbance of the flow to the rest of the flight vehicle. [17, 18]



http://www.gtplanet.net/

Figure 12: Many NACA ducts are found on the Ferrari F40

Although ground ducts and inlets are not commonly seen in modern production cars, our team thought this would be a good solution to the packaging constraint. Inspiration for this type of design came from the radiator placement of the 1983 – 1989 Nissan 300zx which one of our teammates has worked on. The radiator was placed at an angle and practically on the underside of the car. The car itself had a low and raked hoodline limiting front space of the engine compartment and most likely caused designers to place this radiator on the underside of the car. Just like this car, our team thought that placing the scoop underneath the car would deliver the proper amount of air necessary without taking away too much space from the other components of the car.

A Multi Scoop System is commonly employed in modern race cars; however, they are usually absent from production cars. Considering that the engines in these cars need a lot of air to produce power and cool the components, our team felt this design could be utilized for our project.

A Variable Duct Opening may be able to achieve high pressure for our intake system. Specifically, the inspiration for this idea came from new Yamaha sport bikes YCC-I electronic variable-length intake funnel system. The length of the intake runners would adjust according to the speed of the bike. The intake runners would be short at low speeds to deliver air at the optimum conditions for the engine. At higher speeds, the intake runners would lengthen to create more of a ram air effect, increasing flow to the engine and producing more power. [19]

Compressed Oxygen Tanks would deliver pure oxygen to the fuel cell instead of using ambient air. Removing the need for filtration and pressurization, this design would simplify the air intake system and would still meet all the requirements set out for our design project.

Filtration

The purpose of the filter is to remove the harmful contaminants, mentioned on P.11, from ambient air to prevent damage and power losses to the fuel cell stack. Our four major concepts for this filtration component are described in detail below.

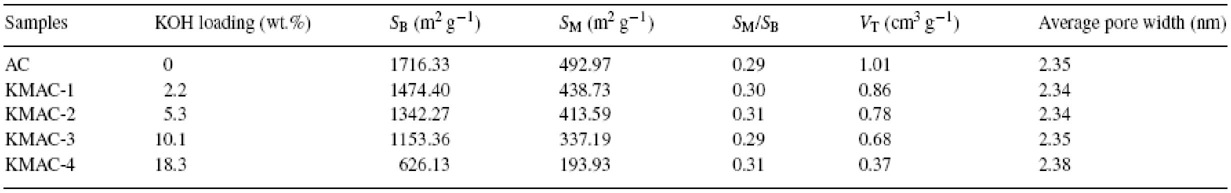
Dust Filters would be used in front of the chemical filter to filter out dust particles and soot particles. Particularly the Visteon dust filter would be a very good candidate for our design. It is efficient and Visteon manufactures it, saving them research and cost [7].

Membrane Filters are commonly used as a filter attached to the fuel cell. It would prevent metallic compounds from entering the fuel cell via water particles [31].

Donaldson Chemical Filter is the only filter we found that is both a dust and chemical filter. It has been specifically designed for a fuel cell [30]. This filter design is advantageous because it combines the dust and chemical filter, thus reducing space.

Active carbon filtration has been widely used in other applications to filter chemicals out of the air. They are more geared towards filtering air for fuel cells than just every day use. A Chinese company that makes fuel cell vehicle powertrains investigated additions to activated carbon filters in order to improve effectiveness in a fuel cell vehicle air intake system. Their research concluded that MAC filters or a Modified Activated Filters, more specifically a KMAC or Potassium Hydroxide solution Modified Activated Carbon filter improves filtration performance [10]. Theses filters have been tested for how well they remove NO_x and SO_2 compounds in the air as well as how CO_2 affects the filter absorption properties. The best combination of potassium solution with activated carbon is the KMAC-3; the components making the KMAC 3 can be seen in Table 3 [10, P.384] from the article below.

Table 3: KOH loading and textural characteristics of adsorbent samples



Samples	KOH loading (wt.%)	S_B (m^2 g^{-1})	S_M (m^2 g^{-1})	S_M/S_B	V_T (cm^3 g^{-1})	Average pore width (nm)
AC	0	1716.33	492.97	0.29	1.01	2.35
KMAC-1	2.2	1474.40	438.73	0.30	0.86	2.34
KMAC-2	5.3	1342.27	413.59	0.31	0.78	2.34
KMAC-3	10.1	1153.36	337.19	0.29	0.68	2.35
KMAC-4	18.3	626.13	193.93	0.31	0.37	2.38

The performance of KMAC-3 compared to other KMACs for NO_x can be seen in Figure 13 [10] from the article below.

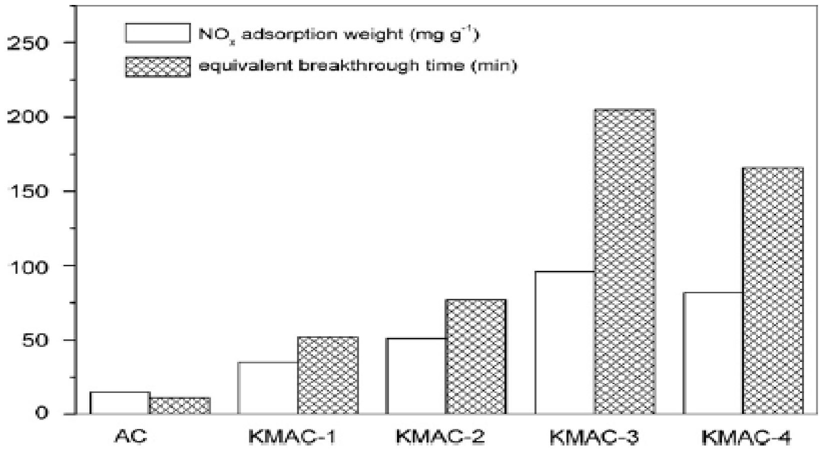


Figure 13: NO_x adsorption weights and equivalent breakthrough times on AC and KMACs.

The performance of KMAC-3 compared to other KMACs for SO_2 can be seen in Figure 14 [10]

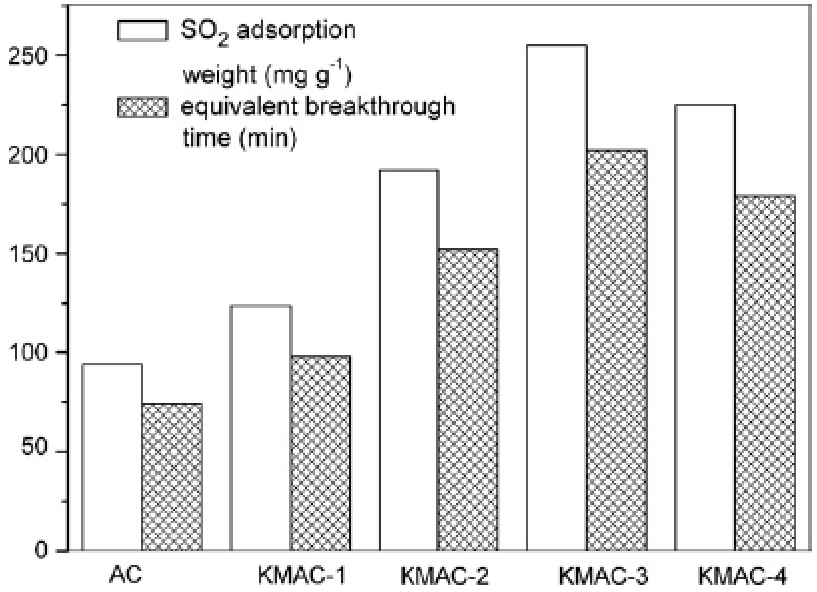


Figure 14: SO_2 adsorption weights and equivalent breakthrough times on AC and KMACs.

When a fuel cell is subjected to 1ppm of NO_x it loses as much as 10 percent of its performance. At 1ppm of SO_2, the fuel cell looses around 30 percent of its performance within just 5 hours of exposure [11]. To make sure that these filters worked, the fuel cells were subjected to SO_2 and NO_x contaminants for 240 hours. With the filter in place (first 175 hours), performance was steady. When they removed the filter, the output voltage of the fuel cell stack dropped dramatically, by about 40 percent [10]. This is shown in Figure 15 [10].

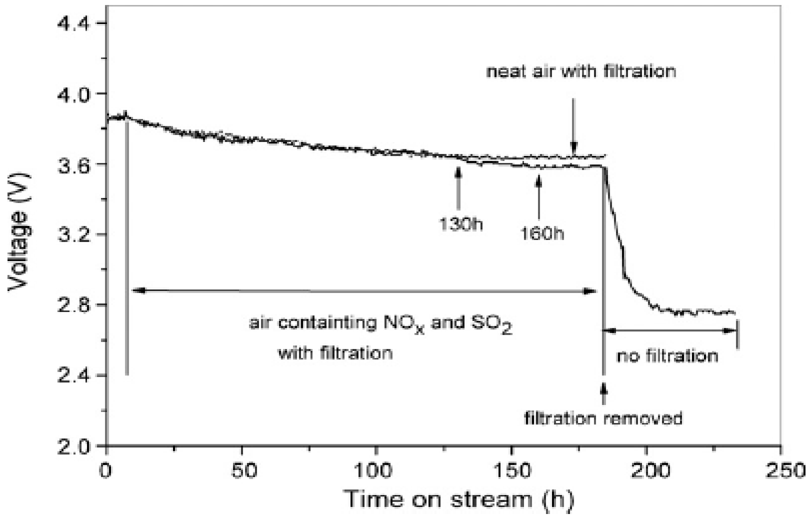


Figure 15: Voltage output curve versus time of 250W stack exposed to NO$_x$ and SO$_2$ with and without filtration.

This made clear that these filters were very effective at filtering NO$_x$ and SO$_2$ particles. CO$_2$ has been found to decrease performance of Activated Carbon filters. To test the KMAC-3 filter's reaction to the CO$_2$ presence, they first saturated the filter with CO$_2$. Then, they added pure NO$_x$ at 65 minutes.

The NO$_x$ begins to replace the CO$_2$ and take its place on the filters surface at around 300 minutes. The CO$_2$ is no longer in concentration and almost all of the NO$_x$ is absorbed. You can see this in the Figure 16a below [10]. To test SO$_2$, they introduced SO$_2$ into the filter at the 210th minute after it was saturated with CO$_2$. As you can see, the SO$_2$ begins to be absorbed and by the 370th minute all of the CO$_2$ is replaced by the SO$_2$ due to its higher acidity [10]. This can be seen in the Figure 16b below [10].

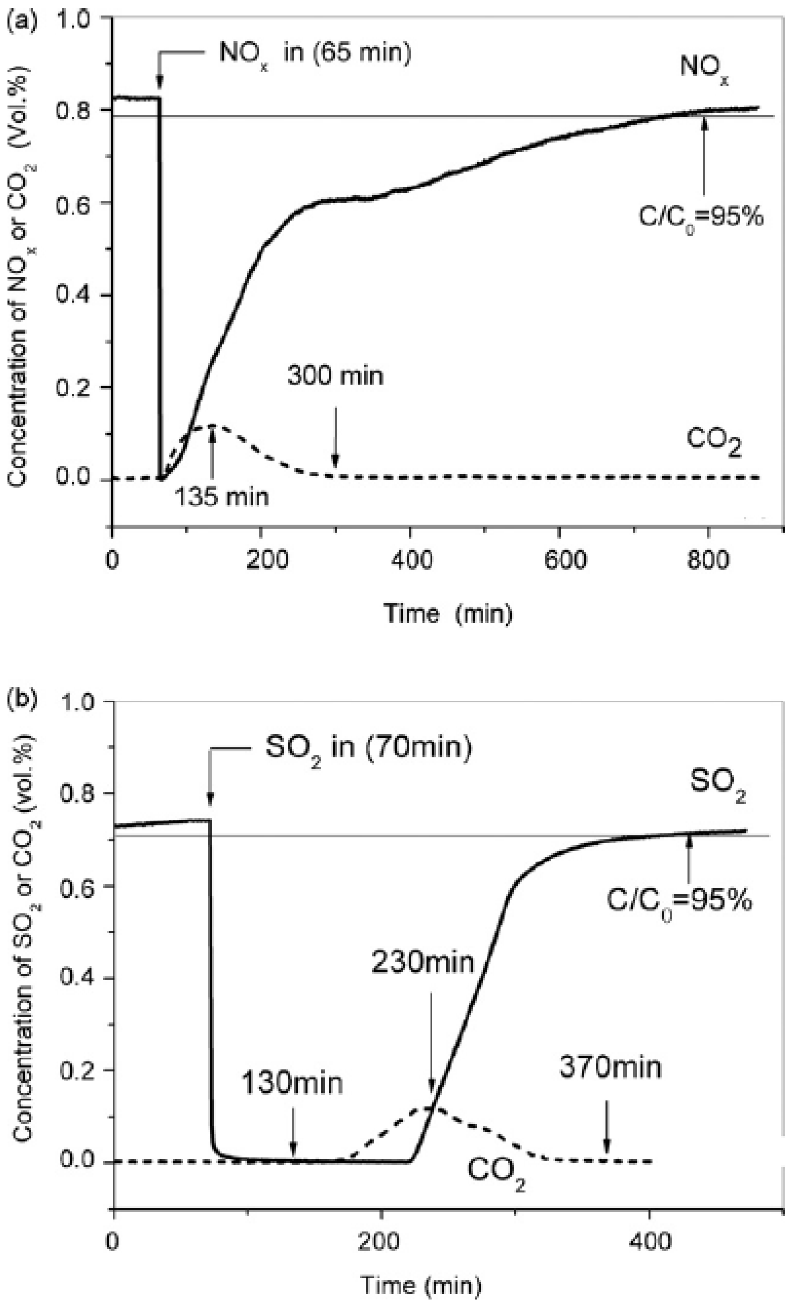
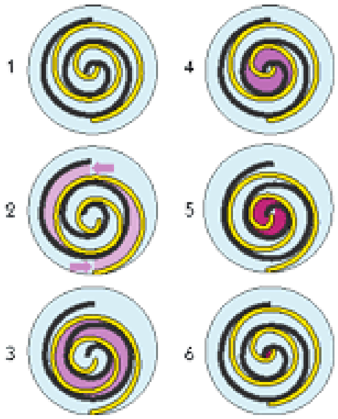


Figure 16: Breakthrough curves of NO$_x$ (a) and SO$_2$ (b) adsorption on KMAC-3 with CO2 presence.

Compression

Besides increasing pressure of the air, the compressor component will also supply the necessary airflow to the fuel cell stack. Studies over the past several years show that a variety of compressors may be used to achieve the desired characteristics for the air intake system [23]. Therefore, we examined various well-known compressor designs for this component's concept generation. A description of our main compressor designs and how they work is seen below:

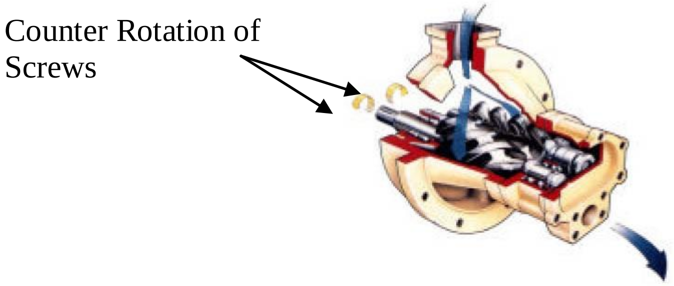
Scroll compressors are rotary positive displacement mechanisms that compress air by rotating two offset spiral disks that are nested together. The lower disk moves in an "orbital" fashion, while the upper disk remains in place. Air is taken in from the ambient through inlet ports on the compressor. The “orbiting” effect then creates sealed spaces of varying volumes which are eventually transferred to the center of the disk where the air is discharged. The air’s volume is decreased and the pressure increased [29]. Figure 17 demonstrates how air enters the outer portion of the scrolls, gets trapped between the disks, condensed towards the middle through the “orbiting” effect and then discharged from the center.



www.fscc-online.com

Figure 17: Steps of air compression between two disks in a scroll compressor.

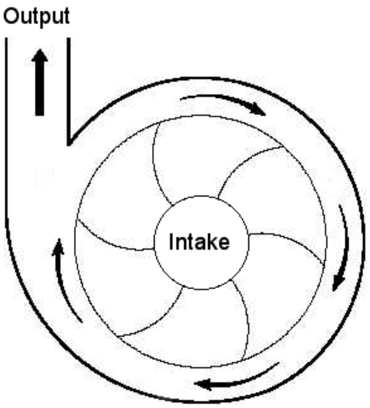
Screw compressors are rotary positive displacement mechanisms that compress air by either using one screw element (single helical) or two counter rotating screws (double helical). As seen in Figure 18, air is drawn in through the inlet and delivered to the screws. As the screw/s rotate, the meshing creates a series of volume reducing cavities, increasing pressure. Compressed air is then delivered at the outlet. Screw compressors may require the use of oil in the compression process; however, more complex compressors can be oil free. Screw compressors that use oil have a filter to extract the oil from the air and then recycle it for additional use.



http://www.itwifeuro.co.uk/Editor/Images/fig3_standard.jpg

Figure 18: Air compression for a double helical screw compressor.

Centrifugal compressors are radial flow mechanisms mechanism that compress air by adding kinetic energy (velocity) through a continuous flow by use of an impeller and then convert the kinetic energy to pressure by slowing the flow through a diffuser. As seen in Figure 19, air comes in through the center impeller, rotates outward towards the wall, and then is released through the outlet.



http://www.sawdustmaking.com/AirCompressors/centrifugal.gif

Figure 19: Air compression for a centrifugal compressor.

Lobe Compressors are positive displacement pumps that compress air through the use of one or more pairs of counter rotating lobes. As seen in Figure 20 below, air is drawn into the compressor through inlet. Air is then trapped against the wall decreasing volume and increasing the pressure and finally pushed out through the outlet.

http://m.b5z.net/i/u/10041456/i/lobe_pump.jpg

Figure 20: Air compression for a lobe compressor.

Humidification

The humidifier component must control the amount of water vapor in the air so that the target of 100% relative humidity is achieved. Much like compressors, there are many proven humidification methods and technologies which can be used in the air intake system. Descriptions of our main humidifier designs are seen below:

Liquid Water Injection humidifiers spray water into the airstream at high pressure. By controlling the amount of water injected into the system, the liquid injection method can control the humidity properly based on the characteristics of the incoming ambient air and the desired final humidity.

Nafion® membrane humidifiers are currently used in fuel cell applications today. They work by allowing the transfer of water to the air through a permeable membrane. The air travels along the membrane until it achieves saturation.

Carbon Foam humidifiers use graphite foam due to its high thermal conductivity as a heat exchanger between the air and the water. Similar to the Nafion® membrane, air becomes saturated after traveling along the carbon foam which contains water on the other side.

Temperature Controller

The goal of a temperature controller is to achieve 85ºC for the air at the inlet to the fuel cell. There were two categories in concept generation for temperature control; they were heating and cooling. We were unsure whether heating or cooling was required for our system until after an analysis using the adiabatic compressor equation was completed.

Induction heating system would entail wrapping a certain length of ducting with wire. By induction heating, the pipes would increase the temperature of the air. This simplifies the design by reducing the space otherwise needed for a dedicated component. The temperature could be controlled by varying the amount of current through the wires.

Air Conditioning Unit would cool the air similar to an air conditioning system in a car by use of a refrigeration cycle. This would allow for precision in the amount of cooling.

Intercoolers are commonly used in cars today to cool airflow charges by either an air-to-air or water-to-air heat exchange. Both systems would effectively remove heat from the system and require fluid for heat transfer. One modification to current designs would adjust the amount of cooling the intercooler would provide. We would adjust the amount of cooling by controlling the exposed cross-sectional area of the intercooler. This can be accomplished by employing flaps similar to window blinds which open and close. This idea came from radiator covers for diesel trucks that are used in the winter. In the winter, less cooling is desired as it allows the engine to reach operating temperatures quicker.

CONCEPT SELECTION

To choose the best design for our air intake system, our team evaluated the concepts for our components individually, discussed the pros and the cons of each concept, and then assembled the best concepts into our final "alpha" design. We examined the concepts for the intake inlet scoop, filters, compressors, humidifiers, and cooling system each in its own Pugh chart (seen in Appendix H). We then weighed each design for how well they meet key characteristics on a scale of 1 (poor) to 5 (excellent).

Intake Inlet Scoop

Although our intake system had many different concepts generated, we could effectively combine multiple ideas to most efficiently deliver the air to the intake system due to the nature of how scoops function. Emphasis was placed on shape and location of the scoop. For our system overall, we will combine the "whale mouth" idea and the low ground duct ideas to most effectively draw in air into the system. Our team evaluated our air intake scoop and ductwork concepts according to the following criteria:

1. Mass Flow: Needs to take in a large volume of air
2. Maintain Pressure: Able to keep integrity and shape under high pressure
3. Efficient: Effectively deliver the air with the proper parameters with little loss
4. Packaging: Needs to fit within an automotive frame easily
5. Filtration: Able to accommodate a filter to keep large particles out of intake system
6. Noise: Must not produce noise when air passes through

7. Durability: Needs to be structurally sound and last the lifetime of the vehicle
8. Cost: Perform as specified and not be expensive to design and manufacture
9. Packaging ability: Fit within the space constraints of a small to midsize vehicle frame

A comparison of all intake/scoop concepts can be seen in the Pugh chart in Appendix H.1.

"Whale Mouth" Design - Incoming air first contacts the front of any vehicle, so placing the "Whale Mouth" concept intake in the front of a car made the most logical sense. The main drawback of this design would be the packaging constraint.

NACA Duct - For the NACA ducts, the drawbacks are that they cannot produce large intake pressures or flow rates, which is specifically the reason why they have been almost completely abandoned for jet intake applications [17, 18]. For these reasons, our team decided not to use this design.

Ground Duct - For the ground duct and inlet idea, this design is the highest scoring out of all the designs as seen on our Pugh chart, Appendix H.1. This is due to the high efficiency of the ducting and the ability to draw in lots of air needed for the fuel cell.

Multi-Scoop System - Upon further analysis of the multi-scoop system, the amount of ducting being looked at was way too much for what would be proper for a production vehicle; especially considering that this duct work would cut into a lot of the passenger compartment of the car. Due to packaging and cost restraints, this design scored low in our Pugh chart.

Variable Intake - Regarding the variable intake concept, although their compact design would work well for something as small as a sport bike, the amount of space our design would need to properly vary the intake opening would be illogical for a small to midsize car. Also the added complexity and cost of the system would conflict with our design constraints.

Compressed Oxygen - The only problem with the compressed oxygen system is that there currently is no sort of infrastructure to supply compressed oxygen for automotive purposes. The high cost of this sort of design is not a very good alternative to the other concepts previously discussed. As much as this idea would be a great solution to our design project, it is not the most ideal with our constraints and was ruled out during our concept evaluation.

Filtration

Filters are very important to the fuel cell, it is critical to make sure that the filter we recommend is very efficient and effective. For our design we chose the Activated Carbon filter for chemical filtration and the Visteon Long Lifetime dust filter for dust particles. We felt that this design would work best in removing harmful chemical elements and dust from the incoming air. Our team evaluated our filter concepts according to the following criteria:

1. Low Restriction
2. Large Surface Area
3. High Efficiency
4. Low Cost
5. Long Lifetime: Both for the dust and chemical filter
6. Replaceable
7. Small Size

A comparison of all filter concepts can be seen in the Pugh chart in Appendix H.2.

***Visteon Dust Filter* -** To choose the best filter we had to look at each concept very carefully and asses its different features. Starting with our first concept, the Visteon Dust filter, we had an on-site tour with our sponsor to discuss filter performances. For current internal combustion engine vehicles, we found these filters can last up to 150,000 thousand miles [20] without maintenance. Their porosity is around 97 percent [20] making air restriction very minimal, therefore minimizing pressure drops. In addition to these specification, Visteon added noise control to the filter to minimize noise generation, which is important for a fuel cell vehicle. For these reasons, the Visteon dust filter was chosen to filter dust out of the air.

***Activated Carbon Filter* –** Our team also chose Activated Carbon filters to filter out the chemicals from the incoming air. Specifically, after looking at the other KMAC filters, the KMAC-3 is the best choice for our final design. According to our research, the KMAC-3 is fairly inexpensive and functions at a very high efficiency in removing the most harmful chemicals from air SO_2 and NO_x. It can take on a non-restrictive design which is important for airflow, and appears to have a long lifetime.

***Membrane Filter* -** Our first concept for a chemical filter was the Membrane filter. This filter attaches to the fuel cell and would clean the air entering the cathode. Membrane filters are best used when the fuel cell gets air that is super-saturated, meaning water particles are present. They are good at separating metal ions and salt that travel in the water with the air, but not good at removing harmful particles from gas that would damage the fuel cell [21]. They have not been as thoroughly tested as other filters for PEMFC use. Because of these complications, our team decided against this idea.

***Donaldson Chemical Filter* -** A filter which removes both dust and chemicals from the air is the Donaldson filter. This filter is designed specifically for a fuel cell and takes care of sulfur compounds, nitrogen compounds, hydrocarbons, and carbon dioxide [22]. These would be good filters to use in our air induction system as they perform exactly what we require. The problem with these filters is that they do not have a desirable lifetime. Their lifetimes are only around 3000 to 5000 hours [22]. Plus the system would have to be built around the filter, due to their lack of versatility. In addition, the filter is much more expensive than requested by Visteon. Although this is a good filter, it does not fit into an air intake system very well.

Compression

To achieve the desired pressure level of 2.5 bar and volumetric flow rate of 50 L/s for the air intake system of a PEMFC, our design requires a compressor to regulate these variables. Our team has chosen the screw compressor for our final design mostly due to its ability to achieve the desired pressure and airflow required for our air intake system. Originally our team had chosen a scroll compressor for our alpha design. However, after further analysis of the required airflow, our team determined that a scroll compressor of reasonable size could not reach the necessary mass airflow rate for our system [37].

In this section, our team has evaluated our compressor choices based on their requirements for fuel cell application in transportation. The list of criteria that our team was looking for in a compressor is seen below:

1. Pressure Ratio: desired 2.5 bars at the outlet of the compressor
2. Oil Content: oil must be prohibited from entering the fuel cell to prevent contamination of the membrane or electrodes.
3. Pressure Ripple: no ripple greater than 100-200 mbar should occur to avoid damage to the membrane [24]
4. Weight: should be as small as possible
5. Size: should be as small as possible
6. Efficiency: power used to run the compressor should be minimized
7. Cost
8. Reliability
9. Noise: Must be as quiet as possible

A comparison of all compressor concepts can be seen in the Pugh chart in Appendix H.3.

Screw Compressor - After evaluating potential compressors for use in our air intake system, our team has chosen the double helical, oil-free screw compressor. The key advantages of a scroll compressor are as follows: [3]

1. Can maintain a pulse free airflow of 2.5 bar outlet pressure
2. Air-stream can be made oil-free
3. Efficient at a wide range of power requirements
4. Can achieve the mass airflow rate required for fuel cells
5. Have a compact size and low weight [26]

The major disadvantage of the screw compressor is its cost. Screw compressors that maintain an oil-free flow generally cost a lot more [26]. However, our team feels that the performance and reliability of this compressor are enough of a reason to choose it over the cheaper alternatives. Another disadvantage of screw compressors is its ability to meet noise requirements as they tend to be louder than most other compressor types. However, this can be remedied by using noise dampening material around the compressor unit.

Scroll Compressor – Initially, our team chose a scroll compressor for use in our air intake system, but after further examination, we realized that scroll compressors could not achieve the desired mass airflow rate required at the outlet of the compressor of our air intake system. While scroll compressors have many positives such as, oil-free operation, low noise, and high pressures, our team must dismiss the idea due to the fact that reaching the desired airflow rate is difficult for such compact size requirements.

***Centrifugal Compressor* -** Another compressor considered for our air intake system was the centrifugal compressor. Centrifugal compressors are most commonly used in today's PEMFC automotive application due to their cost, light weight, and compact size [24]. However, our team chose not to use a centrifugal compressor due to its major disadvantage that it's energy efficiency is only high for a limited range of mass flow and pressure [24]. While the car is at idle or at low speeds (the power requirement to run the car is below 20 kW [24]), centrifugal compressors cannot maintain the desired outlet pressure of 2.5 bar resulting in a low efficiency [23]. Also, some centrifugal compressors that use oil for lubrication have problems keeping the oil out of the airstream [23]. For these reasons, our team chose not to use a centrifugal compressor.

***Lobe Compressor* -** Our team also considered using a lobe compressor for our design because they are relatively cheap [27]. They are able to achieve the required pressure and mass airflow rate. However, lobe compressors are fairly heavy, large, and may cause pressure ripples in the airflow [23]. Due to these faults, the lobe compressor was not chosen for our design.

Humidifier

To achieve the desired 100% relative humidity for the air at the inlet of the fuel cell, our system requires a humidifier. Several methods of humidifying the air may be used for fuel cell, such as: water injection, absorption through a membrane, and absorption through carbon foam. Our team chose water injection as our humidification system because of its ability for high precision in the amount of water being added to the system. Our team has evaluated all our concepts for use in the air intake system of fuel cells in automotive applications using the following criteria:

1. Humidity: ability to achieve desired 100% relative humidity for all air intake conditions
2. Efficiency: achieve humidity at low power consumption
3. Power: low power consumption
4. Cost
5. Lifetime: ability to last five years
6. Size: small humidifier and small water tank
7. Operating Temperature: ability to function at wide range of temperatures
8. Air Flow/Pressure: does not impair other important variables in system

A comparison of our humidifier concepts can be seen in the Pugh chart in Appendix H.4.

***Liquid Water Injection* -** After evaluating potential humidifiers for use in our air intake system, our team has chosen to use a liquid water injector located directly after the compressor. The liquid water injector will spray a calculated amount of water into the airflow based on the temperature, humidity, and mass flow rate of the incoming air. One type of injector considered is the fuel injector as illustrated in Figure 21. The water used for injection will come from a water reservoir tank located near the injector. A pump will be required to achieve pressures greater than 2.5 Bar. The key advantages of the liquid water injection humidifier are as follows: [23, 30]

1. The injector has the ability to properly regulate the humidity of airflow for a wide range of ambient air conditions. [30]
2. The injector is very efficient and requires little power [23]
3. The injector is small in size and has the ability to last the lifetime of the car if water is recycled from the exhaust
4. The injector does not impair any variables like airflow and pressure
5. Water injection assists in the cooling of the airflow and reduces the load on the intercooler [30]

www.technical-illustrations.co.uk

Figure 21: CG model of a fuel injector

***Radial and Linear Nafion® Membrane Concepts* -** Another idea considered for use as a humidifier was using a Nafion® membrane, either in a radial form around our ducting or linear form in a separate cell. The Nafion® membrane allows for water to permeate through to the airflow in order to achieve saturation. The advantages of using the Nafion® Membrane are that there are no moving parts involved in the process, no power is required, but there are no controls to regulate the system when needed. The Nafion® membrane humidifier is also very large in size and not very efficient in achieving the desire 100% relative humidity. Also, the membrane may be damaged at high temperatures. For these reasons our team decided not to use the Nafion® membrane in our air intake system.

***Carbon Foam Humidifier* -** Another humidifier considered for use in a fuel cell was the carbon foam humidifier which uses graphite foam, due to its high thermal conductivity, as a heat exchanger between the air and the water [31]. The carbon foam humidifier has the same advantages and disadvantages to the Nafion® membrane above. Its demise is its poor efficiency, large size, and cost. For those reasons, our team has decided not to use carbon foam as our humidifier.

Temperature Controller

To achieve the proper temperature of 85°C at the inlet of the fuel cell, our system will require cooling of the air after compression. Our team has chosen to use an air-air intercooler to cool the air with the addition of flaps to allow for variable cooling. Our team evaluated our two concepts based on the following criteria:

1. Cooling Capability: ability to control amount cooling at different temperatures.
2. Small Size
3. Low Weight
4. Low Cost
5. Efficiency/Power Consumption

Intercooler - Our team chose the air to air intercooler as the mechanism to cool our air mostly because of its low power consumption. No parasitic losses to the fuel cell system will occur from use of an air to air intercooler. The intercooler would use the ambient air to cool the air in our system. The intercooler would also need to supply variable cooling based on ambient temperature and humidity. Our team feels that using flaps to control the airflow in the intercooler could be an effective way of providing that cooling. However, due to time limitations as well as finite knowledge of intercooler systems, our team has not further investigated this idea to determine its feasibility.

The air to air intercooler design was chosen over the water to air intercooler because it seemed like a simpler design. A water to air intercooler would have required water storage, transport and delivery which would be more difficult to accomplish than using air. For these reasons our team chose the air to air intercooler.

Air Conditioning Unit **–** While our team felt that an air conditioning unit would be an effective way of variable cooling for the air, we also felt that the parasitic losses due to an AC unit would be large. Also, we the AC unit concept would cost a lot, require refrigerants making it more complex, and would take up a lot of space. For these reasons our team dismissed the AC unit concept.

System Order

Once determining the best components for each function of our system, our team focused on the ordering of all these components. The first and most logical component would be the air intake scoop. This is necessary to draw in air from the ambient and provide it to the rest of the system. The second component in our design was the filter. This way the air can be filtered at a lower pressure/flow rate. Also, since the filter is placed before the compressor, the issue of maintaining pressure across the filter is a non issue. After the filter, we then decided to insert a compressor. This will pressurize the rest of the system and will deliver the air at the correct pressure to the fuel cell. The compressor was also placed third to assist with humidification. Immediately after the compressor is the injection humidifier. The main reason for this specific humidifier placement is because the temperature increase from the compressor will allow for more humidification to occur at the higher temperature and pressure. The humidifier will also assist in the cooling of the airflow. Last the air will travel through an intercooler where the air temperature will be reduced.

CONCEPT DESCRIPTION

For our final design, our team put our individually chosen components from the concept selection together into one assembly. This design includes a combination of an activated carbon filter and Visteon dust filter to remove harmful substances, a screw compressor to increase pressure and mass flow rate, a water injection system to increase the humidity, and an air-to-air intercooler to cool the air. A general arrangement of our final design can be seen in Figure 22 below.

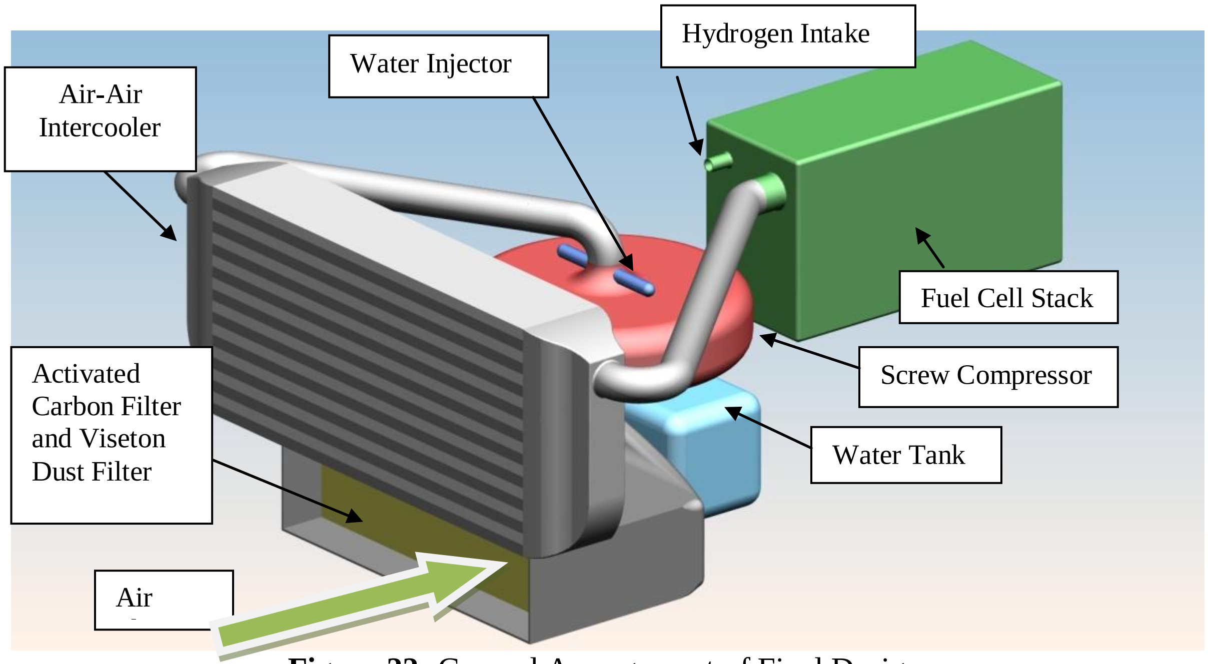


Figure 22: General Arrangement of Final Design

Each one of these components will perform a function that will enable our system to work properly. As talked about in the engineering specifications and customer requirements, our design must deliver air to the fuel cell with the following criteria:

1. Clean Air (NO_x, SO_2, CO and dust must be filtered out)
2. Pressure of 2.5 bar
3. Mass Airflow Rate 0.11 kg/s (for a 100 kW fuel cell)
4. Relative Humidity of 100%
5. Temperature of 85°C

Our team believes that our final design, with the components in their particular order will be an effective method of achieving these desired characteristics. A detailed operational diagram of our final design and what the different components will be doing at different stages can be seen in Figures 23 and 24.

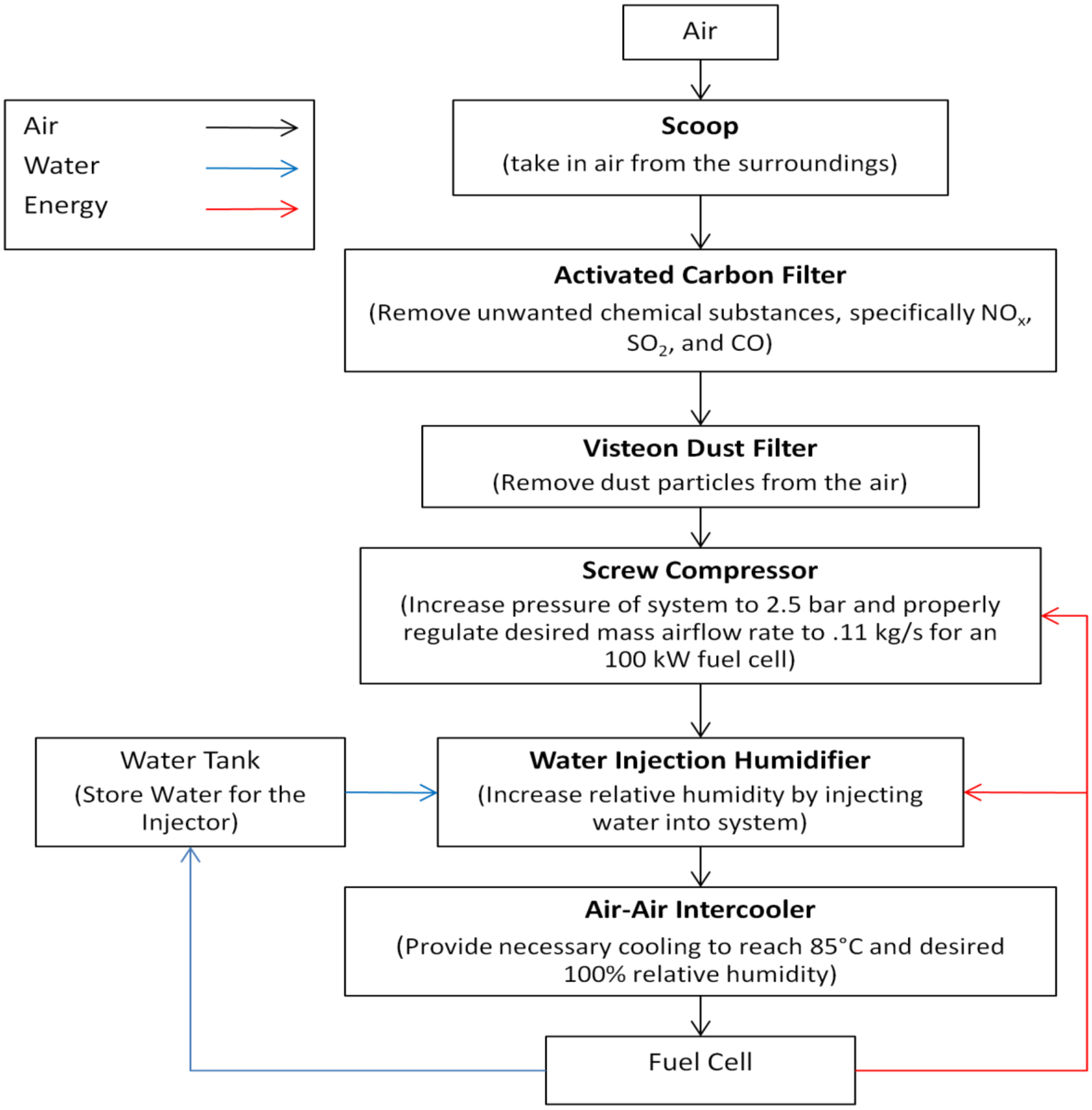


Figure 23: Operational Diagram of Final Design Components

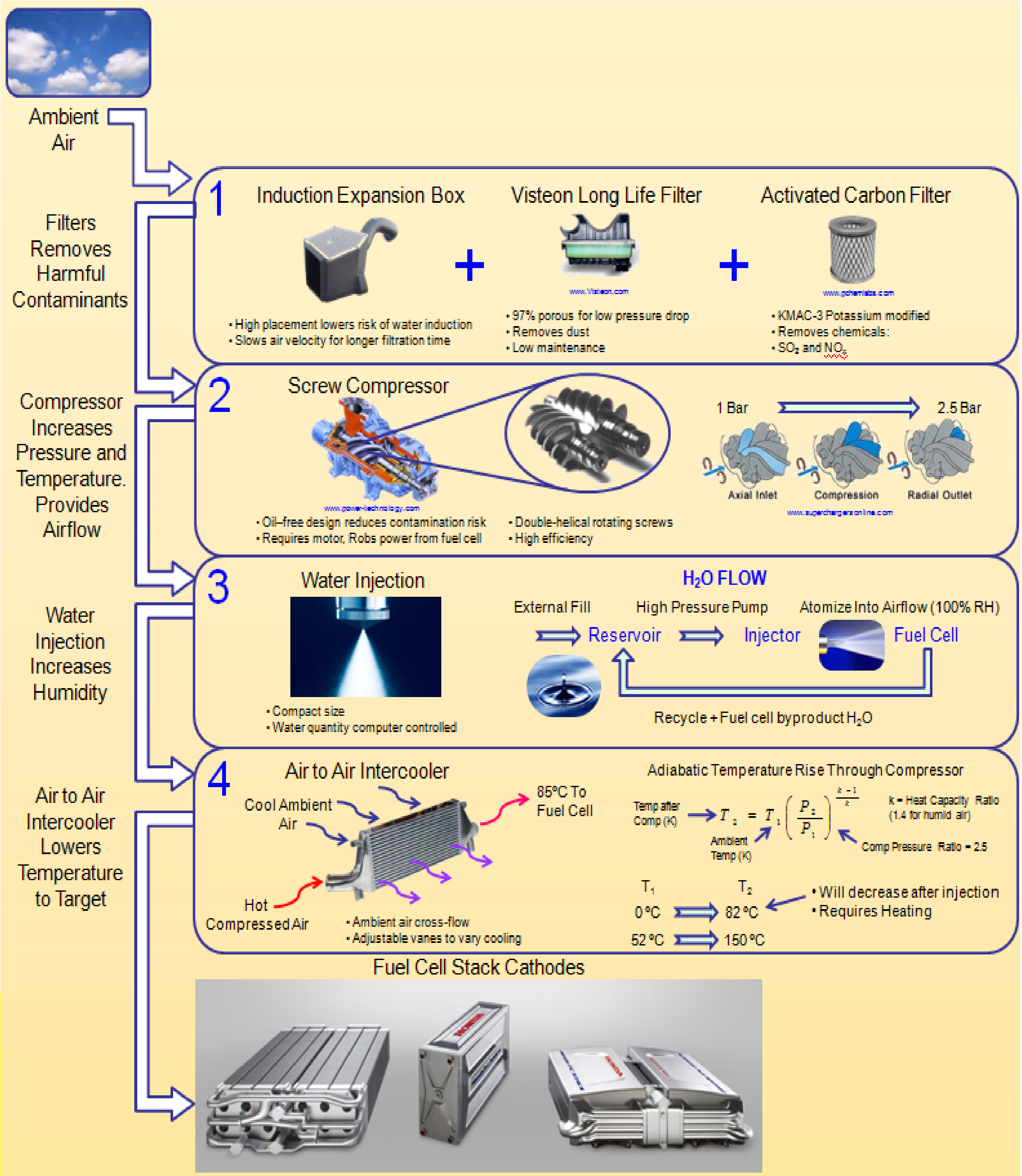


Figure 24: Detailed Description of Final Design Components

ENGINEERING DESIGN PARAMETER ANALYSIS

By connecting the components of our final design through an engineering analysis, our team has developed equations that relate the important variables of our system (pressure, temperature, humidity, etc.) at various points. For validating our final design and prototype, it was important to understand these variables and how they influence one another. By understanding their relation, our team would be able to properly control our input variables to achieve the desired characteristics of our system. The model derived below is a simplified model of our system.

Thermodynamic Model of System

To properly regulate the incoming air to our fuel cell air intake system and control it in order to obtain the desired characteristics (pressure, temperature, humidity, and mass airflow) at the inlet to the fuel cell, our team created a mathematical model of our system. Using primarily thermodynamics, our team created a model that relates the properties of the four major points in our system: at the inlet, after the compressor, after water injection, and after the intercooler at the inlet of the fuel cell. Certain assumptions were made in the calculations for our model. They are as follows: the compressor is assumed ideal (meaning that it is an isentropic process with constant entropy), pressure after the compressor will be constant with constant cross-sectional ductwork, and that our system is perfectly insulated. The reasonability of these assumptions are confirmed by University of Michigan professor of thermodynamics, Pawel Oslewski [38]. The uncontrollable variables in our system are the conditions of the ambient air upon entering the intake system. These variables will need to be measured and are considered known. Also, our team knows the desired characteristics of these variables at the last point of our system. In order to achieve the desired outlet properties of air for our system, our system can control the mass flow of water being injected into the system (Equation 9) and the amount of cooling provided by the intercooler (Equation 10). Our model relates these two variables to the known variables at the inlet state and the desired characteristics at the final state. All equations and calculations were performed using Chapter 13 “Gas Mixtures” from the textbook Fundamentals of Thermodynamics [39]. A detailed description of our model can be seen in Appendix J.

$$\dot{m}_L = \frac{\dot{m}_1\left(\frac{P_{g4}}{P_4} - \frac{\Phi_1 * P_{g1}}{P_1}\right)}{1 - \frac{P_{g4}}{P_4}} \qquad \text{(Eq.9)}$$

Where $\dot{m}_L$ is the mass flow rate of water injected into the air, $\dot{m}_1$ is the initial mass airflow at the intake, Φ_1 is the relative humidity of the ambient air, P_1 is ambient pressure, P_{g1} is the saturation pressure for the ambient temperature of air, P_4 is the pressure of the air at the inlet of the fuel cell, and P_{g4} is the saturation pressure for the temperature of air at the inlet of the fuel cell.

$$\frac{\dot{Q}_{Int}}{\dot{m}_a} = 1.004 * [T_4 - T_3] + .622 * \left(\frac{P_{g4}}{P_4 - P_{g4}}\right) * h_{v4} - \frac{.622 * \left(\frac{P_{v2}}{P_2 - P_{v2}}\right) * \left(h_{v2} - h_{L2} - 1.004 * \left[\frac{P_2 T_1}{P_1} * \left(\frac{P_1}{P_2}\right)^{\frac{1}{k}} - T_3\right]\right)}{h_{fg3}} * h_{v3} \qquad \text{(Eq.10)}$$

Where $\frac{\dot{Q}_{Int}}{\dot{m}_a}$ is the amount of cooling supplied per kg of dry air, T_4 is the temperature at the inlet of the fuel cell, T_3 is the temperature of the air after water injection, P_4 is the pressure of the air at the inlet of the fuel cell, and P_{g4} is the saturation pressure for the temperature of the air at the inlet of the fuel cell, h_{v4}, which equals $h_g(T_4)$, is the partial enthalpy of the vapor at the inlet of the fuel cell, h_{v2} is the partial enthalpy of the vapor after compression, h_{fg3} is the evaporation enthalpy after water injection, h_{v3} is the partial vapor enthalpy after water injection, h_{L2} is the enthalpy of the water being injected, P_2 is the pressure of the air after compression, k is the isentropic constant for air, and T_1 is the ambient temperature.

Using Equation 9, we can estimate the amount of water required for the humidification system in both the final design and prototype design. The mass flow corresponding to specific fuel cell stack powers can be seen in Appendix K. For the final design, Figure 25 shows that the estimated maximum amount of water required is around 33 g/sec. This was calculated under worst case conditions for a 100kW fuel cell with completely dry (0% R.H.) ambient air at 0ºC. The final design targets are the engineering specifications we have listed on P. 14. They are: pressure of 2.5 bar, temperature of 85ºC, and final humidity of 100% R.H.

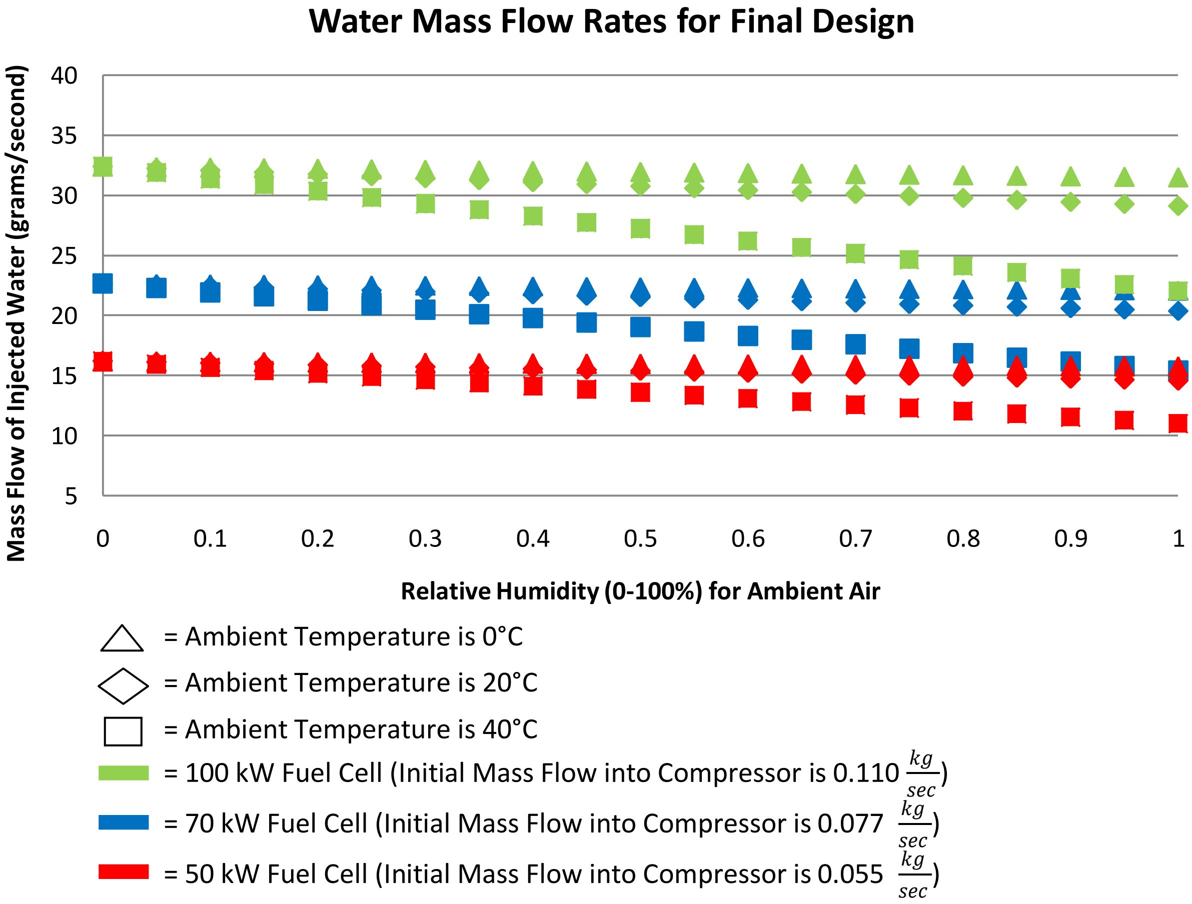


Figure 25: Necessary Water to be Injected for Final Design

For the prototype design, Figure 26 shows that the estimated maximum amount of water required is around 6 g/sec. This was calculated using worst case ambient air conditions (dry, 0% R.H. at 0ºC) and our prototype design targets (1.35 bar pressure, 40ºC at outlet, and 100% R.H. at outlet).

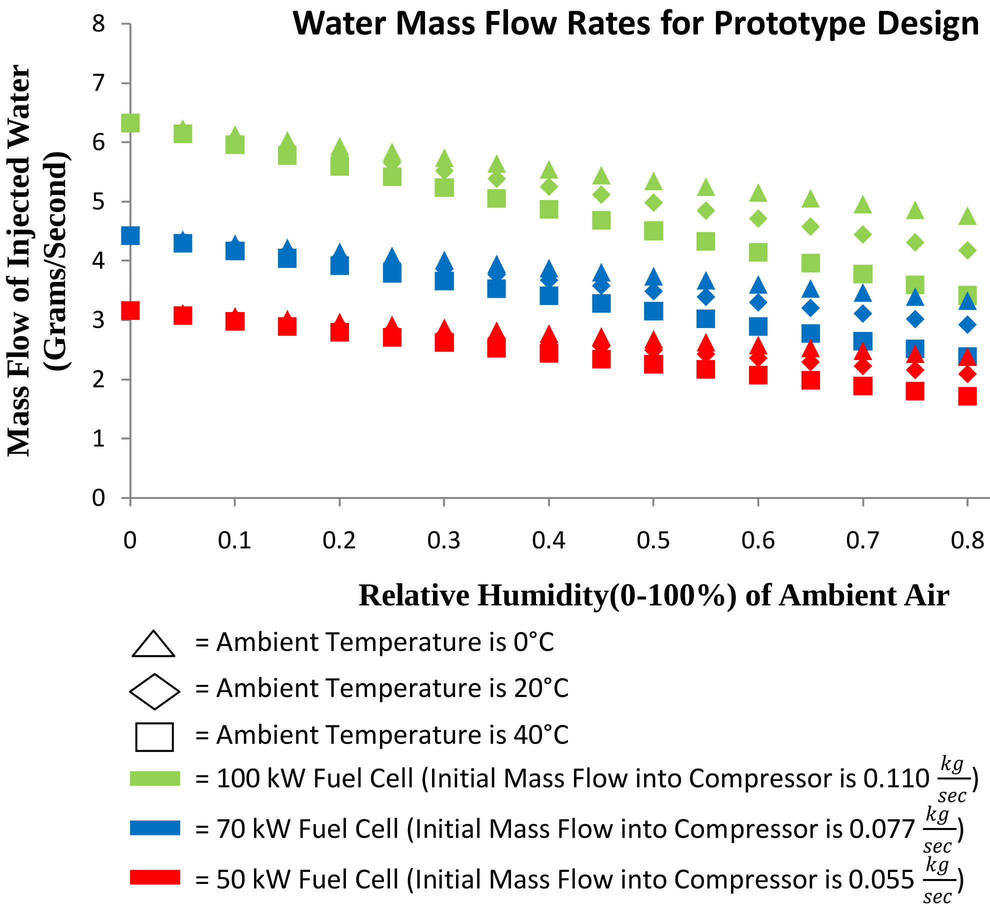


Figure 26: Necessary Water to be Injected for Prototype

From Equation 10, we have calculated the maximum cooling requirement for the intercooler of the final design. About 86 kJ of heat energy must be transferred out per kg of air. This calculation was performed under the following variable inputs: 0.11 kg/s of airflow, 20ºC ambient temperature, 1 bar atmospheric pressure, 85ºC outlet temperature, and 2.5 bar outlet pressure, and 20ºC water temperature of humidification.

Because airflow and pressure are functions of the compressor, these two targets must be met simultaneously. The only control available for the compressor is to vary its speed. The pressure will increase as the speed increases. Airflow rate will also increase as compressor speed increases. Performance will differ based on compressor design. Back-pressure and loads which arise from the rest of the system design, such as ductwork diameter, number and degree of bends, pressure drops across filtration and cooling elements, etc, can affect the compressor performance. Therefore, characterization of the compressor must be performed for all intake systems.

The Model concludes that we will be able to control the humidity, pressure and temperature of the incoming air through the system in order to achieve the desired characteristics at the inlet of the fuel cell. By controlling the amount of water injected and cooling in the intercooler, our system will be able to regulate the pressure, temperature and humidity at the inlet of the fuel cell in order to achieve the optimal characteristics. Also, through proper control, we can ensure that condensation does not occur in the system as relative humidity will only reach 100% after cooling.

Problems with the Model **-** Our model does not address noise in our system or the pressure drop across the filter before entering the compressor. These are two important variables in our system. However, due to limitations in time and the fact that the dimensions of our scoop, filter and ducting are unknown, these variables were not considered in our analysis.

Material Analysis Results

We performed an in depth analysis for the air intake system ducting and the pressure line between the water tank and the injector. This analysis was focused around three factors: minimizing cost while maintaining important functional criteria in order to pick an appropriate material for each part, comparing the environmental effect of using these two materials, and determining the most effective manufacturing process to create these parts.

Ducting

In our system the function of the ducting is to transport the air from component to component. The important characteristics of the material used for ducting are a melting temperature above 150°C, a low thermal conductivity, and a high yield strength. Using these characteristics as a guide lines for material selection along with the CES(Cambridge Engineering Selector) software, we determined Polypropylene (PP, 65-70% barium sulfate) to be a good material choice for the intake system ducting. Polypropylene has a melting temperature between 155-164°C, a high yield strength of $1.49X10^9$ Pa and a low heat conductivity of .297 W/(m*K)

In order to determine an appropriate manufacturing process, we first needed to estimate how many intake systems would likely be produced. With the assumption that our system would likely be produced once the transition from combustion engines to fuel cell vehicles had occurred, we assumed that our production volume would be similar to that of a popular mid-size sedan. Currently, there are approximately 400,000 Camry’s sold each year in the United States.

We found that the key characteristics of the ducting to keep in mind while picking the manufacturing process were:

1. Large production volume
2. Constant diameter and thickness
3. Circular cross section
4. Material is a Polymer

Having a large production volume justifies the cost of investing in fast and efficient machinery (Capital) because the investment cost will be distributed over a large number of parts produced. Having a constant diameter and thickness and a circular cross section removes the need of more complex manufacturing processes such as injecting molding. Because of these reasons, we believe that the most appropriate manufacturing process to create our ducting is polymer extrusion.

Injection line (Hoses)

In our system the function of the injection line is to transport the water from the water tank to the injector. The important characteristics of the material used for ducting are high corrosion resistance to water and capable of withstanding pressures up to 100 psi. Using these characteristics as a guide lines for material selection along with the CES(Cambridge Engineering Selector) software, we determined Polyvinylidene Chloride (PVDC) to be a good material choice for the injection line.

As stated in the ducting section above, we determined our production volume to be around 400,000. Also similar to the ducting are the key characteristics to keep in mind while picking the manufacturing process:

1. Large production volume
2. Constant diameter and thickness
3. Circular cross section
4. Material is a Polymer

Because of these characteristics, the best manufacturing process for the injection line would be polymer extrusion.

Environmental

By using SimaPro, we were able to compare the environmental impact of using Polypropylene and Polyvinylidene Chloride. We found that Polypropylene will have the most negative impact on air, raw material, and waste, but Polyvinylidene Chloride will have a larger impact on water.

For a more detail analysis please refer to Appendix C.

Design for Safety

One of the important factors in our design, especially our prototype, was ensuring proper safety precautions were taken. As mentioned in our material analysis in Appendix C, we used a safety factor of 3 for our target pressures. We felt this would be sufficient as this is commonly used for piping in general. For our prototype we used an overcautious safety factor of 30 as our cutoff pressure was designed to be 10 psi and the PVC piping was designed to withstand pressures of 300 psi.

Another important safety measure designed into our prototype was the addition of a safety pop valve. In the case that the pressure after compressor ever reached 10 psi, the valve would open and ensure the pressure would drop. This was done less for the piping and more just to prevent any unnecessary vibrations that might have arose from running high pressures on the system. An additional safety measure taken for our prototype was using a variable torque drill with a clutch that would release in the case that our compressor would seize. We ran the compressor without using oil for lubrication and preventing possible rupture/flying debris caused from seizure of the compressor was very important in ensuring safety.

Other safety measures included in our design were putting a pressure sensor on the water tank to ensure we did not over pressurize it, putting a ball valve on our water injection line to ensure it was properly closed before pressurizing the water tank, building walls around half the prototype, routing the compressor outlet downwards, and running the hand drill remotely by using a hose clamp to hold the trigger down.

FINAL DESIGN DESCRIPTION

For our final design, our team put our individually chosen components from the concept selection together into one assembly. This design includes a combination of an activated carbon filter and Visteon dust filter to remove harmful substances, a screw compressor to increase pressure and mass flow rate, a water injection system to increase the humidity, and an air-to-air intercooler to cool the air. For our final design, we were not asked to specify particular components from specific companies that may be used in the design. Instead we were asked to come up with an assembly and the specifications that the components in this assembly need to achieve. Visteon will then determine where to get or build the necessary parts themselves. Packaging and sizing of our chosen components will need to be altered to fit the packaging of any car the system may be placed in. A general arrangement of our final design can be seen in Figure 27 below. More detailed figures of our final design can be found in Appendix L.

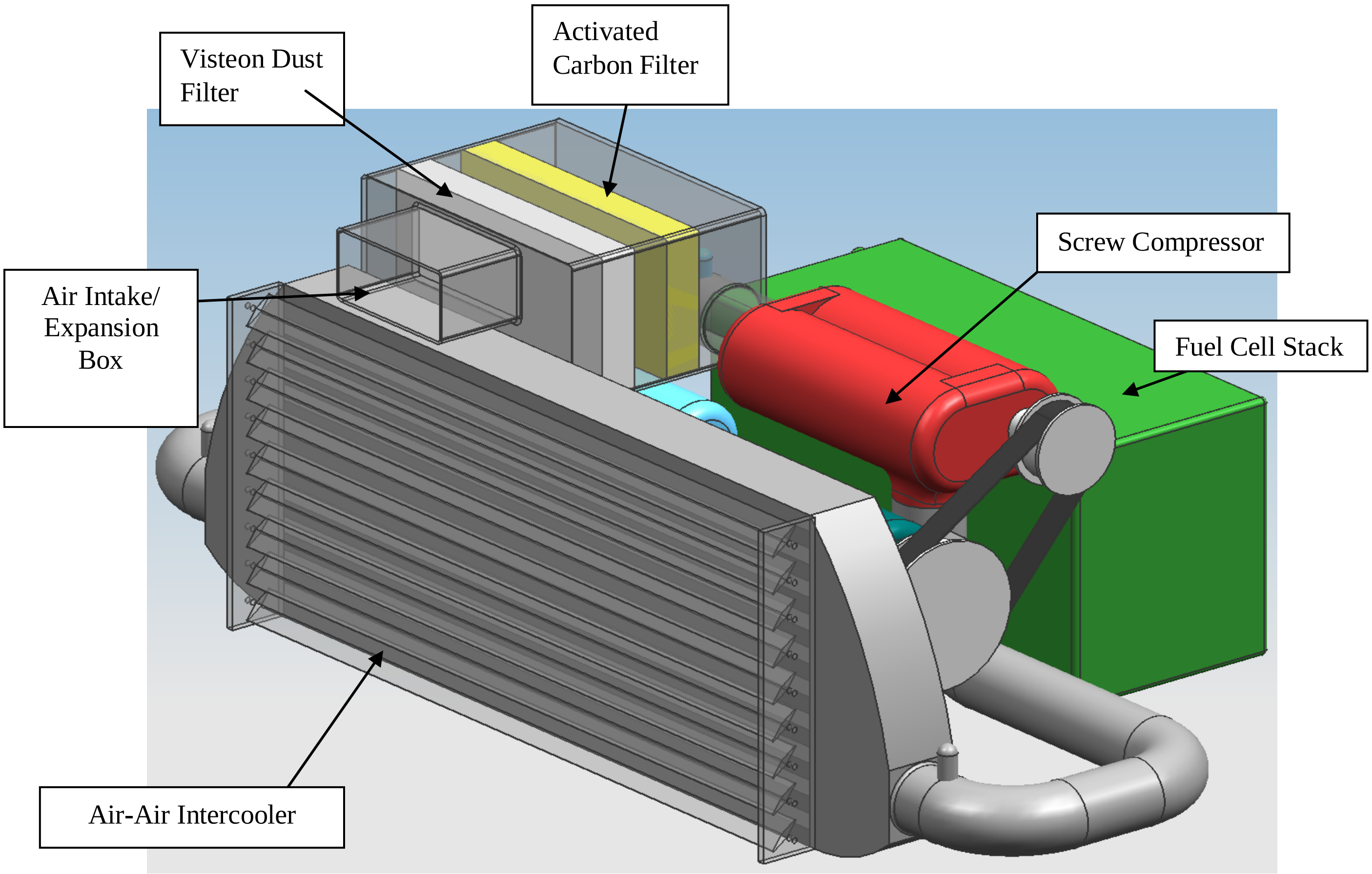


Figure 27: General Arrangement of Final Design

After talking to Visteon about the necessary sizing for an intake scoop, our team has deemed our concept of a “whale mouth” scoop unnecessary. Visteon explained to us that a much smaller size opening for the intake will allow our system to take in the necessary airflow from the surroundings. So rather than listing a scoop as an individual component, we have chosen to start our design with our filters.

However, the location concepts generated under the scoop component remained useful as where to place out filter. We initially felt that the ground location for the scoop was a good idea due to packaging constraints. However, if the intake is too low to the ground, problems may occur with drawing in water from puddles. For that reason, we have decided to move the intake up further in the vehicle to directly under the hood. This will provide protection from puddles and large debris from entering the system. The intake hole will also need a mesh grating to ensure no large debris can possibly enter our air intake system design.

The intake will directly lead into an expansion box (to create a larger surface area) between the scoop and the compressor for two main reasons: First, slower airflow velocities at this point allows for longer time durations in traveling across the filters, and therefore more effective filtration. Second, placing the filters on the low pressure side of the compressor means it will not be subject to such high pressures; filter elements may have negative effects on the airflow quality if it is placed on the high pressure side.

We chose a Potassium Hydroxide solution Modified Activated Carbon filter to remove harmful substances because of its high efficiency and long lifetime. It was found that 1ppm of NO_x entering the fuel cell may reduce performance as much as 10%. At 1ppm of $SO_{2,}$ the fuel cell looses around 30% of its performance within just 5 hours of exposure [11]. The activated carbon filter will be effective in controlling these harmful elements [10].

The Visteon dust filter was chosen to remove dust particles for its high efficiency and lifetime. We do not need to detail this filter as Visteon is our sponsor and is very familiar with its performance capability.

The third component of our design is a double helical, oil-free screw compressor. The screw compressor was chosen due to its ability to achieve the desired pressure of 2.5 bar and the mass airflow rate of 0.11 kg/s necessary for the fuel cell to achieve its maximum power of 100kW. Oil-free is also a requirement, as clean air must be delivered to the fuel cell. In addition, screw compressors are usually compact and fairly light. Power to run the compressor will be taken from the power created by the fuel cell. Therefore it was very important to find a compressor that causes the least amount of parasitic losses. Screw compressors are very efficient and should minimize these losses.

While our team initially chose the scroll compressor for our final design, we later learned that it could not deliver the necessary airflow and for that reason it was dismissed. Current scroll compressors are designed to provide high pressures but low flow rates. A scroll compressor which would achieve the airflow rates of 0.11 kg/s would greatly exceed the packaging restraints [37]. While our team has chosen the screw compressor for the reasons above, we found that lobe and centrifugal compressors are also capable for our air intake design. If Visteon wishes to pursue one of these designs due to cost or for other reasons, the system as a whole would still operate similarly.

After compression, our team chose to humidify the air through liquid injection. Water injection was chosen due to its high precision in controlling the amount of water being put into the system. The system will consist of a 10 gallon water tank that will be pressurized much higher than the 2.5 bar of the total system. This pressure will depend on the spray nozzle, and we recommend experimental testing to determine optimum pressure settings. The system will take the pressurized water and inject it into the system using either one or multiple spray nozzles into the system. Multiple spray nozzles may be needed to achieve the water mass flows required (seen in Appendix K).

Our team suggests using a 10 gallon water tank as a reservoir for injection. A 10 gallon water tank should last approximately 20 minutes. For this reason, it is necessary to recycle the water vapor created in the reaction of the fuel cell. The amount of water vapor created from the fuel cell reaction should be more than sufficient in sustaining the injection system.

Our team designed the system to work at temperature ranges from 0-40ºC due to the fact that fuel cell operation below 0°C is questionable and still being researched. However, if Visteon wants to operate our water injection system at temperatures below 0°C, the temperature of the water would also have to be controlled with a heating mechanism.

The location of our liquid injection is between the compressor and the intercooler. At this location, the water is injected to high pressures and temperatures which will aid in mixing with the airflow [36]. Water injection will also aid in the cooling of the air. By injecting before the intercooler, our design must calculate and control the amount of water being injected such that a relative humidity of 100% is attained after cooling.

The last component of our design is the air-to-air intercooler. The intercooler was chosen for its simplicity in design and low power requirements. However, some way of performing variable cooling, such as using flaps to control the exposed cross-sectional area, must be implemented into a standard intercooler for our design to work. It is important to have variable cooling for our intercooler in order to achieve the proper temperature of the air at the inlet of the fuel cell. The intercooler is located at the front of the car to allow for a large volume flow rate of air exposure for heat exchange to occur.

In our final design, three variables can be controlled to meet the desired characteristics at the inlet of the fuel cell: the compressor speed, the amount of water being injected into the system, and the amount of cooling delivered by the intercooler. The compressor speed can be regulated by the power supplied to it. The water injection rate can be regulated by the back pressure on the water tank. The variable cooling can be regulated by the amount exposed area to a cross flow using flaps.

While our team has developed equations, seen in the Parameter Analysis section, that relate these variables, sensors are necessary as part of our design to measure characteristics at particular points in the system. To start, the ambient pressure, temperature, and humidity must be measured at the inlet of the fuel cell. In addition the mass airflow at the inlet and the humidity after compression should be measured. All information will be processed using a computer data acquisition unit and related to the desired outputs of the air intake system. For more accurate results, pressure, temperature, humidity and mass airflow can be measure at various other points by using more sensors. Visteon already uses pressure, temperature, humidity and mass airflow sensors in many of their other products and those sensors can be calibrated for use in the air intake system as well.

Our components will be connected through ducting. From our material analysis, our team has chosen Polypropylene as the material to be used for our ducting due to its high melting temperature, high yield strength and low thermal conductivity. Our team also chose Polyvinylidene Chloride for our water injection hose line for its corrosion resistance and high yield strength. Unfortunately, our team was not given a specific vehicle to design around. For this reason, dimensioning and packaging of the ducting could not be determined for our final design as those must be made specific to the vehicle.

Noise may also be an issue in our final design. While this was one of our customer requirements, our team feels that Visteon is better suited for dealing with this problem. They currently implement Helmholtz resonators effectively in air induction systems for combustion engines. Frequencies to attenuate will lie within the range of human hearing. However the specific frequencies must be determined through experimentation of the final design once the assembly for a specific vehicle is finalized. The placement for such resonators must also be determined through experimentation since the location of nodes will greatly affect their performance.

PROTOTYPE DESCRIPTION

To demonstrate that our final design is realistic, our team will build a scaled down prototype with the same components used in our final design. These components include an air box filter to simulate the intake and filter pressure drop, a screw compressor, a liquid injection system using a spray nozzle, and an air to air intercooler. Figure 28 illustrates the planned prototype layout.

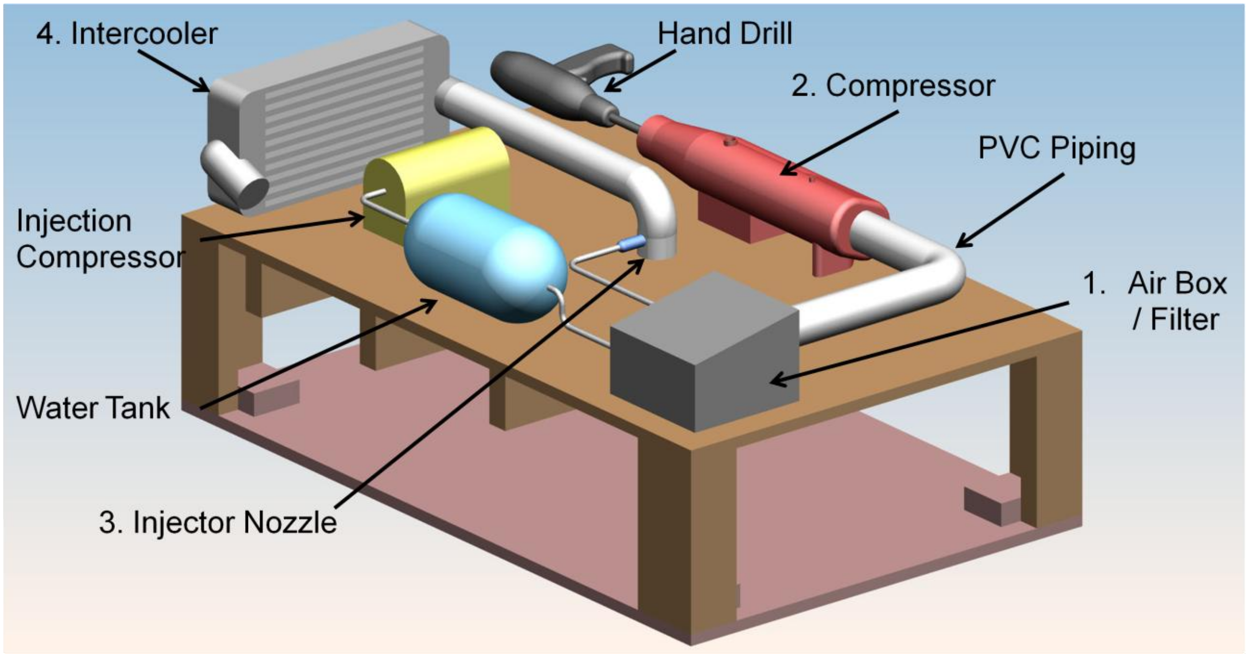


Figure 28: Prototype Layout Design

The air is drawn in through the air box / filter, which is the first component of our prototype. It is attached to the screw compressor through PVC piping. The screw compressor is directly attached to and driven by an electric hand drill. The screw compressor outlet is directed downwards through the platform and is routed back up through PVC piping. Directly after the compressor, before the air is directed back on top of the table, our team placed a pressure release pop valve in case pressures were unexpectedly high for safety reasons. Once the air is routed back above the table, the injection humidifier system sprays water in through a spray nozzle. The water is supplied by a water tank, which is pressurized through pumping by hand. The tank has a pressure sensor attached so it can be pumped to a particular pressure and has a ball valve to release flow when necessary. After injection, the PVC piping routes to the air-to-air intercooler where two hair dryers will supply the necessary air cross-flow for heat exchange. Although not shown, the outlet of the intercooler has additional PVC piping extending out of it which is attached to a ball valve for control of the system's back-pressure. We have temperature, pressure, and humidity sensors located at the end to measure the output. All components and parts are securely mounted to the platform. A detailed list of all materials/components used for our prototype can be seen in Appendix A.

Prototype Vs Final Design

Due to budget and time constraints our prototype will not be able to demonstrate every aspect of our final design. Instead it will focus on the most important functions: pressurization, humidification, and cooling.

Omitted Aspects

The other important aspects of our final design that will not be demonstrated are filtration, noise dissipation, and packaging. Filtration will not be demonstrated because of our limited budget and inability to measure the effectiveness of the filter due to lack of measurement equipment. Noise dissipation will be an important aspect of our final design; however, we will not have the equipment necessary to determine the problem frequencies nor will we have the time to add the appropriate resonators. In addition, Visteon, our sponsor, has much experience in noise dampening for combustion engines, and therefore, has little need in proving this functionality. Last of all, we will not be demonstrating the packaging of our final design. As previously discussed, we have been asked to design a general air intake system for a fuel cell vehicle. While this has required some research into the relative location of our components, there is no specific packaging in which our final design is based upon.

Reduced Targets

For our prototype, we have decided the most important aspects to be pressurization, humidification, and temperature control. We have chosen these functions as they are most vital in the performance of the fuel cell, as well as affecting the functionality of each component. Due to safety concerns and the environment in which the prototype will be demonstrated, we reduced the targets for each function. Our target for pressure was reduced from 2.5 bar in the final design to 1.35 bar for the prototype. This was high enough to demonstrate the ability to increase the pressure to a set value while maintaining a safe system. Our target for humidification was maintained at 100% R.H. because we believed this characteristic was achievable and did not pose a safety risk. For temperature control, we had a target of 40°C, which was lowered from

85°C in the final design to lower safety risk. A summary of the engineering specifications and customer requirements, their targets, and the methods of how they will be/were controlled for both our final design and prototype can be seen in Tables 4 and 5 below. These tables should serve as a brief comparison between our final design and prototype.

Table 4: Final Design Targets and Methods of Control

Engineering Specification/ Customer Requirements	**Target**	**Control**	**Mechanism of Control**
Pressure	2.5 bar	Compressor Speed	Power supplied to motor which runs compressor
Humidity	100% R.H.	Mass flow rate of water injected	Back pressure on water reservoir
Mass Airflow Rate	0.11 kg/s for 100 kW Fuel Cell	Compressor Speed	Power supplied to motor which runs compressor
Temperature	85°C	Variable Cooling Across Intercooler	Flaps to control cross sectional area exposed to cross flow
Filtration	Remove harmful elements(Dust and Chemical Compounds)	Visteon Dust Filter +Activated Carbon Filter	Cross sectional area of filter Velocity of airflow across filter
Noise	Below 65 dBA	Sound Dampening	Resonators Compressor Casing

Table 5: Prototype Design Targets and Methods of Control

Engineering Specification/ Customer Requirements	**Target**	**Control**	**Mechanism of Control**
Pressure	1.35 bar	Compressor Speed	Speed of Hand drill Adjusting opening of end valve
Humidity	100% R.H.	Mass flow rate of water injected	Back pressure on water tank
Mass Airflow Rate	Not Specified	Compressor Speed	Speed of Hand drill Adjusting opening of end valve
Temperature	40°C	Heat flow across the intercooler	Using one of two hair dryers to generate cross flow
Filtration	Not Specified	None	N/A
Noise	Not Specified	None	N/A

Prototype Components

The air enters through the intake of an air filter box taken off a ’99 Ford Taurus. This was purchased from a local junkyard, AAChen Auto. The air intake contains a Mass Air Flow (MAF) sensor, an Intake Air Temperature (IAT) sensor, and a dust filter. Though our prototype will not demonstrate filtration, a paper filter was incorporated for pressure and flow simulation purposes. A picture of this assembly can be seen below.

Figure 29: Air Box with Paper Filter

The compressor is a supercharger taken from a ‘97 Mazda Millennia S from a local junkyard, Woodard’s. It is a double-helical screw type compressor. Though our final design calls for an oil-free compressor, oil-free screw compressor’s are quite expensive and outside our budget. Because our prototype was not actually connected to a fuel cell, this compressor suited our demonstrative purpose. For safety, we oriented the compressor on our platform such that the exit faces toward the ground, and secured it with 10 M8 bolts and 1 ¼ inch washers. Here is a photo of our compressor.

Figure 30: Supercharger Screw Compressor

To run the compressor, we used a RYOBI D46C electric drill with a 3/8 inch chuck. An M14 bolt with the hex head removed acted as the drive shaft between the drill and compressor. The smooth end of the bolt was reduced to 3/8 inch and chucked into the drill. As a safety measure, the drill has a variable torque clutch which can be set such that it slips if the compressor has seized up. The other end of the bolt has a thread pitch of 1.50 that matches the threads of the compressor. The drill is shown below.

www.homedepot.com/webapp/wcs/stores/servlet/ProductDisplay

Figure 31: Ryobi Hand Drill

After exiting the compressor, airflow enters 2 inch PVC piping. The PVC will route the airflow across the board where a pop valve will release pressure if the system reaches 10 psi. This was done to ensure safety when testing as the compressor was bought used and the amount of power required to achieve particular pressures was unknown. A picture of the pop valve already installed in our piping can be seen below in Figure 32.

Figure 32: Safety Pop Valve

The pipe will then route the air back up through the plywood. Once the flow has been routed to the top of the platform it will pass by our water injection system. A Monarch spray nozzle with a tip angle of 80° is connected to a water tank which is pressured from hand pumping. Pictures of our nozzle and water tank with its attached pressure gauge can be seen below in Figures 33 & 34. This pressure pushes the water through a spray nozzle creating a fine mist in the PVC piping. The nozzle is directly fixed and sealed into the piping. The amount of water injected into our system will be controlled by a changing the pressure in the water tank. We placed a pressure sensor on the water tank so that we can accurately supply a particular back pressure on the water. A ball valve has been attached to the piping from the tank. When closed it will allow us to build up pressure in the tank by hand pumping and then it can be opened to allow the water to enter the system whenever we run it.

Figure 33: HydroGardens Monarch Atomizing Nozzle

Figure 34: Roundup® Manual Pump Water Tank

After the air flow has been humidified, the PVC will route the air to the intercooler where heating will occur. We purchased an air-to-air intercooler off a ‘91 Ford Thunderbird 3.8 L Supercharged V6 from a junkyard, AAChen Auto. The intercooler is attached to the platform by using two L-shaped brackets and four ¼” bolts. The air will flow through a series of fins while being heated through convection by cross flow of air generated by two hair dryers. The amount of heating will be adjusted by controlling the settings of two hair dryers and their proximity to the intercooler.

Figure 35: 1991 Ford Thunderbird 3.8 L Supercharged V6 Intercooler

After the intercooler, our team will attach additional PVC ducting that leads to a 1” diameter ball valve at the end where we will control the back pressure on our system to 1.35 bar. The PVC ball valve was purchased from Home Depot. A picture of the ball valve can be seen below in Figure 36. Before reaching the ball valve at the end of the system, we will also use a pressure, humidity, and temperature sensor in the PVC pipe. These sensors will be used to validate our final results. The pressure sensor is a boost gauge from AutoZone. The humidity sensor is an HIH-4033 sensor made by Honeywell and was purchased online. For temperature readings, we used an Omega thermocouple reader acquired from Tom Bress, instructional core manager for the mechanical engineering department at the University of Michigan. Pictures of our pressure gauge, humidity sensor, and thermocouple reader are shown below.

Figure 36: 1” PVC Ball Valve

Figure 37: Pressure Gauge

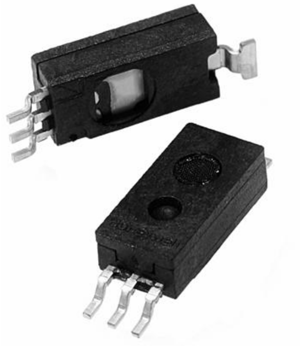


Figure 38: HIH-4033 Humidity Sensor

Figure 39: Thermocouple Reader

FABRICATION PLAN

Many areas of our prototype require custom fabrication to complete the design. A full list of the prototype materials and parts used in the fabrication can be found in Appendix A. This section details the manufacturing and assembly process.

Prototype Platform

First, a platform needs to be created as a base or "test rig" upon which all components are attached. The platform must be raised because our prototype design has ductwork both above and beneath. As seen in Figure 28, a simple table structure is chosen to provide this platform. The material chosen is ¾ inch (1.9 cm) thick plywood, and the stock size is 4 feet (1.22m) x 8 feet (2.44m). A circular saw is used to reduce the size to our design of 30 inches (0.762m) x 48 inches (1.22m). Figure 40 below shows the cut line.

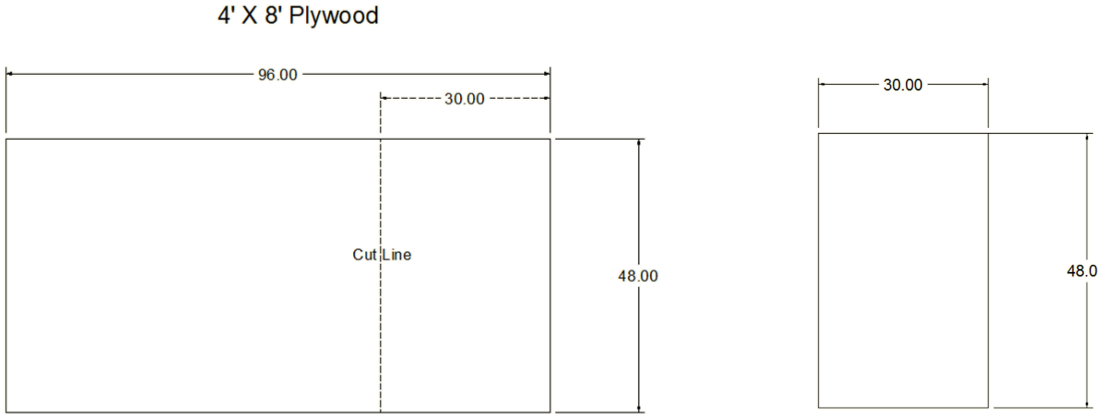


Figure 40: Prototype platform base fabrication
(Dimensions are in Inches)

Next, to raise this platform up, lumber (two by fours) is used to create the legs of our table structure. The legs are 11 inches (27.94 cm) high, and a circular saw is again used for the cut as shown in Figure 41 below. A total of eight pieces are required for the formation of all four legs to be placed at the corners of the table.

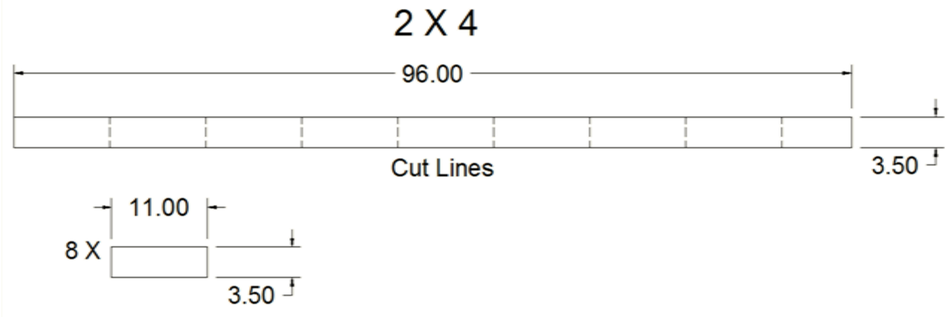


Figure 41: Cutting of Platform leg pieces (Dimensions are in Inches)

Each leg requires two pieces. First, one piece is laid flat on the ground and another one placed on top, such that it makes an L-shape. It is important that both the outside edge and bottom are flush. Then, the two pieces are secured together using three 2” deck screws at approximately an even length apart. This step is repeated three more times so that four leg posts are created.

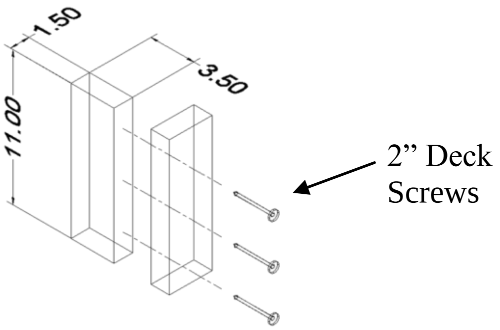


Figure 42: Platform Legs Fabrication

Now it is time to attach the leg posts to the 30 inch x 48 inch plywood. One leg assembly is placed at each corner of the plywood. They are oriented such that their longest dimension is perpendicular to the platform surface. One leg is secured at a time with three 2” deck screws from above as indicated by Figure 43. The screw locations are not critical, but approximately along the midpoints of the leg cross-section. Our criteria involved maximizing load distribution by spreading out the screw locations as evenly as possible.

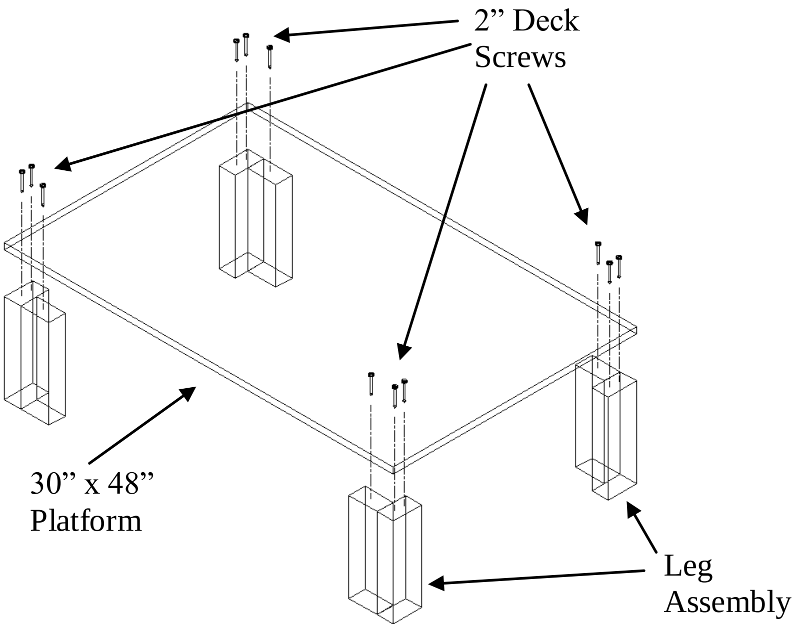


Figure 43: Prototype Platform Leg Attachment

After the table has been created, a means of transportation must be created as well. We chose to use a simple cart design with castors. The cart also has stoppers on the top surface which match the L-shape of the legs to prevent slipping and movement of the table structure. The cart is made out of the same ¾ inch plywood and cut with a circular saw to the same 30 inch x 48 inch dimensions as the platform. The four pre-drilled mounting locations on each castor are used to screw the castors to the cart. An example for the attachment of one castor is shown in Figure 44 below.

Figure 44: Mounting of castor to cart

Exact mounting locations are not critical, and therefore approximated. The only criterion for the screws is length; they must be short enough so as not to stick out on the other side. Once the four castors are mounted to the corners of the cart, the stoppers are created. Each stopper consists of 3.5 inch (8.89cm) rectangular squares cut out from lumber (two by fours) using a circular saw as shown in Figure 45.

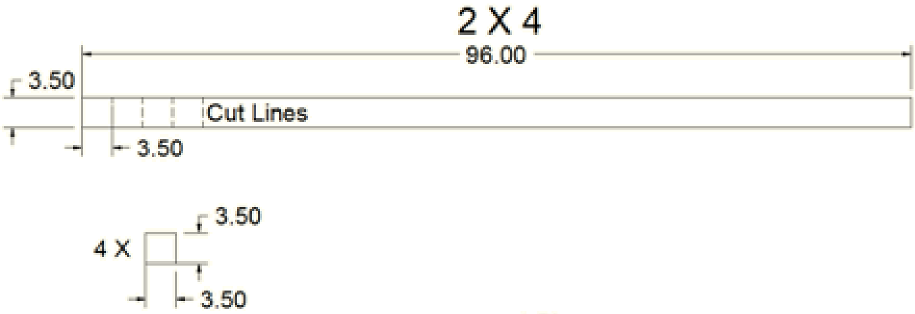


Figure 45: 2 X 4 Used to Create Platform Stoppers
(Dimensions are in Inches)

Once the squares have been cut from the two by four, they are placed on the 30 inch x 48 inch plywood such that they are 1.5 inches (3.81 cm) from each edge. Then, each piece is secured using 2” deck screws from beneath.

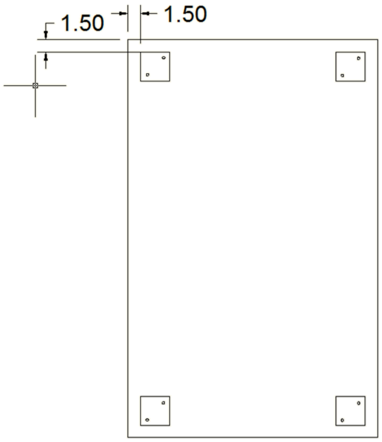


Figure 46: Location of Stoppers on Transportation Cart
(Dimensions are in Inches)

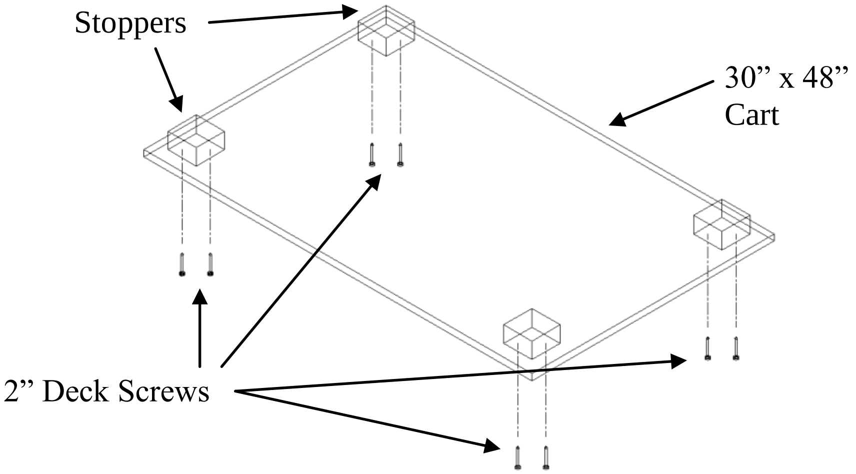


Figure 47: Assembly of Stoppers onto Transportation Cart

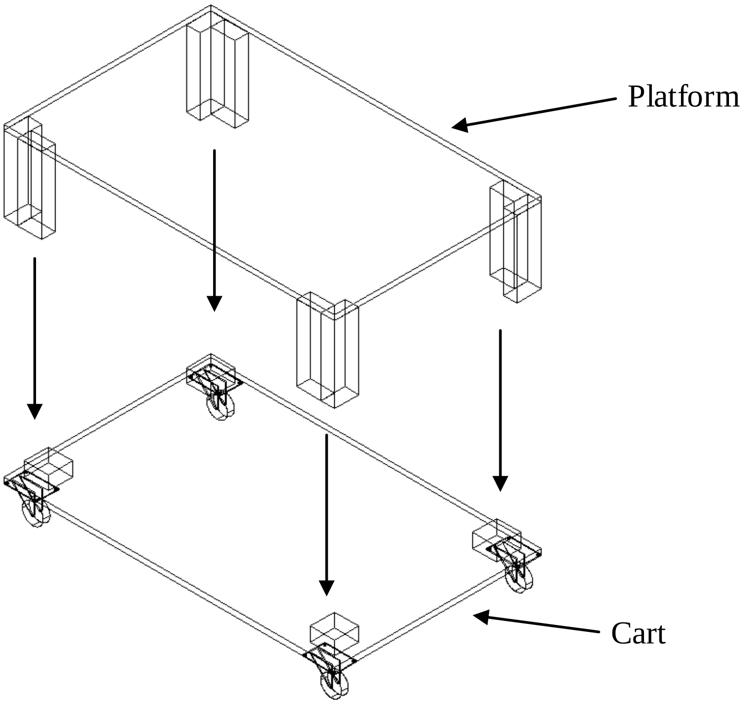


Figure 48: Table and Cart Assembly

To provide support and increase bending strength of the platform, three pieces of lumber (two by four) are cut to a length of 26 inches (66 cm) with a circular saw.

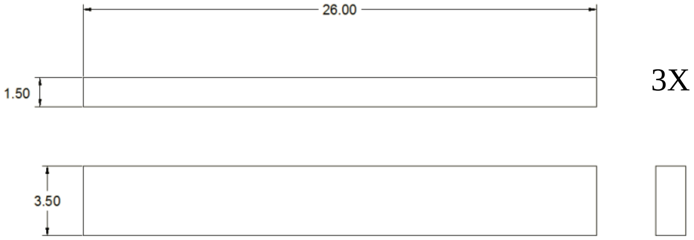


Figure 49: Support Beam Dimensions

They are fixed underneath the platform at the locations shown in Figure 50. The orientation of the support beams is chosen to maximize the bending stiffness of the platform against the bending moments created by the drill and compressor shafts. Three 3” deck screws about 9 inches (22.86 cm) apart are applied from above for each support beam.

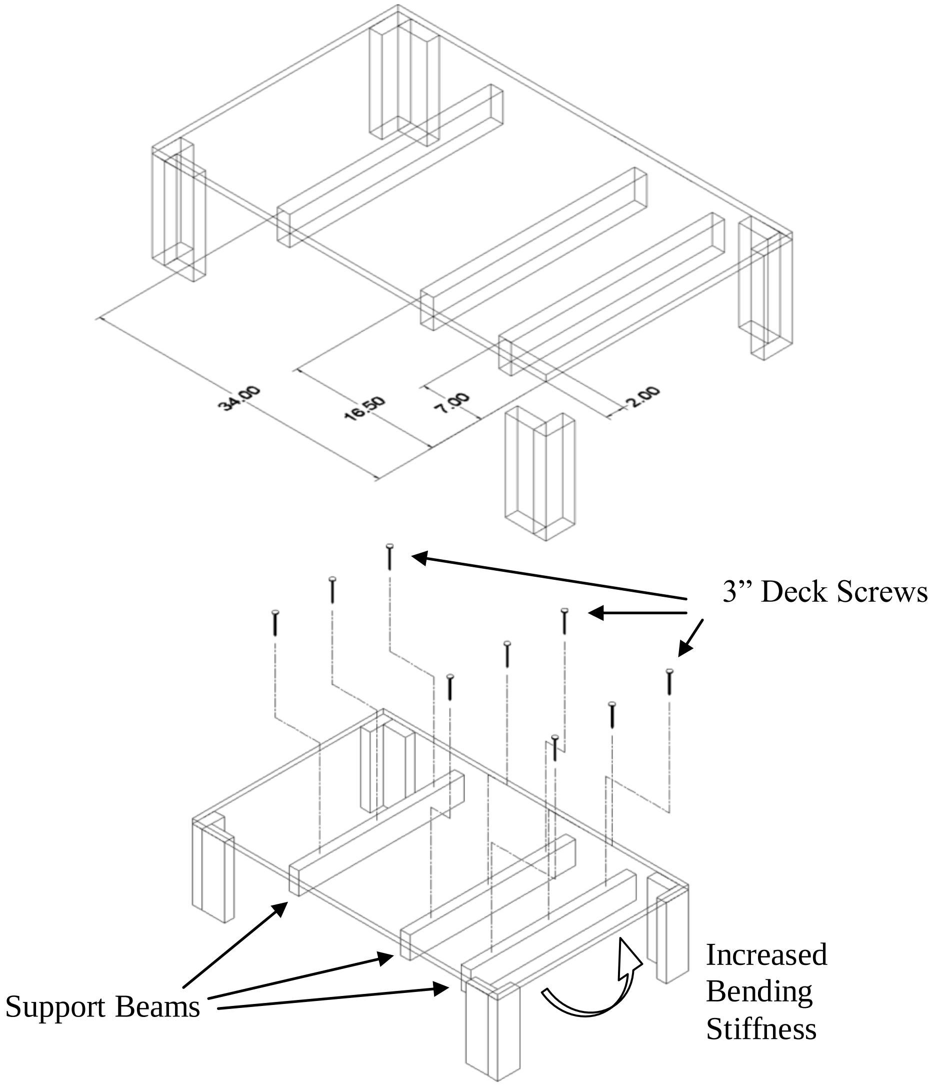


Figure 50: Support Beams for increased bending stiffness

A support beam is also placed in the longitudinal direction of the platform to increase stiffness against the bending moment caused by the weight of the compressor. This beam is made with a piece of lumber (two by six) cut to a length of 37.5 inches (95.25 cm) with a circular saw.

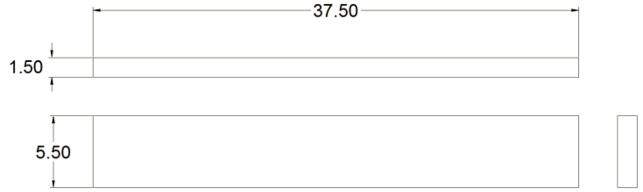


Figure 51: Longitudinal support beam dimensions

It is placed along the edge closest to the compressor mount location, between the leg posts, and fastened using six 3” deck screws from above, placed about six inches evenly apart as shown in Figure 52.

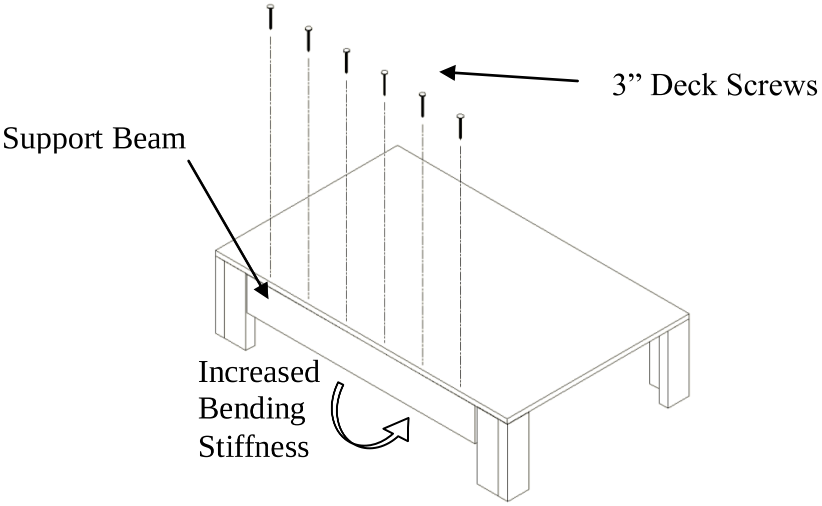


Figure 52: Longitudinal Support Beams

One safety measure that is built into our prototype includes walls on the two most dangerous sides. ¾ inch plywood is used to make these walls along the edge where the compressor and drill mount, as well as the edge where the intercooler outlet faces. The finished walls are shown in Figure 53 below.

Figure 53: Safety Wall Locations

For the wall along the compressor, the ¾ inch plywood is first cut to 48 inches (1.22 m) x 23 inches (58.42 cm) with a circular saw.

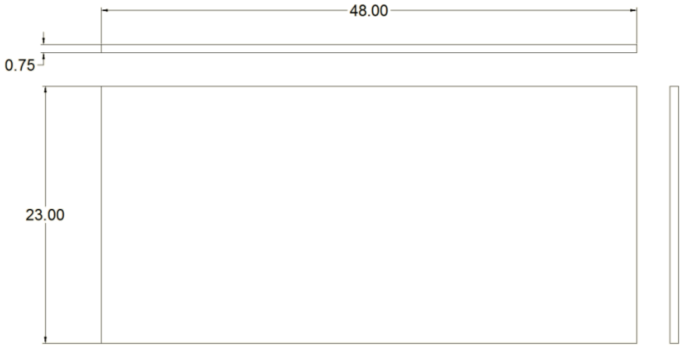


Figure 54: Dimensions of Wall Along Compressor (in inches)

Next, lumber (two by four) is used to create the attachment posts. Using a circular saw, two pieces are cut to a length of 33.5 inches (85.09 cm) and fixed 21 inches (53.34 cm) into the wall along each width with six 3" deck screws each such that 12 inches (30.48 cm) protrudes from the bottom wall edge. A third piece is cut to 27 inches (68.58 cm) and also fixed 21 inches into the wall at its midpoint with six 3" deck screws.

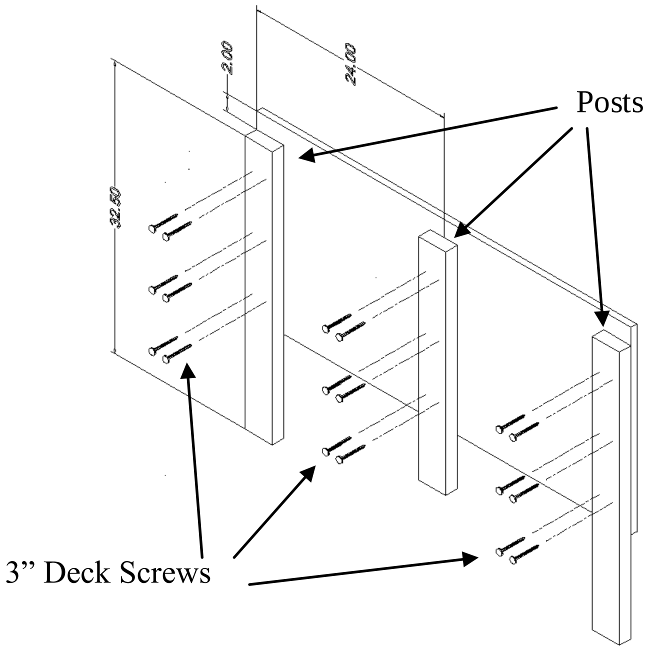


Figure 55: Attachment posts for compressor side safety wall

The protrusions allow for attachment to the table at the leg posts. Four 3" deck screws are used for each post and the locations are shown in Figure 56, below.

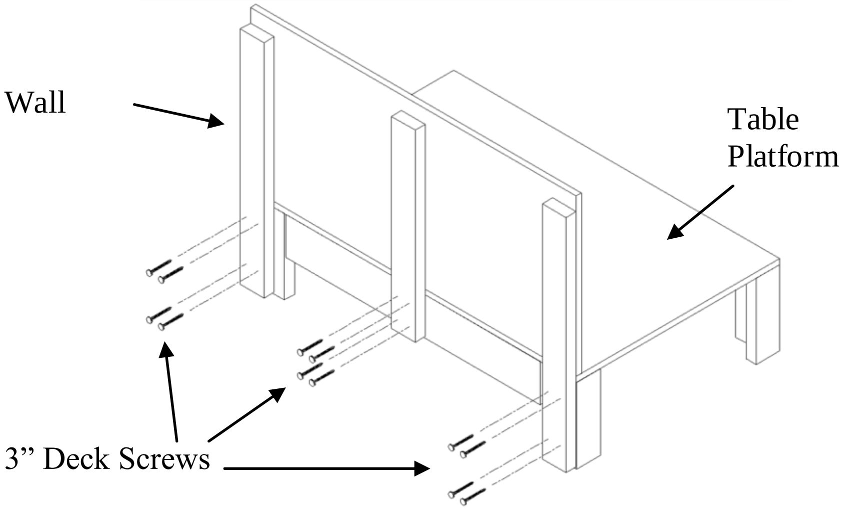


Figure 56: Attachment of compressor side safety wall to platform

The wall facing the ducting's final outlet is built in the same manner. The remaining ¾ inch plywood is cut to 22 inches (55.88 cm) x 22.5 inches (57.15 cm) with a circular saw.

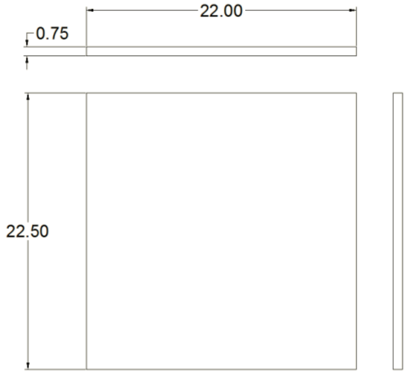


Figure 57: Outlet side safety wall dimensions

Next, lumber (two by four) is used to create the attachment posts. Using a circular saw, these are cut to a length of 32.5 inches (82.55 cm) and fixed 20.5 inches (52.07 cm) into the wall along each width with four 3" deck screws each such that 12 inches (30.48 cm) protrudes from the bottom wall edge.

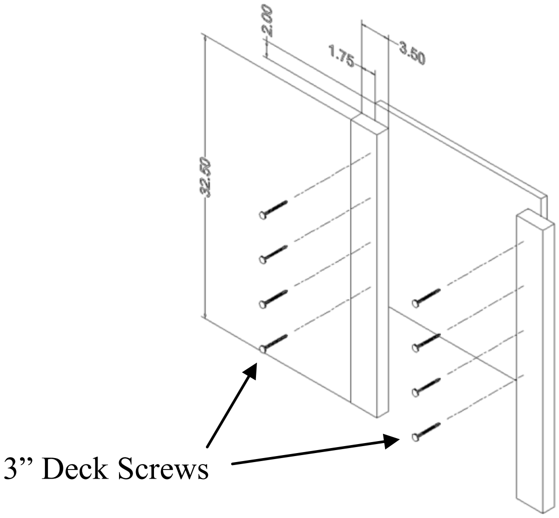


Figure 58: Attachment posts for outlet side safety wall

The protrusions allow for attachment to the table at the leg posts. Four 3" deck screws are used for each post and the locations are shown in Figure 59.

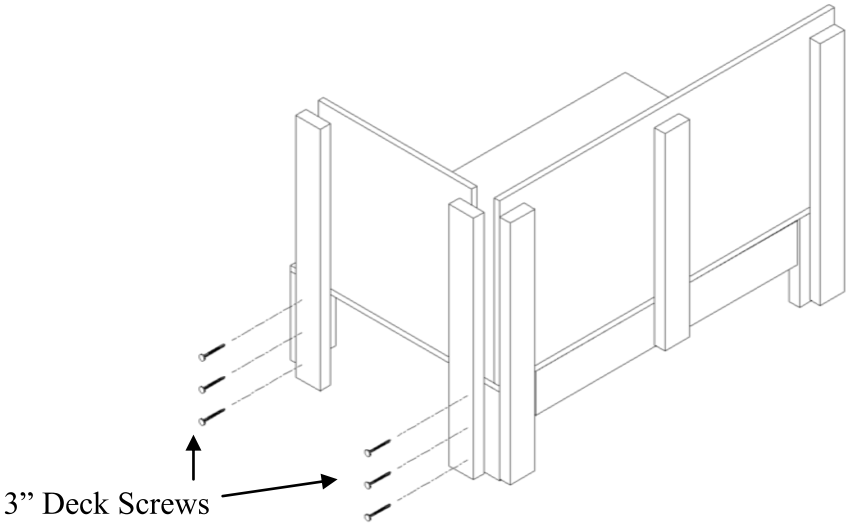


Figure 59: Attachment of outlet side safety wall

Now that the “test rig” is completed, we can begin assembling of the prototype components. The first component we mounted is the compressor.

Mounting the Compressor

The compressor placement is determined to be lengthwise with the platform along the walled edge. This location is shown in Figure 60 below.

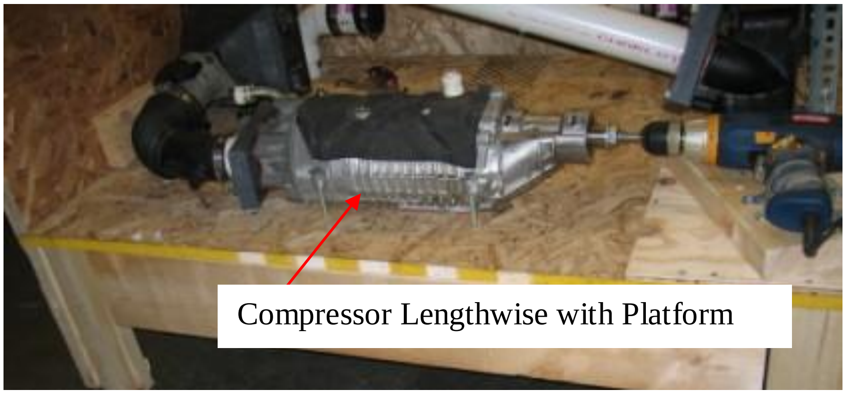


Figure 60: Compressor Location on Platform

We chose to mount the compressor such that the flat surface of the exhaust flange is seated against the platform surface. To do this, we first marked the parts of the compressor which extrude beyond this datum plane, such as the vacuum hose ports and fitting pegs.

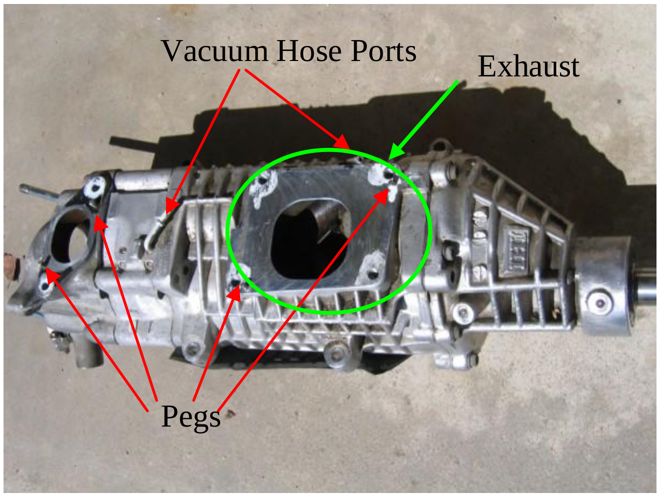


Figure 61: Compressor underside with extrusions to flat surface

Using whiteout and placing the compressor in the appropriate spot, we are able to stamp the areas on the platform which must be recessed for clearance. A hand drill is used to remove material until the compressor sits flush with its flanges.

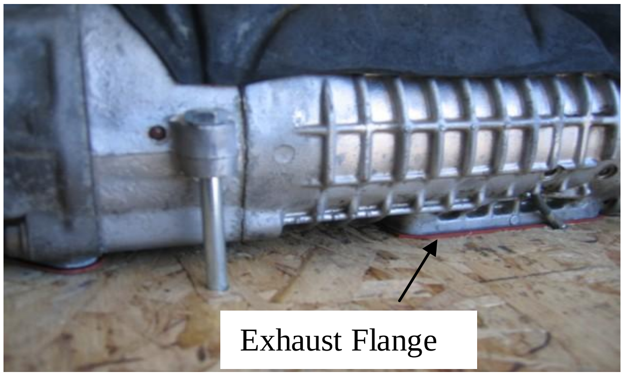


Figure 62: Compressor sits flush on platform with exhaust flange

Next, the stock bolt locations of the compressor are marked onto the platform with the same whiteout technique. All bolts used by the compressor are metric M8 bolts with 1.25 pitch. 3/8 inch holes are drilled with a hand drill clear through the platform for the bolts. Large 2” fender washers are used to distribute the clamping force as much as possible. The four bolts along the perimeter of the compressor are tightened down to 10 lb-ft and directly hold the compressor to the platform.

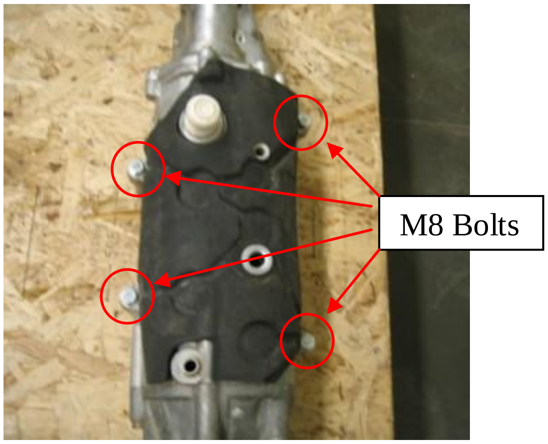


Figure 63: Bolt Locations for Compressor Mount

The exhaust of the compressor now faces downwards, toward the platform. We will have an adaptor piece to connect PVC piping to the platform, but first a hole must be cut into the platform to allow air to pass through. Since the PVC piping has an inner diameter of 2 inches (5.08 cm), a hole saw of 2.125 inch diameter (5.4 cm) is used to create the hole.

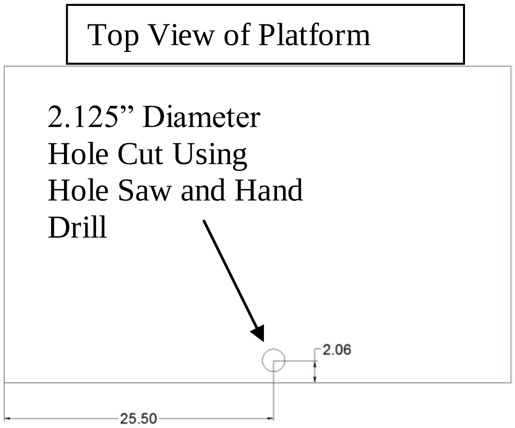


Figure 64: Compressor Exhaust Opening in Platform

Another flange near the compressor inlet also faces downwards towards the platform. This was designed into the compressor for a bypass valve; however it will not be used for our prototype. Therefore, we will seal this off, using the platform and a gasket, to allow only one inlet to the compressor.

Figure 65: Bypass valve flange at inlet sealed

The compressor exhaust adaptor is created with a 1 inch (2.54cm) thick slab of PVC. A band saw running at 125 ft/min is used to cut the PVC to our dimensions of 5.5 inches (13.97 cm) by 4.75 inches (12.07 cm). Then, a drill press at about 300 rpm is used with a ½” drill bit to create holes for the bolt locations. Finally the hole for the PVC pipe must be made. Since the outer diameter of the PVC pipe is approximately 2.375 inch (6.03 cm) in diameter, a lathe must be used. The dimension of this hole, 2.39 ± 0.01inch (6.07 ± 0.025 cm), is critical. If it is made too small, the PVC piping will not fit inside easily enough for gluing. If it is made too large, the gap between the PVC pipe and the block makes gluing extremely difficult. Once the center of this hole is marked, the PVC block is placed on a lathe with a 4-point chuck in the spindle. A center drill is used to ensure the alignment, and an initial hole is drilled. A 1” drill bit in the tailstock is used to create as large of a starting hole as possible. Then, a boring bar is used on the tool post to enlarge the hole to specification.

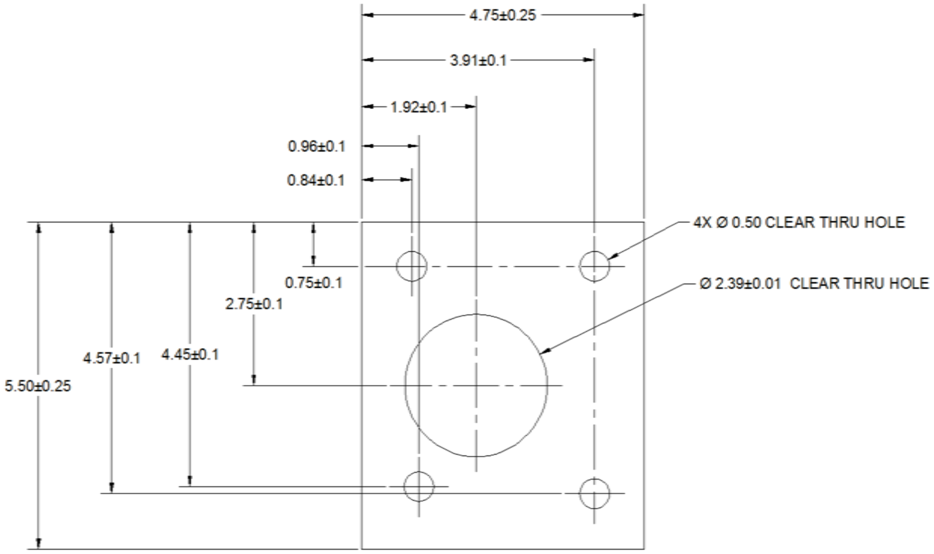


Figure 66: Compressor Exhaust Adaptor Dimensions (in Inches)

A piece of 2” PVC pipe is cut to a length of 3 inches (7.62 cm) by use of a hacksaw. Primer is applied to outside of one end, as well as the inside of the PVC adaptor block. Then, the PVC cement is applied in the same fashion. The PVC pipe is inserted approximately ¾” inside the block and held for at least two minutes. The assembly is allowed to dry for a complete 24 hours before handling.

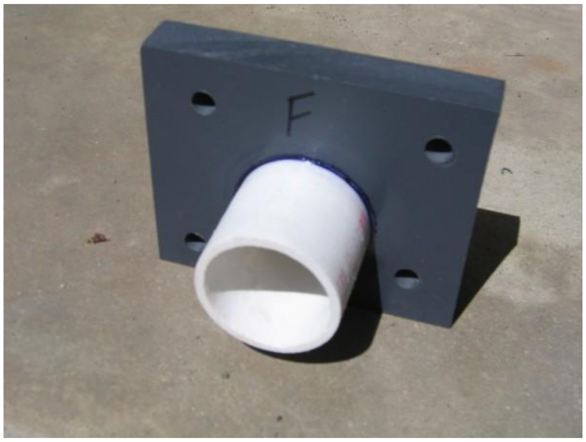


Figure 67: Compressor Exhaust Adaptor

Four M8 bolts inserted from underneath with 1.5” fender washers hold the compressor exhaust adaptor to the platform.

Figure 68: Compressor exhaust adaptor mounted

A similar process is used to create the adaptor between the air box and the compressor. A slab of 1 inch thick PVC is reduced to 3.25 inches (8.255 cm) by 7.25 inches (18.42 cm) by use of a band saw operating at 125 ft/min. The holes for both the mounting studs and M8 bolts are created on the drill press running at 300 rpm with a ½” drill bit. The 2.39 ± 0.01inch (6.07 ± 0.025 cm) hole for PVC pipe attachment is again made using the lathe.

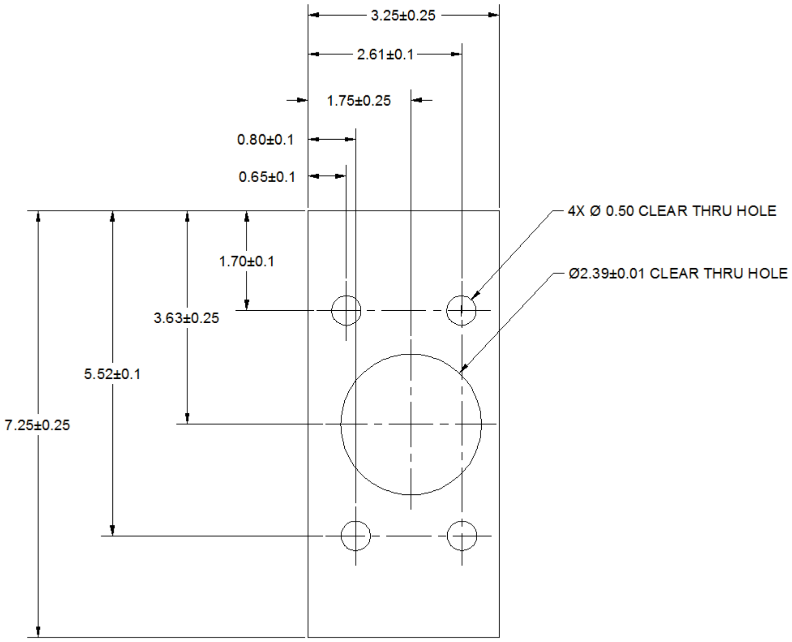


Figure 69: Air box to Compressor Adaptor Dimensions (in Inches)

The 2” PVC pipe must be cut to a length of 3 inches (7.62 cm), and is done so with a hacksaw. Primer is applied to outside of one end, as well as the inside of the PVC adaptor block. Then, the PVC cement is applied in the same fashion. The PVC pipe is inserted approximately ¾” inside the block and held for at least two minutes. The assembly is allowed to dry for a complete 24 hours before handling.

Figure 70: Air Box to Compressor Adaptor

Gaskets must be made to seal and prevent air leakage. They are made by cutting thin sheets of rubber to the proper sizes and shapes to fit each flange. Four specific locations around the compressor require gaskets. These are: between the air box adaptor and compressor inlet flange, between the platform and compressor exhaust flange, between the platform and compressor exhaust adaptor, and between the inlet bypass valve flange and the platform. Figure 71 below displays an example of a finished gasket.

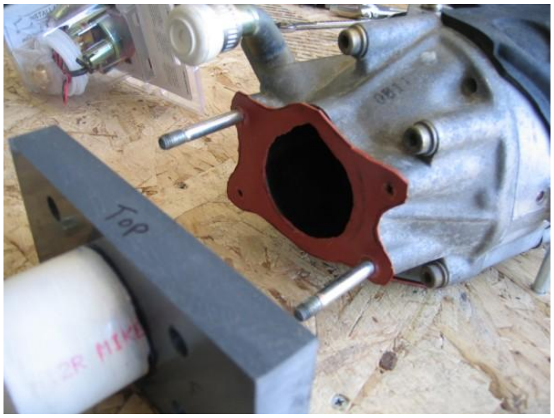
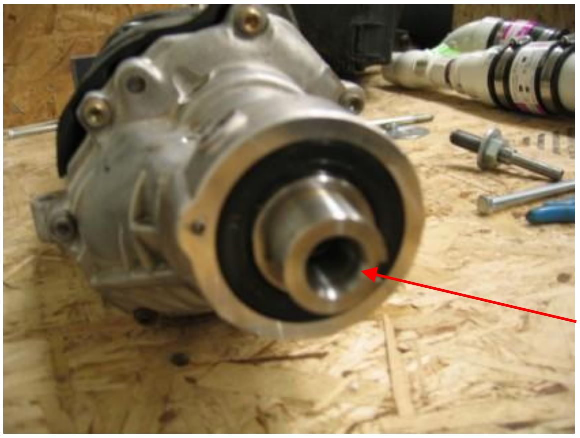


Figure 71: Air Box Adaptor Gasket on Compressor

To run this compressor, the shaft is connected to the hand drill with a custom made adaptor.

Compressor to Drill Adaptor

The compressor shaft has inside threads because a bolt is originally used to hold a drive pulley on at this end. The pulley has been removed, and the shaft's threads utilized in an adaptor piece.



M14 x 1.50
Threads Inside
Shaft

Figure 72: Compressor Shaft Inside Threading Used for Adaptor Shaft

To start, we find the proper bolt which matches the shaft diameter and thread pitch; this turns out to be a metric M14 bolt with 1.5 pitch. We purchase as long a bolt as possible (12 cm) because the unthreaded end will be lathed down to < 3/8" and chucked into the hand drill. First, the thread length is matched up to the original pulley bolt. A dye is used to extend the threads so that a nut threaded to the end will act as the stopper or replacement bolt head. Then the original bolt head is removed by using a hacksaw. To lathe the smooth end of the bolt down, a fixture first needs to be made to prevent damage to the bolt threads. This fixture is made from a 3.5 cm diameter piece of cylindrical steel stock. A ½" hole is drilled into the center and taped to match the 1.50 pitch thread. The bolt can now be threaded into this fixture, which is placed into a collet in the lathe spindle. A turning tool is placed into the tool post, and then centered vertically to the bolt. The lathe is set to run at 100 rpm, and multiple passes are made to reduce 1.5 inches (3.81

cm) of the bolt to a diameter of 0.3 inches (7.62 mm). Specifically, 0.04 inches of the diameter are removed per pass with four passes required.

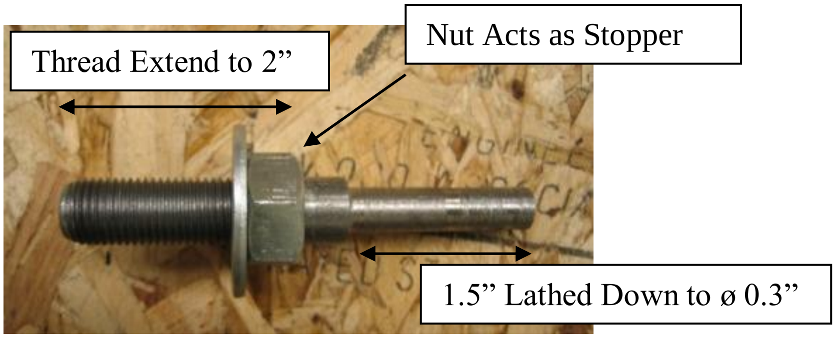


Figure 73: Compressor to Drill Shaft Adaptor

Mounting the Drill

The hand drill must be mounted in such as way that the shafts align with the compressor shaft. A 1/8 inch thick board in combination with a piece of lumber (two by four) is used to bring the hand drill to the proper height as shown in Figure 74.

Figure 74: Compressor Shaft and Drill Chuck Must Align

The 1/8 inch board is screwed permanently into the platform with six ¾” deck screws. Three 3/8 inch holes are drilled clear through the thicker lumber piece, thin board, and platform so that M8 bolts with large 1.5” fender washers can be used to hold the entire assembly together. Finally, the hand drill is fixed into place with two U-clamps around the handle. Foam insulation pieces are inserted between the clamps and drill to evenly distribute the holding force while at the same time preventing damage to the hand drill.

Figure 75: Support to Raise Drill to Proper Height

Mounting the Intercooler

The stock mounting points on the intercooler have been utilized with custom brackets to hold the intercooler to the platform. First, L-shape aluminum rails are cut to an approximate length of 10 inches (25.4 cm) by using a band saw at 100 ft/m. These are fixed to the intercooler with 5/16 inch bolts and nuts with appropriate washers. Next, L-brackets are attached by matching to the holes and slots in the rails as shown in Figure 76.

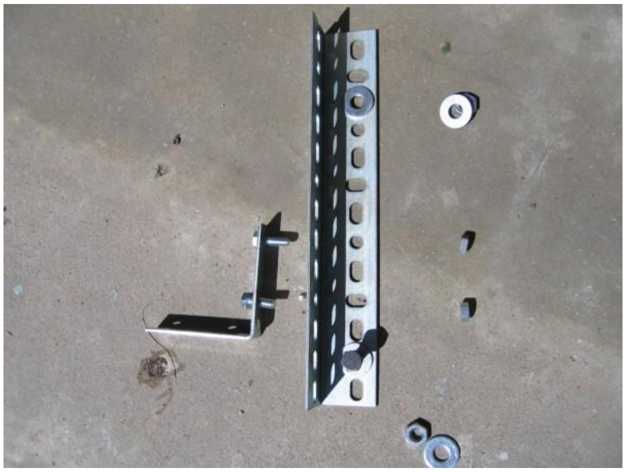


Figure 76: L-Bracket and Aluminum Rail for Intercooler Mounting

1/4 x 20 bolts and nuts are used to secure the L-brackets to both the aluminum rails and to the platform.

Figure 77: Intercooler Brackets Assembled

The stock flanges for the intercooler are utilized for connections to the PVC ductwork. Each flange requires an adaptor similar to the adaptors found on the compressor inlet and outlet. Luckily, the two flanges of the intercooler are identical, and thus the adaptors are identical as well. To make these adaptors, first a 1” thick slab of PVC is reduced to 5.75 inches (14.61 cm) x 4 inches (10.16 cm). Then, holes for the mounting studs are created by using a ½” drill bit on a drill press operating at 300 rpm. The 2.39 ± 0.01inch (6.07 ± 0.025 cm) hole for the PVC pipe is created in the lathe with the same method as that for the compressor adaptors. Once the center of this hole is marked, the PVC block is placed on a lathe with a 4-point chuck in the spindle. A center drill is used to ensure the alignment, and an initial hole is drilled. A 1” drill bit in the tailstock is used to create as large of a starting hole as possible. Then, a boring bar is used on the tool post to enlarge the hole to specification.

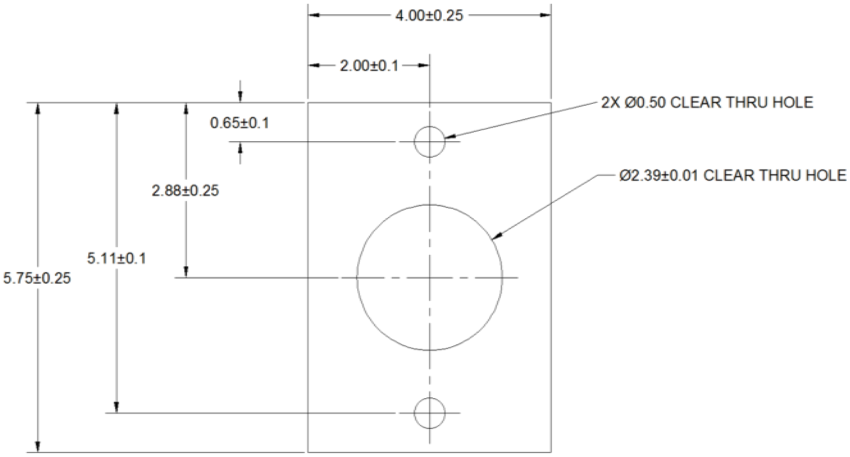


Figure 78: Intercooler Adaptor Dimensions (in Inches)

This time, however, an additional step needs to be taken so that the adaptors sit flush with the beveled edge on the intercooler flanges.

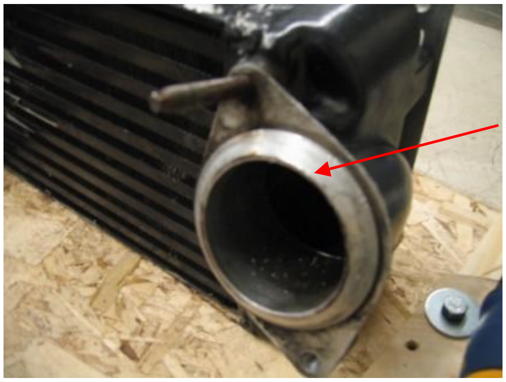

45°
Beveled
Surface

Figure 79: Intercooler Flange with Beveled Surface

First, the angle of the bevel (45°) and length of the hypotenuse (0.52 inches (1.32 cm)) is measured using calipers. Then, the tool post angle is set to 45° and the lathe is used to cut a negative form of this exact shape. Measurements of the hypotenuse are measured after each pass until 0.52 ± 0.1inches is reached.

For the inlet adaptor, a piece of 2” PVC pipe is cut to a length of 6.5 inches (16.51 cm) by use of a hacksaw. For the outlet adaptor, 17.5 inches (44.45 cm) is used. In each case, primer is applied to the outside of one end, as well as the inside of the PVC adaptor block. Then, the PVC cement is applied in the same fashion. The PVC pipe is inserted approximately ¾” inside the block and held for at least two minutes. The assembly is allowed to dry for a complete 24 hours before handling.

Figure 80: Intercooler Adaptor Assembly

Gaskets are also needed between the intercooler flange and the adaptors. These are made from the same thin rubber sheets as in the compressor gaskets.

Figure 81: Rubber Gasket on Intercooler Flange for Adaptor

Water Injection Assembly

The Roundup® sprayer must be modified slightly to fulfill our purposes. First, a pressure gauge is attached to the line to measure water pressure behind the spray nozzle. To do this, the stock line is cut at the middle into two pieces using scissors. ¼” male barbs are fitted into each end of the line and secured with hose clamps. The ¼” NPT threads on the barbs allows easy attachment of the pressure gauge to both ends of the line. Teflon tape is used to ensure a seal with the pipe threading.

Figure 82: Water Tank Pressure Gauge Attached to Line

For attachment of the Monarch™ misting nozzle, the stock handle is removed from the line, and another ¼” male barb fitted to the end. Because the nozzle has a 1/8” male end, an adaptor is required. The only adaptor available is a female 1/8” to a male ¼”. Because of this, a ¼” female-female coupler is also required in order for attachment of the ¼” brass ball valve. The ball valve acts as a switch. This nozzle will spray into PVC piping through the use of an angled tee connector. A cap which threads onto this tee is used to house the nozzle. First, a 7/16” hole is drilled into the center, and then taped with a tapered ¼” NPT tap from the inside. The nozzle, 1/8” to ¼” adaptor, and ¼” female coupler are threaded on the inside, and the brass ball valve is then threaded onto the adaptor from the other end, thereby sandwiching the tee cap.

Figure 83: Injector Connections Mounted by Sandwiching PVC Pipe Cap

Teflon tape is used on all the threads to ensure a good seal. This sufficiently holds the nozzle in place while minimizing the chance for leaks.

PVC Connections

In order to transfer air between components of the prototype, PVC piping is used as the ductwork. 2” inner diameter PVC is used in all the piping and, unless otherwise mentioned, all PVC pieces are joined together using the primer and cement. From the compressor exhaust adaptor, a 90º elbow is attached.

Figure 84: PVC Ductwork After Compressor Outlet

Next, the 10 psi safety pop valve is placed by using a tee. Since the pop valve is manufactured with ½” national pipe threading (NPT), a reducer with matching ½” thread is needed. Teflon tape is used to ensure a tight seal between the threads

Figure 85: 10 PSI Pop Safety Valve

Piping after the tee leads to a second 90º elbow, directing the piping upwards. At this location, a hole must be made in the platform for piping to continue. For added clearance, a 3 inch (7.62 cm) square is cut using a jig saw.

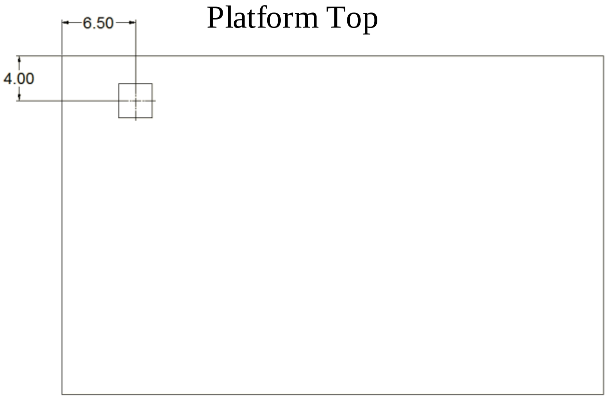


Figure 86: Hole Cut Through Platform for PVC Piping

Now, the vertical pipe is cut to 6 inches (15.24 cm) and joined through the square hole to the elbow beneath the platform. A third 90º elbow is attached at this point to redirect the piping towards the intercooler. It is here that the tee which holds the water injector nozzle is connected.

Figure 87: Water Injector Tee Connection

First, a piece of 2” PVC pipe cut to 2.5 inches (6.35 cm) with a hacksaw is attached to the exit side of the tee while a 11 inches (27.94 cm) piece is attached at the other end. Instead of PVC cement, rubber couplings hold this assembly between the 90º bend and the intercooler inlet adaptor.

Figure 88: Rubber Couplings for PVC Connection

This allows for easy removal of the water injector piping when needed.

At the intercooler outlet, and as the final piece of the prototype, a 1” diameter ball valve is attached. To do this, an adaptor is created between the 2” diameter piping and 1” connector with male NPT threads, onto which the ball valve threads. No 2” to 1” adaptor exists, so an additional step is used. The piping is first reduced to 1.5”, and finally to 1”.

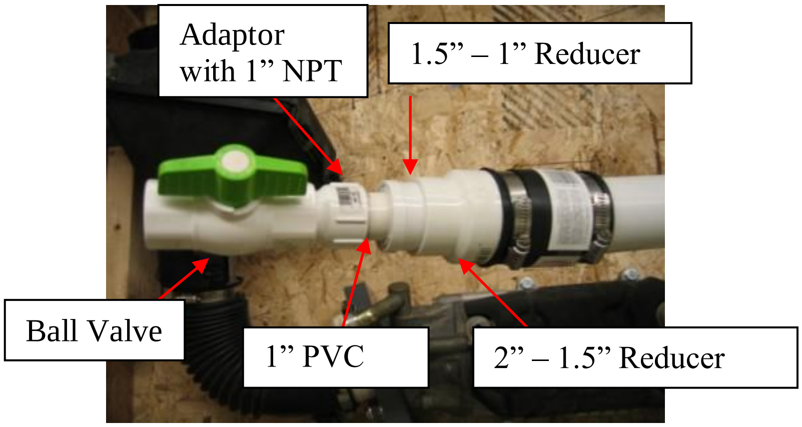


Figure 89: Pipe Reduced to 1" for End Ball Valve

This ball valve assembly is attached to the ductwork by a rubber coupling.

Sensors

The rubber coupling just at the intercooler inlet adaptor is used to attach the first thermocouple into our system. The wire is inserted such that the tip extends to the center of the pipe. Tightening the hose clamps on the coupling holds the thermocouple wire in place and also creates a tight seal. The second thermocouple and humidity sensor are placed in the same manner at the rubber coupling just before the end ball valve.

The Honeywell humidity sensor needs soldering to attach wires to its three leads. 24 gauge wire is used for all three leads. First, approximately ¼" at the ends of all wires are stripped. Then, a soldering iron is heated to 500°F and the tip cleaned with a moist sponge. Resin core solder is used and each wire is directly soldered onto a lead. Finally, heat shrink and a heat gun are used to insulate and protect the exposed wire. For added protection, electrical tape is used to wrap all wires together.

Figure 90: Humidity Sensor

The Sunpro$^{®}$ boost pressure gauge comes equipped with a hose line and ¼" male NPT brass connector on the end.

Figure 91: Pressure Gauge Attachment

This is utilized for direct attachment of the gauge onto the 2” PVC piping after the intercooler exit. Much like the attachment of the water injector nozzle, a 7/16” diameter hole is drilled into the side of the PVC pipe with a hand drill and taped with a ¼” tapered NPT tap. Now the brass connector can simply thread into the ductwork. Of course, Teflon tape is used to ensure a tight seal.

Figure 92: Pressure Gauge Attachment to PVC Duct

Final Design Fabrication Differs

There is a large difference between the fabrication of our prototype and the manufacturing of our final design. For instance, the final design will be made to fit a vehicle, not a wooden platform. The final design will also not require many of the custom fittings and brackets mentioned for the prototype, as mounting locations and brackets will be designed directly into the final product. Ductwork between components may not necessarily use PVC material, and most likely will not have a constant two inch diameter cross sectional area. This ductwork design is very flexible and can change from vehicle to vehicle for best accommodation. Specifically made tools for mass production by molding or extrusion processes is likely. This will allow for even more flexible design. Sensor locations can also vary along the ductwork; however, their placement in relation to the components is fixed for both prototype and final designs.

VALIDATION PLAN

Because our project is the design of a system rather than the design of a single component, it was essential that our prototype illustrate that these components could be combined in a specified order to achieve a desired output. We determined that the components that were most necessary for validation of our design were the compressor, humidifier, and intercooler as these components' function affects the same characteristics. To ensure that our prototype was representative of our final design, we used components that were of the same design type though inconsistent with exact sizing.

The goal of the prototype is to demonstrate that our assembled system can achieve set targets for pressure, humidity, and temperature by controlling a screw compressor, water injector, and air-to-air intercooler. By proving this is possible with our prototype, we can validate that the final system design is capable of properly controlling these characteristics.

Due to safety, cost, and time, our prototype is smaller in size than the final design for a fuel cell vehicle. Our final design has the desired characteristics of 2.5 Bar, 85°C, and a relative humidity of 100% at the inlet of the fuel cell. As a result of scaling down, our new targets were a pressure of 1.35 bar, and a temperature of 40° C. Our final design target relative humidity of 100% remained the same for the prototype.

Before we could control the system as a whole, we needed to be able to predict the output of our components for a variety of inputs. To do this, our team performed characterization experiments for the compressor, humidifier, and intercooler individually.

Compressor Characterization Experiment

To achieve our desired pressure, our team needed to find the right settings for the drill speed and the opening of the end ball valve (back pressure) for the system. For this experiment, our team ran the hand drill at various input speeds to drive the shaft of the compressor. To control the compressor speed remotely, we used a hose clamp around the trigger of the hand drill. The hose clamp was tightened around the trigger from about half speed to full speed. For each test, we adjusted the opening of the end valve by hand from open to close, recording the different pressures our system achieved using a boost pressure gauge attached at the end of the system. By varying the speed of the compressor, we were able to determine the necessary rotational speed and end valve setting to obtain our desired final pressure. Once we found the necessary operating speed of the compressor, we tried to determine the resulting temperature and mass flow rate. We measured the mass airflow rate at the inlet using the equipment provided by Visteon and attached it to our Air Box. This would have enabled us to calculate the required heating and humidification for different ambient conditions. We followed the procedure seen below:

1. Tighten hose clamp around the trigger of the drill using a screw driver before running the system.
2. Leave end ball valve entirely open to generate zero back pressure
3. Turn drill on by plugging into wall outlet
4. Slowly adjust ball valve from open to closed
5. Record pressures from boost pressure gauge located at the outlet of the compressor

6. If the pressure did not reach target of 1.35 psi, turn drill off by unplugging it.
7. Repeat steps 1-6 until proper pressure was achieved, tightening the hose clamp slightly further each time
8. Record mass airflow rate using apparatus provided by Visteon on the air box.

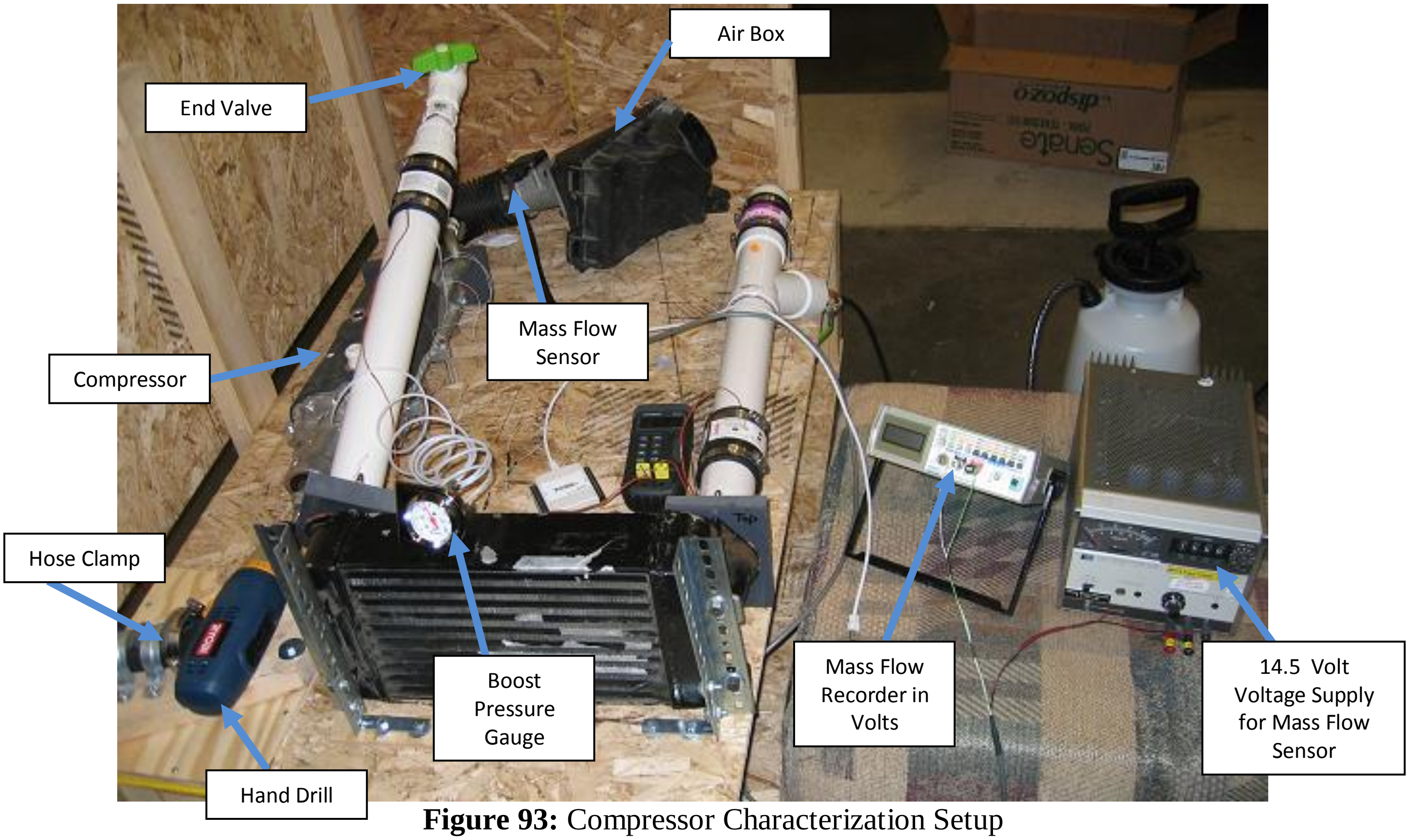


Figure 93: Compressor Characterization Setup

Water Injection Characterization Experiment

To inject the proper amount of water into our system, our team needed to characterize the mass flow of the water at different pressures. To do this we first filled the tank with approximately 1200 ml of water. We then pumped the water tank up manually to a specified gauge pressure using the pressure gauge attached to the water tank and keeping the ball valve attached to the line closed. We performed tests at gauge pressures of 10 psi, 15 psi, 20 psi, 25, psi, 30 psi, and 35 psi. We would then open the ball valve completely and allow water to be sprayed into a container of 591 ml. We recorded the time it took for the container to become full and then shut the valve to stop the water from spraying. By measuring the volume and dividing by the time, we then determined the mass flow rate of the water. This allowed us to determine what setting will give us the flow rate needed to achieve 100% R.H. The results of this test can be seen in the following section.

After determining the mass flow rate of water corresponding to different pressures, we attached our injection system into the entire assembly. We ran the compressor at a lower speed to keep our hand drill from overheating and opened the end valve completely to ease the load on the drill. We ran our water injector at different pressures to determine which flow rate could achieve a relative humidity of 100%. Tests were run for 8-10 minutes. We recorded the relative humidity of the air using our purchased humidity sensor, the Honeywell HIH-4033, located at the end of the assembly at the outlet of the intercooler. We supplied a five volt input voltage to the sensor and recorded the output voltage. The relative humidity could then be determined from the calibration chart for our humidity sensor seen below in Figure 94.

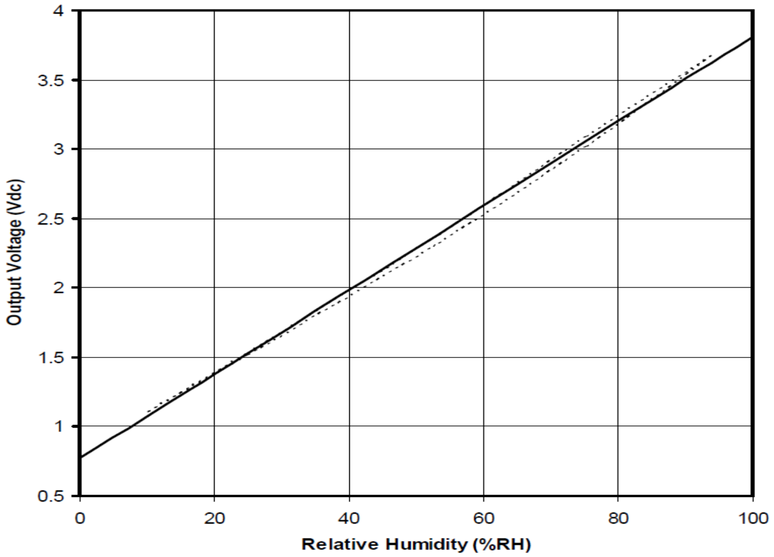


Figure 94: Relative Humidity calibration curve at 25°C with an input Voltage of 5 Volts

Unfortunately, the hand drill would over heat long before the sensor could measure the humidity of the air. If we had been able to determine the relative humidity, our team would have then made adjustments to the pressure in the tank by either lowering or increasing the pressure depending on whether the humidity was too low or if we observed condensation. This way we could have experimentally determined the proper pressure to achieve a relative humidity of 100%. We followed the procedure seen below:

1. Fill water tank up with 2000 ml of water
2. Pump water tank to desired pressure manually (verifying using gauge located on water tank) starting at 10 psi
3. Open end valve completely
4. Set drill to low speed(a speed that our team felt was lower than 50% of its max speed). This was done visually rather than calculated.
5. Turn on hand drill by plugging it in
6. Spray water into system by opening control valve located on water line
7. Take recordings of humidity using humidity sensor located after the intercooler outlet. Humidity sensor required input voltage of 5 volts. Readings were taken every 5 seconds using Labview 4.0
8. Wait for readings to reach steady state or stop after 10 minutes
9. Repeat steps 1-8, increasing pressure 5 psi with each iteration

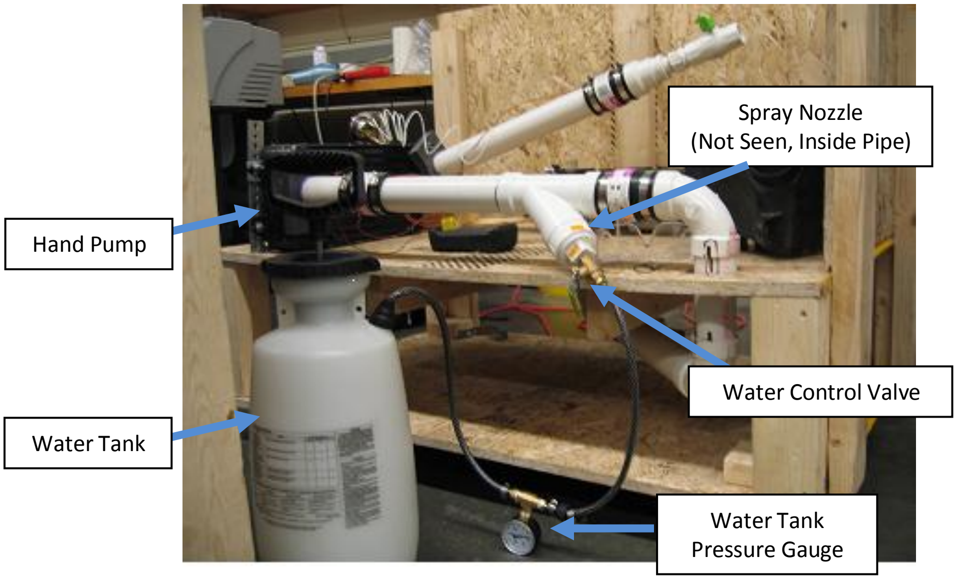


Figure 95: Water Injection Characterization Setup

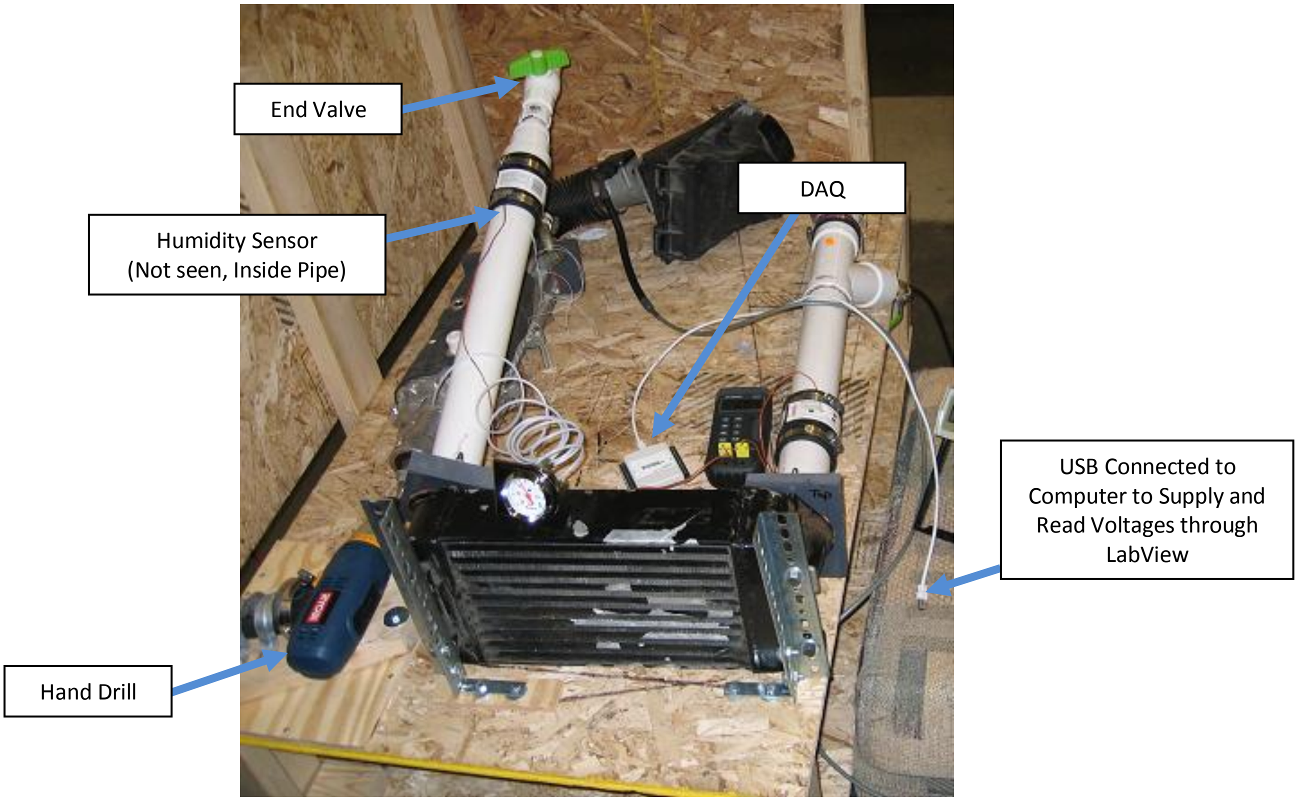


Figure 96: Water Injection Characterization Humidity Reading Setup

Intercooler Characterization Experiment

For the intercooler characterization test, our team measured the temperature difference across the intercooler using two thermocouples while supplying a cross flow of air across the intercooler. We set the hand drill at the previously determined speed and end valve opening needed to achieve our target pressure at the outlet. The water injection system was not run for this experiment. Once achieving the desired pressure, our team recorded the temperature difference, if any, between the intercooler inlet and outlet. We then used either one or two hair dryers set on high speeds to supply a heated cross flow across the intercooler. After temperature appeared to reach steady state, we would then record the temperature difference between the inlet and the outlet of the intercooler. We followed the procedure seen below:

1. Set drill to proper speed and end valve to proper opening to achieve desired pressure
2. Turn drill on by plugging it in to an outlet
3. Verify proper pressure from boost gauge sensor located at the outlet of the intercooler
4. Record temperature difference between inlet and outlet of the compressor, if any, using our thermocouples.
5. Turn on one hair dryer to high and blow air at back of intercooler
6. Wait for temperature difference to reach steady state and then record temperature difference using Omega thermocouple reader
7. Turn second hair dryer on high and blow air from both hair dryers at back of intercooler
8. Wait for temperature difference to reach steady state and then record temperature difference using Omega thermocouple reader

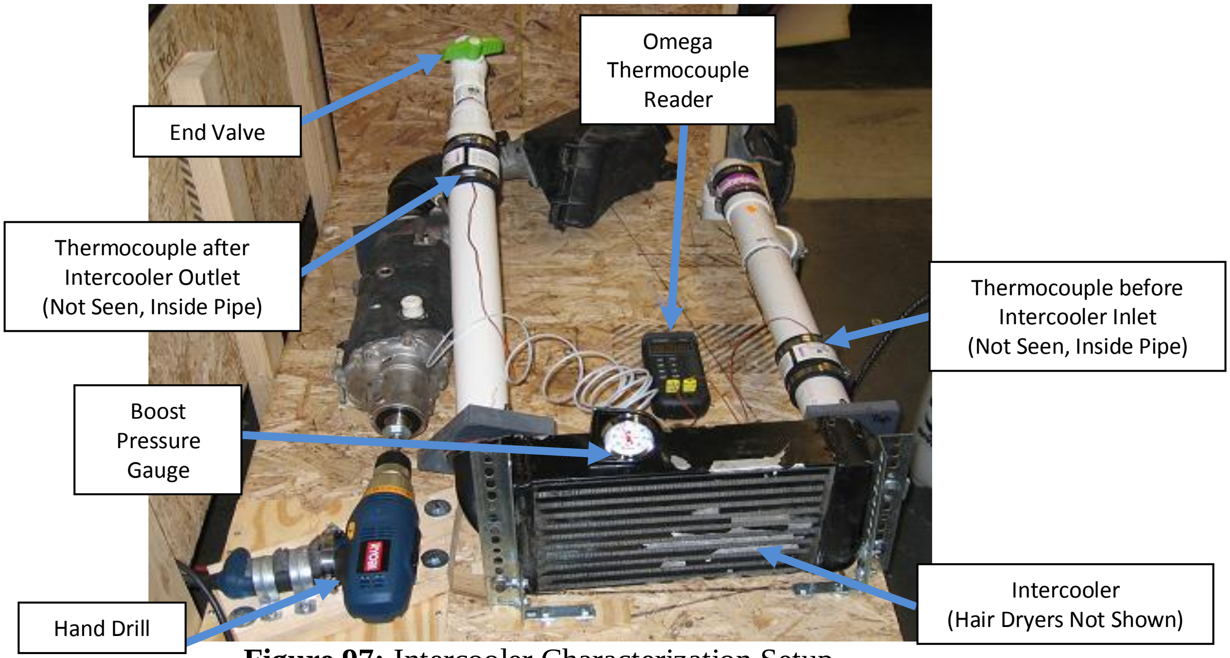


Figure 97: Intercooler Characterization Setup

VALIDATION RESULTS

By testing our prototype, our team obtained many results both numerical and through observation that were highly educational when applying them to our final design. Our team observed a maximum pressure rise of 3.5 psi, a maximum temperature increase of 10°C which resulted in an outlet temperature of 33°C, and could not ever get a significant reading from our humidity sensor. While we originally had prototype targets 5 psi pressure increase, final temperature of 40°C, and a relative humidity of 100%, our team quickly realized that these targets were not feasible. This was due to limitations in our prototype setup, mostly due to the inability of the compressor to achieve the necessary speed to deliver a high enough pressure and airflow. As a result, we could not reach our target pressure of 5 psi and there was no temperature increase from compression due to limited airflow (showing that the process is non-adiabatic).

Numerical Results

From our compressor, water injection, and intercooler characterization experiments, our team obtained data about the pressure, flow rates, temperature, and humidity of our system. To start, our prototype was capable of controlling the pressure of the system from 0-3.5 psi. This was done by regulating the speed of the compressor and the back pressure on the system. The speed of the compressor was controlled by the speed/torque provided by the hand drill and the back pressure was controlled by setting the opening of the end valve. Also, our team was unable to record any significant data from our mass airflow sensor calibrated by Visteon. All we observed was noise.

From the water injection characterization experiment, our team was able to determine the mass flow rates of water at various pressures from the water tank seen below in Table 6. We saw that as the back pressure increased, so did the flow rate through the nozzle. As our team plans on controlling the humidity of our final design by the amount of water injected, the correlation between the back pressure of the water tank and the mass flow of water out of the nozzle is useful in demonstrating the control our final design would need.

Table 6: Mass Flow Rates of Water at Different Tank Pressures

Trial	Starting Pressure (psi)	Ending Pressure (psi)	Time (seconds)	Mass Flow Rate of water (ml/sec)
1	15	14	305	1.94
2	20	17	279	2.12
3	25	22	247	2.4
4	30	27	215	2.75
5	35	32	199	2.97

Unfortunately our team was unable to properly finish the water characterization experiment by observing different relative humilities for different amounts of water injected. The humidity sensor purchased was unable to reach any sort of steady state within the ten minute test time. Our team needed to purchase a sensor that was affordable with our budget. However, this sensor and other sensors in this price range require upwards of half an hour to reach steady state. Our test setup was not meant to run for extended periods of time and no significant data was recorded from our humidity sensor.

Lastly, our team recorded an increase in temperature related to the amount of cross sectional area of the intercooler exposed to a heated cross flow. While our final design calls for cooling of air due to the large temperature increase from compression, our prototype was unable to achieve any temperature increase across the compressor. As a result our prototype demonstrated temperature control across the intercooler with two hair dryers. We observed an increase of 4-5°C with one hair dryer supplying a cross flow over the intercooler and an increase of 9-10°C when two hair dryers were supplying a cross flow over the intercooler.

Visual Observations

Just as important, if not more so, are the observations our team recorded from testing of our prototype. Many of the problems our team faced in our prototype are problems that our final design may face as well.

To start, our compressor was unable to reach the speed required to generate our target of 5 psi due to the lack of power provided by the hand drill. Our team learned firsthand how large a parasitic loss the compressor could be on our entire system. Our team tested several drills, and for every one of them, the rotational speed significantly decreased as the end valve was closed. This was just visual evidence of the load the compressor placed on these drills even at low pressures. At large pressures, clearly much more powerful devices will be necessary to achieve our desired pressure of 5 psi.

Another observation made in our system was that there was no temperature increase from compressing our air. We think this is due to the low flow rates we were running our system at. In an adiabatic process, our team expected a significant temperature increase. As our system is not ideal, the adiabatic equation did not hold and we saw little to no temperature increase. This may also be a problem faced in our final design. If we do not achieve the temperature increases expected in our final design, at lower ambient temperatures, there would be no need to cool but instead a need to heat the air up to our desired 85°C.

Lastly, our team observed a failure in our humidification system to control condensation/water from accumulating in the pipes. There are several things in our prototype that led to this result:

1. The airflow was too low to properly absorb the amount of water being injected into the system.
2. The spray nozzle did not properly atomize the water particles
3. The nozzle was located too close to the wall causing the water to act more as a stream than a mist

Every time our team ran the water injection system, we had to empty a significant amount of water from the piping. This could be a serious problem in the final design if not properly addressed.

Engineering Specifications Untested

Due to cost, safety, and time, our team was not able to build and test all components of our final design. However, through our engineering analysis and research, we feel with high certainty that all our specifications can be met.

One component of our final design that was not demonstrated by our prototype is the air filter. Filtration is important to ensure that damage due to harmful substances entering the fuel cell does not occur; however, we do not believe this it is necessary to demonstrate. Demonstration of our filtering system would be difficult within our budget, and we lack the equipment necessary to measure the composition of the air necessary to prove the filtration effectiveness. While our team is not building or testing a filter, we feel that our combination of a dust filter and an active carbon foam filter will meet the desired specifications. We recommend Visteon perform standard filtration tests to confirm our design choice.

Moreover, our prototype does not demonstrate the noise level of our system. Our final design requires a noise level below 65 dBA. Noise levels were not tested for several reasons: we do not have the finances for the measurement tools and our compressor (the major noise generating component of our system) is being run at lower speeds than the final design and therefore will make less noise. We believe Visteon has better experience and much more expertise than our team to properly assess sound propagation and determine the most effective method of eliminating the sound.

DISCUSSION

The major challenges the design faces in achieving our final engineering specifications and customer requirements are achieving the optimum intake humidity, temperature, pressure, air purity, air flow, and low noise. From the results of our testing, our team has gained a better understanding of the strengths and weaknesses of our final design and its ability to meet its requirements.

Control and Efficiency

One of the major challenges that our final design faces is the parasitic losses on the fuel cell stack involved in running the compressor, water injection system, and airflow across the intercooler. In our prototype, our team observed firsthand that the power supplied by many different drills to the compressor was not sufficient to obtain a pressure increase of 1.35 bar. In our final design, we need to obtain a final pressure of 2.5 bar which is significantly higher. In addition, we will have to supply a high pressure to the water injection system to achieve a fine mist and run airflow across the intercooler for cooling. All these systems will be run from the power generated by the fuel cell stack and the more power needed to run them, the less efficient our assembly becomes.

However, we feel that one of the major strengths of our final design is that each component has its own control which can regulate the outputs of the design. Since each components can control particular characteristics (compressor controls pressure, water injector controls humidity, intercooler controls temperature), our design can utilize a sophisticated control system to properly regulate our components. The advantage of the control system is that it can always optimize the settings for the compressor, water injector, and intercooler, no matter the ambient conditions.

In our prototype we demonstrated control of the pressure by controlling the speed of the compressor and the back pressure. We also demonstrated control of the temperature difference across the intercooler by the amount of cross flow supplied by the hair dryers. Our humidity readings were insignificant but we were able to demonstrate the control of the amount of water being injected into the system by setting a back pressure on our water tank. While we were only able to demonstrate control of one variable at a time in our prototype, given more time/money we would seek to demonstrate simultaneous control of pressure, temperature and humidity. For our final design we believe that by controlling the compressor, water injector, and intercooler, parasitic losses by these components can be minimized.

System Order

Another strength of our final design is the component order in their final assembly. By placing the filters first, our final design can increase the cross sectional area of the expansion box and allow for slower airflow across the filters. This increases the effectiveness of these filters by increasing the filtration time.

Our design then compresses the air to 2.5 bar which also increases the temperature of the air significantly. The outlet of the compressor will also be of smaller piping then the inlet/air box to increase the mass flow per unit area. The increase in pressure, temperature, and airflow per unit area provided by the compressor make humidification easier. One of the main problems with our prototype was that the lack of temperature, pressure, and airflow per unit area increase made it difficult to determine the amount of water being injected into the air that is being absorbed. Instead we observed too much water in our piping. This was also due to the fact the our mist nozzle did not provide the fine mist necessary for the injection system to function properly.

After compression, our water injection system and intercooler function together to achieve the proper relative humidity of 100% and temperature of 85°C. Our water injection system was placed before the intercooler for two main reasons. First, by injecting water into the system, the hot airflow can absorb more of the moisture needed for the final output. This will also decrease the amount of cooling required by the intercooler. Second, since the airflow is going to be cooled after water injection, the relative humidity through cooling will increase. Therefore, our design calls for a control system that injects less than the necessary water to achieve 100% relative humidity at the time of water injection. Instead, the relative humidity will be increased to a point where the final relative humidity of100% will be achieved through cooling the airflow in the intercooler. If controlled properly, this could minimize condensation in our ducting. However, this is a very delicate balance and very delicate control would be necessary for this to work well. While we have provided fundamental equations to do this, the system/controls would require a large amount of testing and time to perfect in the future for all operating conditions.

Unfortunately, for our prototype, we were unable to demonstrate the type of control necessary to achieve a balance between compression, humidification, and cooling. With more time, better sensors, and a stronger power supply attached to the compressor, demonstrating this type of control would be one of the main objectives our team would have pursued in validating our final design.

Condensation

Another major challenge faced by our final design will be condensation in the piping. For the same reasons we feel the delicate control between the water injection system and the cooling in the intercooler can be a strength, it can also be a weakness of our design. If not controlled properly, large amounts of condensation may occur in the ducting. Testing at all ranges of ambient conditions and flow rates would be necessary to effectively determine a proper control of our system. Also, possibly using a valve to remove water from the piping is an option to consider in controlling condensation. Water could collect in a U-Shaped bend. On either side of the U-Shaped bend, the pipes could be slanted slightly downwards to more effectively collect water. At the bottom of the U piece, you could place the valve and purge the system of the water whenever necessary (a system already being used for vehicles with pressurized air brakes).

As previously stated, we observed a lot of water in our prototype after running the water injection system. We feel this was due to low airflow and no temperature increase from the compressor, as well as the inability of our spray nozzle to supply a fine mist. However, we feel these problems will be of a smaller scale for our final design as the compressor will be running at higher speeds causing more of an adiabatic compression resulting in higher airflow and temperature at its outlet. Also, more suitable high pressure nozzles/injectors should be used in our final design which are capable of achieving the necessary fine mist. With more time and money, our team would have tried to fix this problem several ways. We would have bought more appropriate mist nozzles and got a larger power supply for the compressor to achieve the desired temperature increase and mass flow rate.

Also, for the final design, increasing the diameter of the piping where water injection occurs should be considered. One of the problems observed in our prototype was that the water spray was not given enough space from the nozzle to the wall of the pipe to really spread out. Instead it acted more as a stream instead of a fine mist. With a larger area for the mist to spray, the air could be more effective at absorbing the water in our final design.

Temperature

Another observation from our prototype was that adiabatic compression did not occur, as the adiabatic equation for temperature increase did not hold. Our team saw no temperature increase from compression.

In our final design, at low temperatures, the need for cooling is unnecessary. As previously calculated, at 0°C, the temperature at the outlet of the compressor using the adiabatic equation would be 82°C. This is already below our target of 85°C. In addition, water injection will further cool the outlet temperature of 82°C. In this case, we originally justified that air entering the fuel cell below 85°C does not damage the fuel cell but instead decreases the efficiency slightly. Since 82°C was only slightly lower than the target and still higher than the operating fuel cell temperature of 80°C, we felt this would be an acceptable loss.

However, if adiabatic compression does not occur and temperature increases are minimal under certain circumstances, then the need for heating across the intercooler may be necessary. Heating could be supplied by wrapping electrical wire around the fins of the intercooler and supplying a current through those wires. However, when considering this, our team suggests comparing the tradeoffs involved in having an additional heating system. One would have to compare the efficiency loss due to a lower temperature to the cost of adding the system and efficiency loss due to running the heating system which would act as another parasitic component on the fuel cell. The best way to determine these things is through testing the final design at low flow rates and low ambient temperatures (approaching 0°C).

A general restriction of our final design is that it only would function at temperatures above 0°C. This is a restriction many fuel cell vehicles are currently facing as below 0°C, water in the piping, water tank, and created from the fuel cell reaction will freeze. If Visteon were to pursue marketing our design in regions that approach or go below 0°C, heating of the water reservoir, possibly the piping, and the fuel cell itself might be things that need to be considered.

Filtration

Air purity is of a great concern for our team because the conditions of the outdoor air, especially in highly polluted areas, may have negative impacts on the fuel cell. Not only is performance and efficiency at risk, but longevity of the fuel cell itself. The chemical filter we chose in our final design involves a potassium hydroxide (KOH) modified activated carbon filter. This filter's performance for a PEMFC has been tested and experimental data shows high effectiveness. However, the experiment was run under controlled settings to evaluate its filtration of main contaminants such as NO_x and SO_2. We do not entirely know how well this type of filter will function for other, less harmful chemicals. In addition, sizing is still uncertain due to lack of mainstream use in PEMFC applications.

Also, standardized data for the necessary filtration rates for PEMFC applications are still unknown. While there clearly are chemical filters being used in fuel cell vehicles today, they are still of the first generation and their longevity and effectiveness are still being tested and determined. Given more time, our team would have further pursued obtaining the standards used for chemical filters in fuel cell vehicles today. As Visteon is well connected in the automotive industry, this may be something they have more luck in then our team did in contacting automotive companies and chemical filter manufacturers.

Our prototype did not really address the filtration aspect of our final design. In hindsight, we probably would have focused our entire prototype on the filtration as it is one of Visteon's key interests in our prototype. We feel that maybe in the future, an ME 450 project solely focused on developing a chemical filter for use in fuel cells may be a good idea.

Noise

Maintaining low noise generation of below 65 dBA is a challenge that our final design may face. The ideal conditions for the inlet air and packaging may create a situation in which noise is an issue. Above certain pressure drops, air flow through ducts may produce whistling sounds [34]. The use of a compressor and/or turbocharger may also produce unfavorable dBA levels. One high priority customer requirement is to have as quiet a system as possible due to the lack of an internal combustion engine in a traditional vehicle. To address this problem, our team has discussed using Helmholtz resonators and quarter wavelength resonators to attenuate unwanted frequencies. However, the most effective method of determining which frequencies will need attenuation in the system is through testing. We feel that any noise attenuation necessary for our system could be done using similar methods used for combustion air intake systems today. We know Visteon has much experience in implementing noise controls and would be better suited to tackle this problem through testing at their facilities.

Packaging

Our final design was not made for a specific vehicle, but instead was designed for a generic small to mid size vehicle. As a result, placement of our components within the vehicle was not directly determined. We have identified the order of the components to be filter/intake, compressor, water injection system, and then intercooler from which the flow will be routed to the fuel cell.

We can recommend certain locations for these components but these locations may be subject to change according to the packaging requirements of the specific fuel cell vehicle. Our design suggests having the filter box/intake located underneath the hood of the car similar to the Honda FCX Clarity in Figure 98. This is done for two main reasons. First, the intake is at the front of the car which will allow for more airflow to easily enter the system. Second, by being elevated off the ground and protected from direct exposure to the road, this will minimize the chance of water from puddles and large particles thrown up and entering the system.

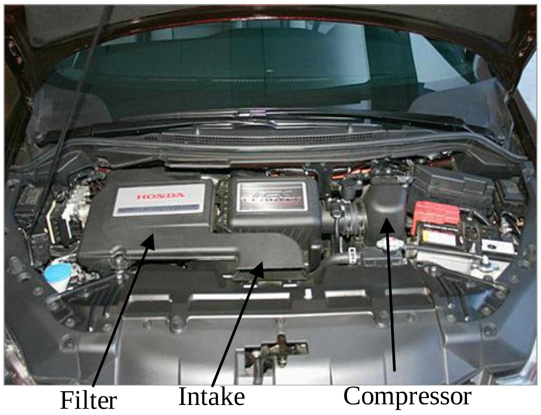


Figure 98: Honda FCX Clarity [16]

After the filter, we suggest placing the compressor as close as possible in order to minimize ducting/cost. The water injection nozzles should then be located directly after the compressor to ease humidification. The water tank may be placed wherever it may fit within the packaging of the vehicle. Since the water vapor created from the fuel cell reaction must be recycled to our water tank, our team is not sure if the tank should be located closer to the outlet of the fuel cell or the injection nozzle. The intercooler should then be placed at the front of the car to maximize cross flow (seen in Figure 99). Afterwards, ducting will be required to take the airflow to where the fuel cell is located in the center of the vehicle.

Also, it is a good idea to minimize the amount of cornering and sharp bends in the ductwork of our system. The less cornering and bends there are in the system, the less there is a chance of pressure ripples and drops which may be damaging to the fuel cell membrane or decrease efficiency. Also, avoiding quick changes in piping diameter after compression is suggested for the same reasons. If piping diameter needs to be changed for any reason (possibly for water injection) the change should be as gradual as possible.

Along the way, we have made certain assumptions about fuel cell vehicles. From our research we have determined that the fuel cell stack is most commonly placed in the middle of the vehicle below the front seats. Also we have assumed that the hydrogen tanks are located in the rear of the vehicle. For the batteries that run the car, our team has seen them located either in line with the rear tires or in line with the front tires. This is seen visually in Figure 99 below where the batteries are located in line with rear tires.

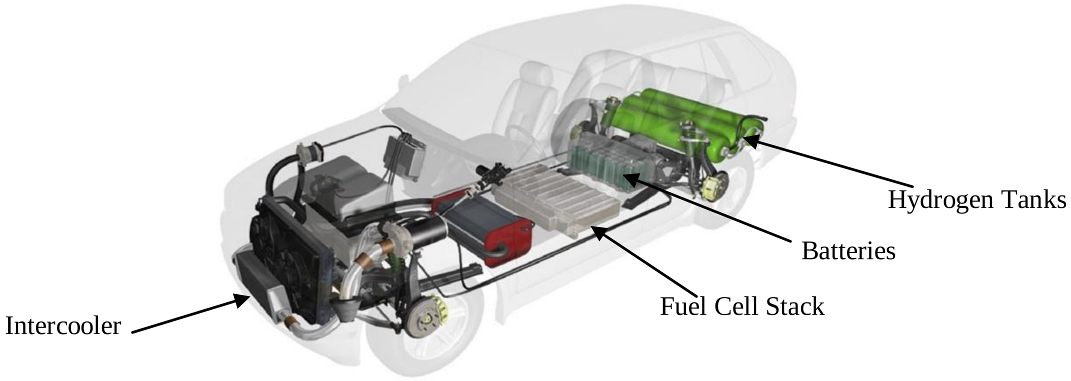


Figure 99: Composite Fuel Cell Arrangement [15]

One of our suggestions to Visteon is to find a particular vehicle to model our fuel cell air intake system for. This will help in determining actual packaging requirements and more meaningful testing.

Fuel Cell Power Requirements
For the purpose of our project, our team designed an air intake system for a fuel stack that is capable of delivering 100 kW. We assumed the worst case scenario in that the car would constantly require that 100 kW to run at all times and need a mass airflow of 0.11 kg/s.

In actuality, newer fuel cell vehicles are being designed to charge a battery which then powers the car. For small to mid size fuel cell vehicles, this would not require constant maximum power being delivered from the fuel cell stack to the battery. If the fuel cell is constantly recharging a battery, then the power output of the fuel cell tends to be less than 100 kW. As a result less airflow needs to be delivered and less water needs to be injected.

In older fuel cell models, there is a small battery used to start the engine but power is mostly delivered directly from the energy being created by the fuel cell. For these models, when driving at lower speeds, less power would be necessary, hence requiring less airflow.

In the future, it would be a good idea for Visteon to choose a specific design for either a car that runs almost solely on the energy provided directly by the fuel cell stack or a car that runs on a battery which will constantly be recharged by the fuel cell stack.

RECOMMENDATIONS

As a result of all the research, design generation, and prototyping that our team has now completed, we have developed particular recommendations for future work in designing a functional fuel cell air intake system.

An important step in the continuation of our project is testing our design with an actual fuel cell. This requires designing and building of a full scale prototype which can be tested in conjunction with the fuel cell size for which it has been designed. We recommend picking a specific vehicle in which to design the air intake system.

Some cars run the fuel cell all the time in order to constantly recharge a battery and others run the fuel cell based on when the car needs. For these different setups, the air intake system will have to supply different mass flow rates of air. We used a 100 kW fuel cell stack power requirement that constantly is running but this number may be lower. Determining the actual power requirement for a specific vehicle will influence parameters such as: compressor speed, amount of water injected into the system, and filter longevity.

Also, by designing for a specific vehicle, Visteon will be able to properly place components in the vehicle and dimension piping between the components. By finalizing a packaging scheme, Visteon can identify and fix any potential noise problems in the system. In addition, testing can be done to minimize pressure ripples created by curvature in the ductwork and the back pressure supplied from the fuel cell can be measured.

Make sure to pick an appropriately sized compressor and characterize it through experimentation. One of the major challenges of designing a fuel cell air intake system is reducing the parasitic losses it incurs on the fuel cell. In minimizing parasitic losses, particular attention should be taken in the choice/design of the screw compressor. It is important to maximize the compressor’s efficiency as this component will require the most power to operate. To ensure that the compressor can meet all requirements, extensive testing should be done at a variety of ambient conditions and loads.

Next, determine the temperature rise over the compressor. This is necessary in order to design an appropriately sized heating and cooling system. Our design incorporates cooling through the intercooler based on the use of the adiabatic compression equation which would result in temperature increases well above our target of 85°C. However, as demonstrated in our prototype, there was no temperature increase across the compressor when we achieved a pressure of 1.24 Bar. We believe that experimentation is necessary to get a more accurate picture.

We recommend considering the inclusion of a heating system in addition to the cooling system. Heating could be supplied by wrapping electrical wire around the fins of the intercooler and supplying a current through those wires. When the heating system is active, the variable fins of the intercooler should be completely closed to stop cross-flow of ambient air. However, when considering a heater, our team suggests comparing the tradeoffs involved in having an additional heating system. One would have to compare the efficiency loss due to a lower temperature to the cost of adding the system and efficiency loss due to running the heating system which would act as another parasitic component on the fuel cell. The best way to determine these things is through testing of the final design at low flow rates and low temperatures (approaching 0°C).

From our prototype, we found that condensation may occur in the air intake system and soak the membrane of the fuel cell. In the future, our team recommends trying the following methods that may reduce or avoid condensation. The first method involves incorporating a U-shaped bend in the ducting just after the injector. It is important that the piping on either side be slanted towards this bend. By placing a valve at the bottom of the bend, the excess moisture can be purged out of the system through using pressure in the ducts. In addition to eliminating the condensed water from the system, several additional steps can be taken to minimize condensation in the first place. First, a fine mist nozzle to ensure atomization of the water at high pressures can be used to make evaporation into the air easier. Second, increasing the piping diameter at the injection location is recommended to provide more space for the mist to spread instead of immediately impacting the ducting walls.

We recommend testing of system controls under a wide range of ambient conditions and flow rates. One of the important aspects for our final design to work as an assembly is the delicate control system needed to regulate our compressor speed, amount of water injected and cooling simultaneously. These variables can be related through theoretical equations. However, as demonstrated in our prototype, these equations may not hold and their validity needs to be confirmed experimentally.

Lastly, our primary focus of this project remained on the intake side of the fuel cell. However, using the water vapor and energy from the exhaust is crucial in increasing the efficiency of the system. From our estimates, a 100kW fuel cell will only be able to run for approximately 20 minutes on a 10 gallon tank of water. This means the water vapor exiting the exhaust must be recycled into the humidification system. In addition to the water, the heat and pressure energy from the exhaust should also be integrated back into the system. One possible method is to use a turbocharger to help spin the compressor.

SUMMARY AND CONCLUSIONS

With the anticipation of emerging technologies for automotive vehicles, Visteon Corporation has sponsored our project to design and develop an air intake system for a proton exchange membrane fuel cell (PEMFC) vehicle. Our goal was to create such a system which optimizes the fuel cell's performance and efficiency.

The key engineering specifications found for the air intake system are a flow-rate of 45 liters/sec (for a fuel cell stack that produces 100 kW power), a relative humidity of 100% at the inlet, a temperature of 85°C, a pressure of 2.5 bar, and air purity. The important customer requirements for the system's performance are noise (below 65 dBA), cost, packaging, serviceability, and durability.

To meet these specifications and requirements, our team split the project into the following functions: air intake, filtration, pressurization, humidification, and cooling. For each function our team generated as many concepts as possible. Each concept was then compared through a Pugh chart for its particular sub-function and evaluated on its ability to perform the necessary criterion.

For our final design, our team put our individually chosen components from the concept selection together into one assembly. This design includes a combination of an activated carbon filter and Visteon dust filter to remove harmful substances, a screw compressor to increase pressure and mass flow rate, a water injection system to increase the humidity, and an air-to-air intercooler to cool the air. The order of these components was chosen to maximize the efficiency of our system after calculating the tradeoffs of different possible layouts.

Our prototype is composed of the same components as our final design minus the chemical filter. Our plan was to demonstrate that by using our chosen components, in their particular order, our final design can regulate the pressure, temperature, and humidity of ambient air and deliver it to a fuel cell at pre-specified targets. Our initial targets for our prototype were a relative humidity of 100%, temperature of 40^{o}C, and pressure of 1.35 bar at the outlet. Our results were a pressure of 1.24 bar, a temperature increase to 33°C, and an inability to record significant humidity measurements. Failure of our system to reach our initial targets was mostly due to the lack of power supplied to the compressor (small airflow/rotational speed) and an inadequate humidity sensor. However, our team did demonstrate that we could control pressure by regulating the compressor speed and back pressure on the system; control the heat exchange across the intercooler by regulating the cross sectional area of the cross flow; and control the amount of water entering the system by regulating the back pressure of our water tank.

After creating our final design and manufacturing our prototype, our team has gained a better understanding of the many challenges our design will face. Our design needs a delicate control system to properly regulate the compressor speed, amount of water injected and cooling across the intercooler. The control system will require sensors that give quick feedback, less than a minute. As our system will operate under many different ambient conditions and loads, it is important to perform testing for all conditions.

Another important issue with our final design is the amount of power the screw compressor will need to raise the pressure to 2.5 bar and deliver a flow rate of 0.11 kg/s. The compressor will pose the largest parasitic loss on the fuel cell system and for this reason its efficiency needs to be maximized.

Another important challenge that needs to be addressed in our final design is condensation in the ductwork. While we feel this may be minimized by properly controlling our system's components, it is still important to consider alternative solutions such as a valve to purge the system of water.

In conclusion, our team has delivered the requested information from Visteon about the specifications necessary for a fuel cell air intake system and has also provided a unique assembly of components to meet these specifications. In the future, more testing would have to be done to determine the necessary control of our assembly. Also, our assembly will have to be mated to a particular fuel cell vehicle and stack to truly perform accurate testing.

ACKNOWLEDGEMENTS

Throughout the semester, our team has received invaluable guidance from many individuals. We would like to spend this section of the report to acknowledge their help and time by saying thank you.

To start, we would like to thank Professor Gregory Hulbert for all his help and input on our project. The weekly meetings we had with him always helped guide our project in the right direction. This project could never have been completed without his help.

Next, we would like to thank our sponsors Visteon Corporation for giving us the opportunity to undergo this project in the first place. Specifically, we would like to thank Josh Sparks and Tony Arruda for meeting with us so many times and answering any questions our team had regarding our project.

Another special thanks goes to our GSI Dan Johnson who spent countless hours answering our questions and making sure that we were always SAFE!!! Even at our worst moments, Dan always provided a comforting opinion.

We would also like to thank our friends at the machine shop Bob Coury and Marv Cressey. These two individuals saved our team countless hours and headaches by providing simple solutions to many of our biggest machining problems. They showed a lot of patience and always answered our questions, no matter how strange they may have been.

In addition, we would like to thank all the professors that have helped us mold and shape our project into what it is today.

Professor Anna Stefanopolou basically got our project moving. When we were struggling to find information on fuel cells, she made herself available to answer all our questions and provide valuable sources where we could learn a lot more. We would also like to thank the graduate students Jim Marcicki and Jason Siegel at Professor Stefanopolou's fuel cell lab for a tour and providing valuable information from their first handed experience with fuel cells.

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Special thanks goes to Tom Bress who provided us with our thermocouples and data acquisition system.

Lastly, we would like to thank all the people who helped us out along the way: the people at all the salvage yards we went to for giving us great deals on all our components purchased, the

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APPENDIX A: BILL OF MATERIALS

Below is a list of all material used in creation of our prototype. Tax and shipping fees were not included in cost.

	Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
1	Supercharger	1	IHI	N/A	$40	Woodards American Auto Parts	Compress air to desired pressure
2	Hand drill	1	RYOBI	033287138517	$39.97	Home Depot	Supply torque to drive Compressor
3	1” M Adapter	1	Home Depot	012871626050	$0.53	Home Depot	Screw into ball valve
4	1” PVC Ball Valve	1	Home Depot	232807	$4.92	Home Depot	Regulate back pressure
5	¼” Brass Piping Male Connector	1	Home Depot	048643072213	$1.75	Home Depot	Attach brass piping from injector to ball valve
6	5/8 inch stud	4	Home Depot	761542002449	$1.77	Home Depot	Safety walls
7	14 mm nut	1			$1.60	Carpenter Bros	Part of compressor-hand drill assembly
8	Flex coupling 2” to 2”	4	Home Depot	018578000056	$4.33	Home Depot	Attach piping
9	PVC Bushing	1	Home Depot	012871626630	$1.02	Home Depot	Adapt 2” pipe to ball valve
10	50 mm M8 Bolt	1			$2.15	Carpenter Bros	
11	Fitting	1	Home Depot	012871559488	$1.18	Home Depot	Adapt threaded 1” to 1” pipe
12	Boost/Vacuum Gauge	1		CP8203	$24.98	Advance Auto Parts	Read pressure at outlet of system
13	2’X2’X3/8” Board	1	Home Depot	099167465302	$4.57	Home Depot	Part of test rig (fixture of hand drill)
14	Rubber Gasket	2	Home Depot	037155008766	$3.99	Home Depot	Create seals between piping and components
1	Standard 2” Dry	1		2111205	$5.99	Tractor	Measure pressure of water tank

5	Gauge					Supply Co.	
16	Saw Kit	1		70882017280	$9.99	Meijer	Drill large holes in PVC and wood
17	6’ of 2” diameter PVC pipe	1	Home Depot		$4.23	Home Depot	Used as our team’s piping
18	2’X6’X 8’ Board	1	Home Depot	090214000101	$3.18	Home Depot	Test rig
19	PVC Cement	1	Home Depot	038753310138	$3.76	Home Depot	Gluing PVC pipes
20	Fitting	1	Home Depot	012871558771	$2.52	Home Depot	Used in water injection system
21	SS Clamp	1	Home Depot	078575126029	$0.85	Home Depot	Clamp hose piping
22	Barb	1	Home Depot	048643071025	$2.23	Home Depot	Used in water injection system
23	¼” Brass Coupling	1	Home Depot	048643072152	$2.33	Home Depot	Used in water injection system
24	¼”X1/8” Connector	1	Home Depot	048643072190	$1.41	Home Depot	Used in attaching spray nozzle to tubing
25	Fitting	1	Home Depot	012871559235	$2.19	Home Depot	Used in attaching spray nozzle to tubing
26	Fitting	1	Home Depot	012871559396	$0.83	Home Depot	Used in water injection system
27	Fitting	1	Home Depot	012871558238	$2.91	Home Depot	Used in water injection system
28	2.5” PVC Connectors	4	Home Depot	039003093931	$4.97	Home Depot	PVC corners and connectors to route ducting from component to component
29	23/32 Plywood	1	Home Depot	776391550003	$10.95	Home Depot	Test rig setup
30	Monarch Nozzle M-5 Brass	2	Monarch	M-5	$2.15	Monarch.com	Spray nozzles for water injection system

31	6” Digital Caliper	1		864649	$26.99	AutoZone	Measurement purposes
32	Brass Pop-Safety Valve	1	McMaster-Carr	4772K802	$17.64	mcmaster.com	Ensure safety in case of too much pressure
33	Intercooler	1	Ford	N/A	$100.00	ABCAT Auto Salvage	Provide cooling to system
34	Humidity Sensor	1	Honeywell	HIH-4033	$18.99	Digi-key.com	Record humidity readings
35	5/8” Rubber Seal	1	ACE	51244	$2.79	ACE	Seal compressor hole
36	Hose Clamps	4	ACE		$0.89	ACE	Seal
37	Compressor Bolt	1	ACE		$4.60	ACE	Attach compressor to hand drill
38	Hose Clamp 3/8” to 7/8”	1	ACE	41143	$1.19	ACE	Seal
39	12”X12”X3/4” PVC Block	1		N/A	Free	Machine Shop	PVC pipe to intercooler inlet, compressor inlet, and compressor outlet adapter pieces
40	6”X4”X1” PVC Block	1		N/A	Free	Machine Shop	PVC pipe to intercooler outlet adapter piece
41	6” of 1” diameter PVC Pipe	1		N/A	Free	Machine Shop	Pipe connecting end ball valve to adapter piece
42	DAQ	1	National Instruments	NI USB 6009	Free	Tom Bress	Send input voltage to humidity sensor and record outlet voltage
43	Thermocouple Reader	1	Omega	H12	Free	Tom Bress	Read temperature difference across the intercooler
44	Hair Dryer	1	Conair		Free	Tim Diepenhorst	Used to supply cross-flow of air to the intercooler
45	Screws	≈140			Free	Machine Shop/Tim Diepenhorst	Build test rig(frame, walls, spacer piece under drill, drill clamps)
4	M8 Bolts	10	ACE		$1-1.49	ACE	Mount compressor to test rig, attach

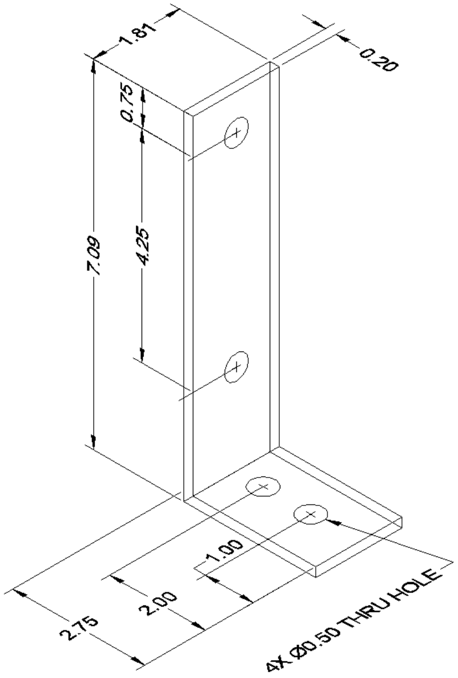
6							adapter pieces to compressor inlet/outlet and intercooler outlet.
47	¼” Bolts	10	ACE		$0-0.59	ACE/Machine Shop	Mount drill stand and intercooler
48	L Brackets	2			Free	Machine Shop	Mount angle iron pieces attached to compressor to test rig
49	Angle Iron Piece	2			Free	Machine shop	Attach intercooler to L brackets
50	¼” nuts	11	ACE		$0.27	Ace/Machine Shop	Used on ¼” bolts
51	Washers	≈40	ACE		$0-0.33	Ace/Machine Shop	Used on bolts
52	2 Gallon Water Tank	1	Home Depot	841688001701	$19.92	Home Depot	Used as water tank for water injection system
53	Thermocouples	2			Free	Tom Bress	Used to take temperature readings across the intercooler
54	14.5 Volt Voltage Supply				Free	Visteon	Supply input voltage to mass flow sensor
55	Air Box/Filter + Mass Flow Sensor	1			Free	ABCAT Auto Salvage	Represent the intake/filter of our final design and record mass flow at the inlet
56	PVC Bushing	1	Home Depot	012871627415	$1.26	Home Depot	Adapter piece to connect safety pop valve to T- shaped PVC pipe
57	8 oz PVC Primer	1	Home Depot	038753307824	$5.93	Home Depot	Gluing PVC parts
58	Fitting	1	Home Depot	012871559068	$0.86	Home Depot	Adapter piece to connect safety pop valve to T- shaped PVC pipe
59	Fitting	1	Home Depot	012871557538	$1.50	Home Depot	T-shaped PVC pipe for safety pop valve
60	Clip	2	Home Depot	739236204141	$0.39	Home Depot	Hose clamp for sealing water tank line
61	2” clip	1	Home Depot	739236204165	$0.51	Home Depot	Hose clamp for sealing water tank line

62	Pipe Insulation	1	Home Depot	803014117531	$1.38	Home Depot	Sound/vibration dampening for drill
63	24”X28”X.1” Acrylic	1	ACE	11869	$13.99	ACE	Used to build see through safety wall around drill to compressor attachment

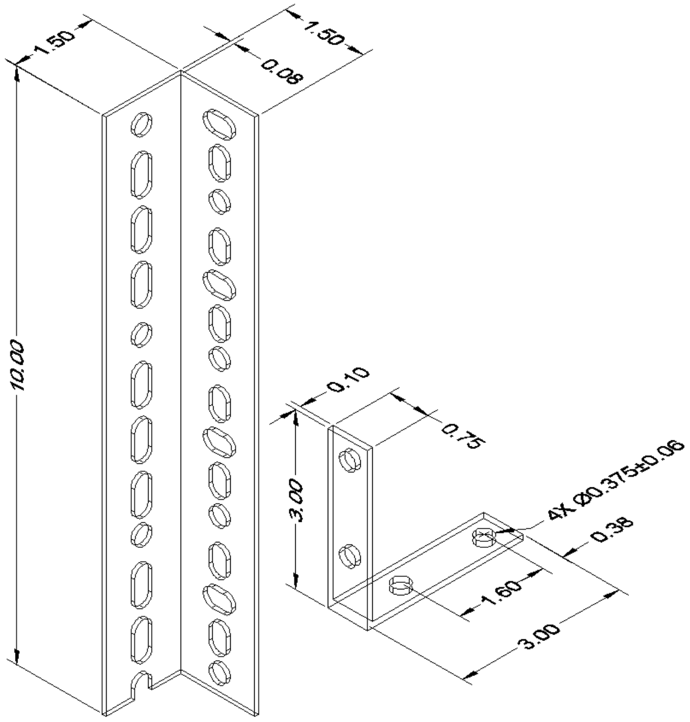
APPENDIX B: DESCRIPTION OF ENGINEERING CHANGES SINCE DESIGN REVIEW #3

Intercooler Mounting Brackets

OLD



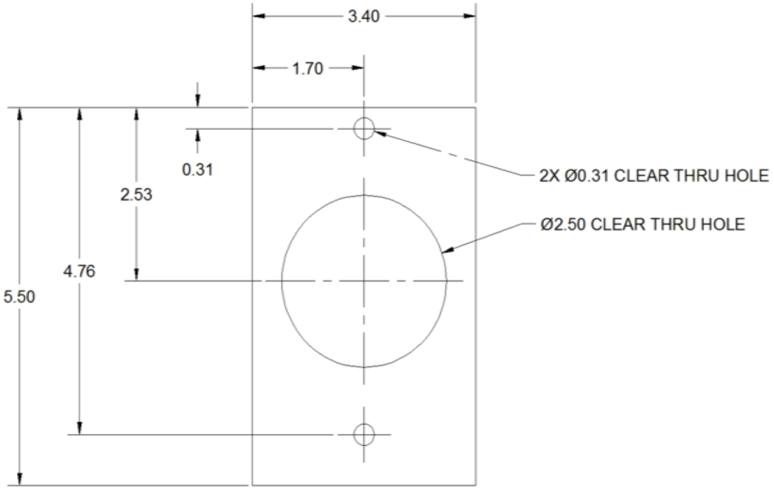
NEW



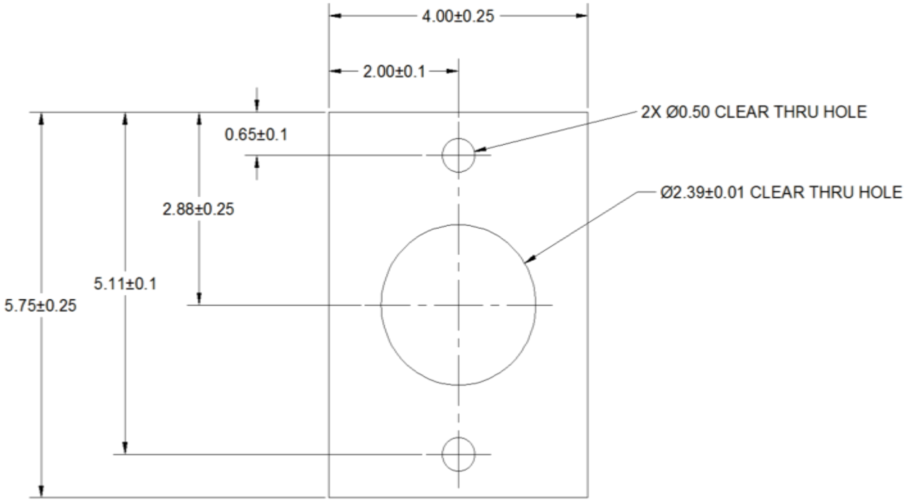
- Material changed from steel to aluminum, Dimension (in inches) change
- Tolerance Added to Drill Holes
- Changed from one 90° L-bracket to straight 10’’ rail bolted to 3’’ X 3’’ inch L-bracket

PVC to Intercooler Adapter

OLD



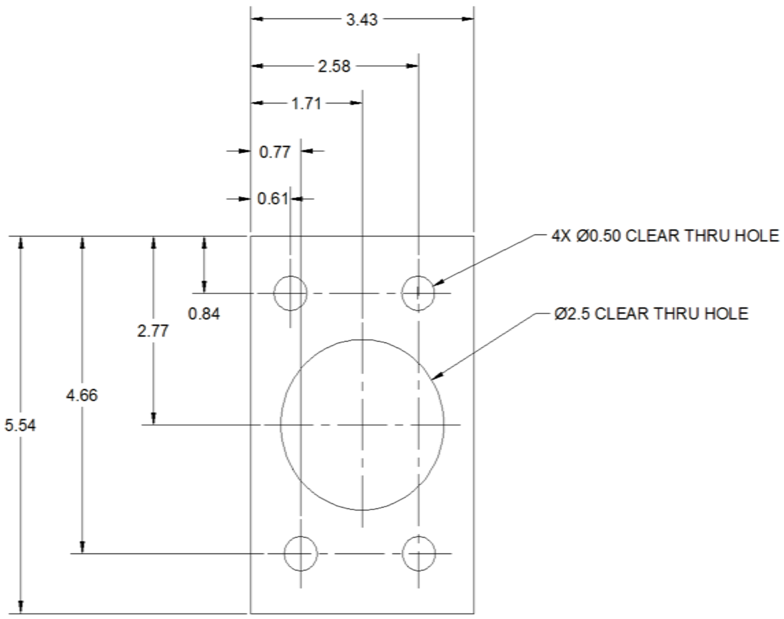
NEW



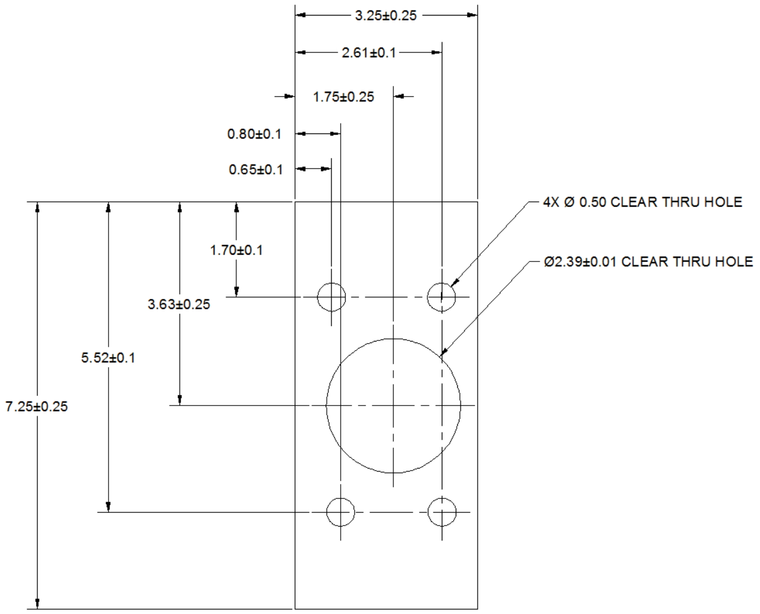
- Material changed from wood to PVC
- Block dimensions changed from BLANK X BLANK to 4’’ X 5.75 ‘’
- Center hole changed from ø2.5’’ to ø2.39’’
- Created Tolerances

Airbox to Compressor Adapter

OLD



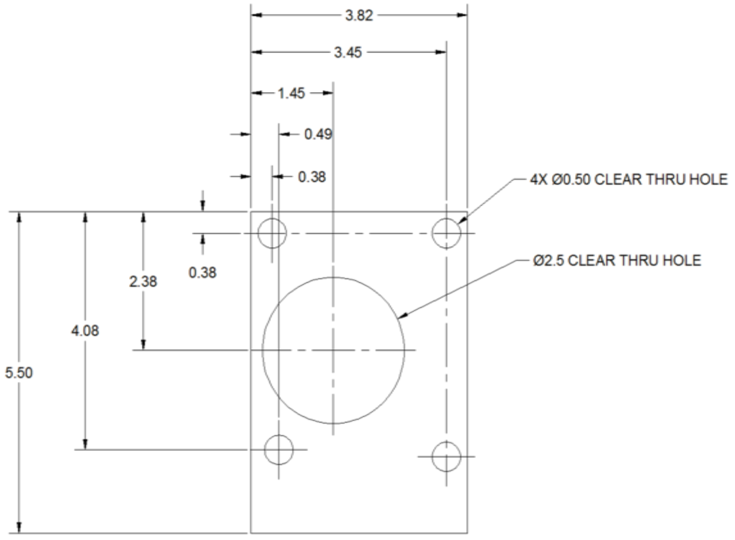
NEW



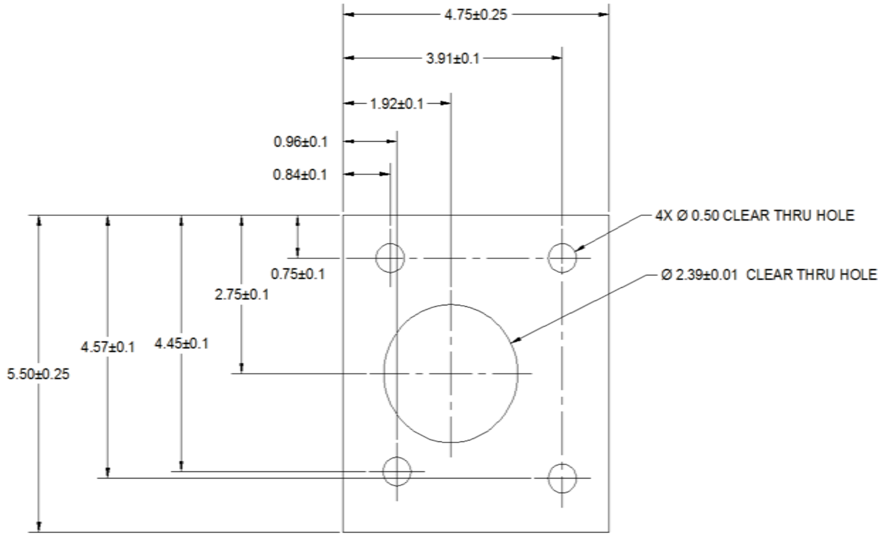
- Material changed from wood to PVC
- Block dimensions changed from 3.43 X 5.54 to 3.25’’ X 7.25 ‘’
- Center hole changed from ø2.5’’ to ø2.39’’
- Created Tolerances

Compressor to PVC Adapter

OLD



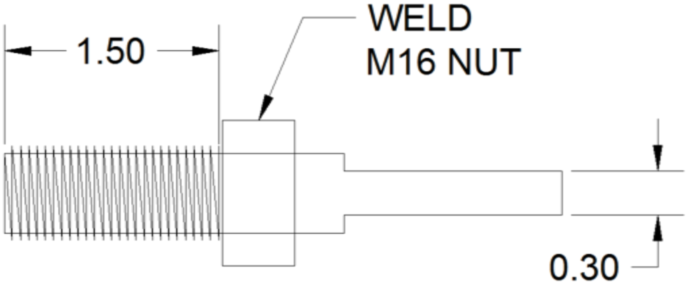
NEW



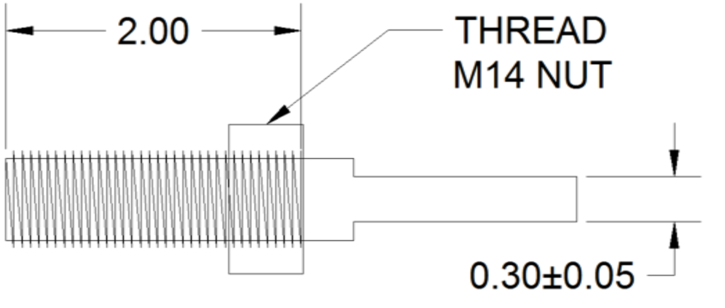
- Material changed from wood to PVC
- Block dimensions changed from 3.82 X 5.50 to 4.75’’ X 5.5 ‘’
- Center hole changed from ø2.5’’ to ø2.39’’
- Created tolerances

Drill to Compressor Adapter

OLD



NEW



- Threads extended from 1.5’’ to 2.0’’
- Bolt was changed from an M16 bolt with 1.50 pitch to a M14 bolt with 1.50 pitch
- Attachment of nut changed from welding to threading
- Added tolerance for lathed end

APPENDIX C: DESIGN ANALYSIS ASSIGNMENT (MATERIAL SELECTION)

C.1 Functional Performance

Ducting

1. Function, Objective, and Constraints
    a. Function: Transport air from component to component
    b. Objective: Minimize Cost
    c. Constraints:
        i. Melting Temperature above 150ºC
        ii. Low Heat Conductivity(Eliminates metals)
        iii. High Yield Strength
2. Cost(C) = Material Price Per Volume(PPV) × Volume of Material(V)

    To minimize volume, minimize thickness(t)
    $V \approx L \times 2\pi R \times t$

    Minimizing t requires maximzing material strength(σ)
    $\sigma > P \times R / t$
    $t > P \times R / \sigma$

    <u>Given(Constraints)</u>
    P = Pressure (2.5Bar)
    R = Radius of Ducting (2.25inches)
    L= Length (Determined by System Geometry)

    <u>Factors determined by Material Choice</u>
    σ & PPV

    Material Indices (M) = σ/PPV
3. <u>Top Five Choices from CES</u>
    a. PBT(General Purpose)- Polybutylene Terephthalate
    b. PET(unfilled, semi-crystalline) – Polyethylene Terephthalate
    c. PP(65-70% barium sulfate)- Polypropylene
    d. PP(Homopolymer, high flow)- Polypropylene
    e. PP(Homopolymer, low flow)- Polypropylene
4. We have chosen PP(65-70% Barium Sulfate).
    a. Melting Temperature- 155-164C> 150C
    b. Yield Strength – 1.49e9 Pa > 1.35e6 Pa
    c. Low Heat Conductivity- .297W/m×K

    We found this to be the cheapest option that satisfies all the given criteria. Polypropylenes are currently used in automotive parts including intake systems for combustion engines and this type was the strongest of the polypropylenes.

Water Tank Line

1. Function, Objective, and Constraints
    a. Function: Transport water from tank to spray injection

    b. Objective: Minimize Cost
    c. Constraints:
        i. Resistant to Corrosion(Rust)
        ii. Withstand high pressures(≈100psi)
2. Cost(C) = Material Price Per Volume(PPV) × Volume of Material(V)

   To minimize volume, minimize thickness(t)
   $V \approx L \times 2\pi R \times t$

   Minimizing t requires maximizing material strength(σ)
   $\sigma > P \times R/t$
   $t > P \times R/\sigma$

   <u>Given(Constraints)</u>
   P = Pressure (100psi)
   R = Radius of Line (.375inches)
   L= Length (Determined by System Geometry)

   <u>Factors determined by Material Choice</u>
   σ & PPV

   Material Indices (M) = σ/PPV
3. <u>Top Five Choices from CES</u>
    a. Polyvinylidene chloride (Copolymer, Barrier Film Resin, Plasticized)
    b. Polyvinylidene chloride (Copolymer, Barrier Film Resin, UnPlasticized)
    c. Polyvinylidene chloride (Copolymer, Injection)
    d. Fluoro Elastomer(FKM, 20-35% carbon black)
    e. Ethylene Butyl Acrylate
4. Our top choice for hoses in the system is c the Polyvinylidene Chloride (Copolymer, Injection). The reason we chose this over the other four is because it is inexpensive relative to the other choices and meets all of our criteria mentioned above. The choices a and b are similar materials, but they are manufactured in more complicated fashions. Choice d is too expensive for mass production and choice e is used for coating the hoses not make the hoses.

C.2 Material Selection Assignment (Environmental Performance)

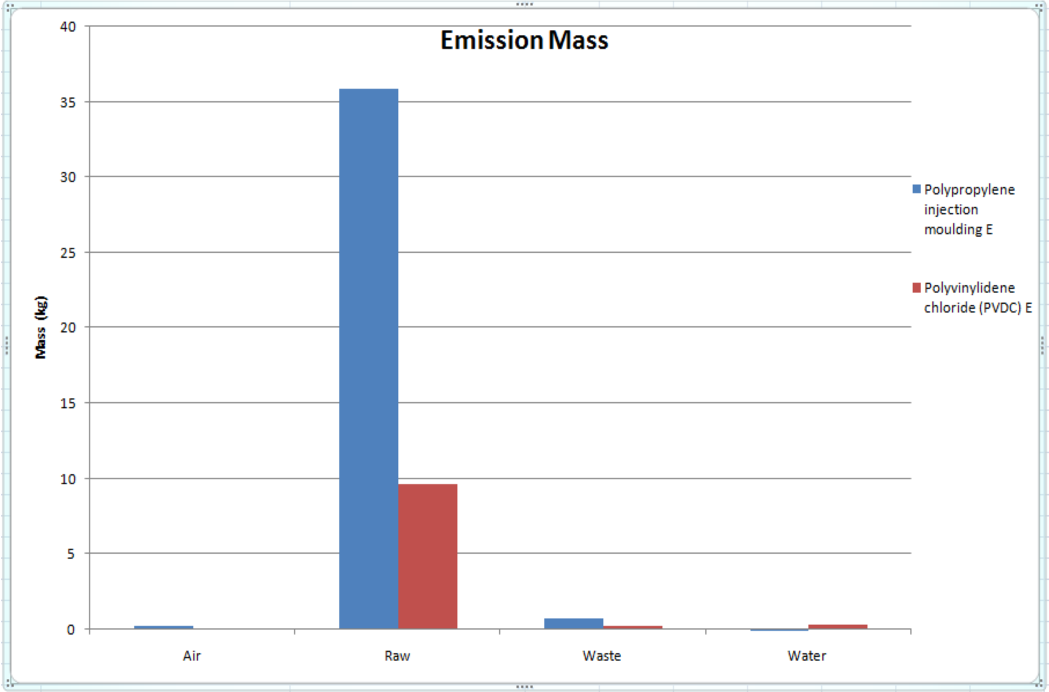
Ducting/Hoses

1. PP(65-70% barium sulfate)- Polypropylene
2. Since we do not have a specific vehicle that we are designing for we can only approximate the length of the material we will need for the ducting. With our previous assumption for packaging, that the fuel cell will be located halfway from the front to the end of the vehicle, and that a midsize sedan is approximately 4.8m, we approximate that the duct length will be 2.4m.
    a. $\sigma = PR/t \rightarrow t = PR/\sigma$

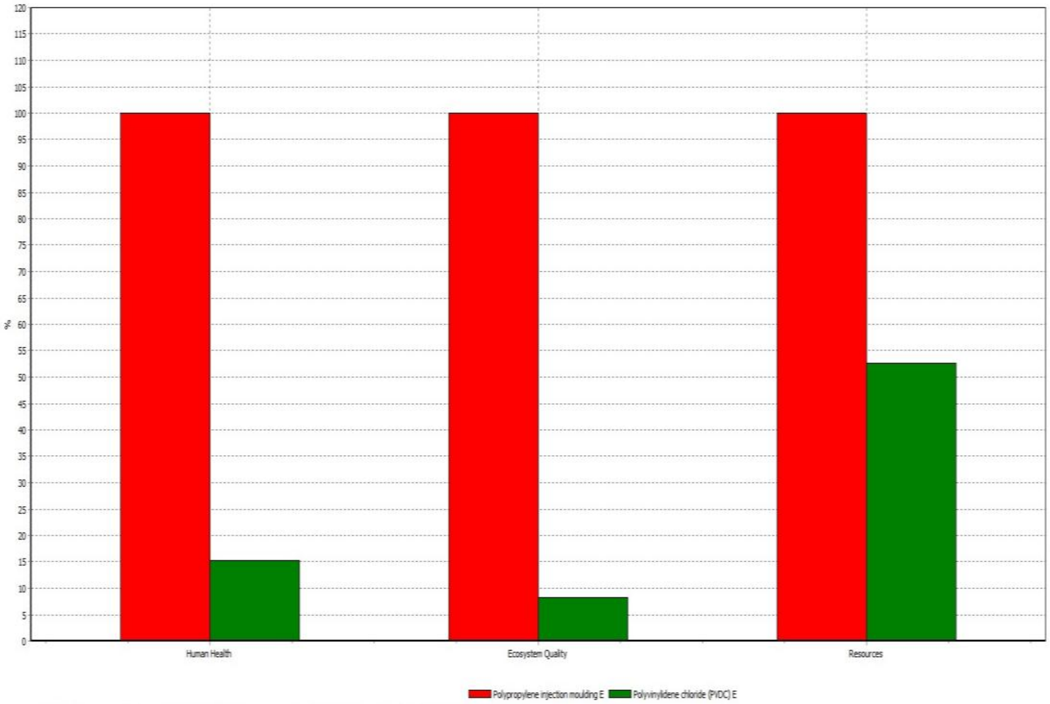
        i. P = Pressure
        ii. R = Radius of Duct
        iii. t = Thickness of Duct
        iv. Safety Factor = 3
    b. P = 2.5bar – 1Bar = 1.5Bar → 150kPa
    c. R = 1in → .0254m
    d. σ = 1.78E4kPa
    e. t = (3×150kPa×.0254m)/1.78E4kPa → t = 0.000642 m
    f. $A = \pi\times(R_o^2 - R_i^2) = \pi(.026m^2-.0254^2) = 0.000104m^2$
        i. R_o = Outer Radius
        ii. R_i = Inner Radius
    g. $V = A\times L = 0.000104m^2\times2.4m = 0.000249m^3$
        i. L = 2.4m
    h. $\rho = m/V \rightarrow m = \rho\times V \rightarrow m = 1890kg/m^3\times0.000249m^3 = .471kg$
        i. $\rho = 1890kg/m^3$

3. Polyvinylidene chloride (Copolymer, Injection)
4. Since we do not have a specific vehicle that we are designing for we can only approximate the length of the material we will need for the hoses. With our previous assumption for packaging, that the components are going to be relatively close to each other, we want to be on the safe side and overestimate, so we are approximating the hose length to be 2ft.
    a. $\sigma = PR/t \rightarrow t = PR/\sigma$
        i. P = Pressure
        ii. R = Radius of Duct
        iii. t = Thickness of Duct
        iv. Safety Factor = 3
    b. P = 100psi → 689.47kPa
    c. R = 0.375in → 0.009525m
    d. σ = 1.93E4kPa
    e. t = (3×689.47kPa×0.009525m)/1.93E4kPa→ t = 0.001021m
    f. $A = \pi\times(R_o^2 - R_i^2) = \pi(.01054m^2-.009525m^2) = 0.000064m^2$
        i. R_o = Outer Radius
        ii. R_i = Inner Radius
    g. $V = A\times L = 0.000064m^2\times0.3048m = 0.00002m^3$
        i. L = 1ft → 0.3048
    h. $\rho = m/V \rightarrow m = \rho\times V \rightarrow m = 1650kg/m^3\times0.00002m^3 = 0.0324kg$
        i. $\rho = 1650kg/m^3$
5.

a. Excel graph of total emissions

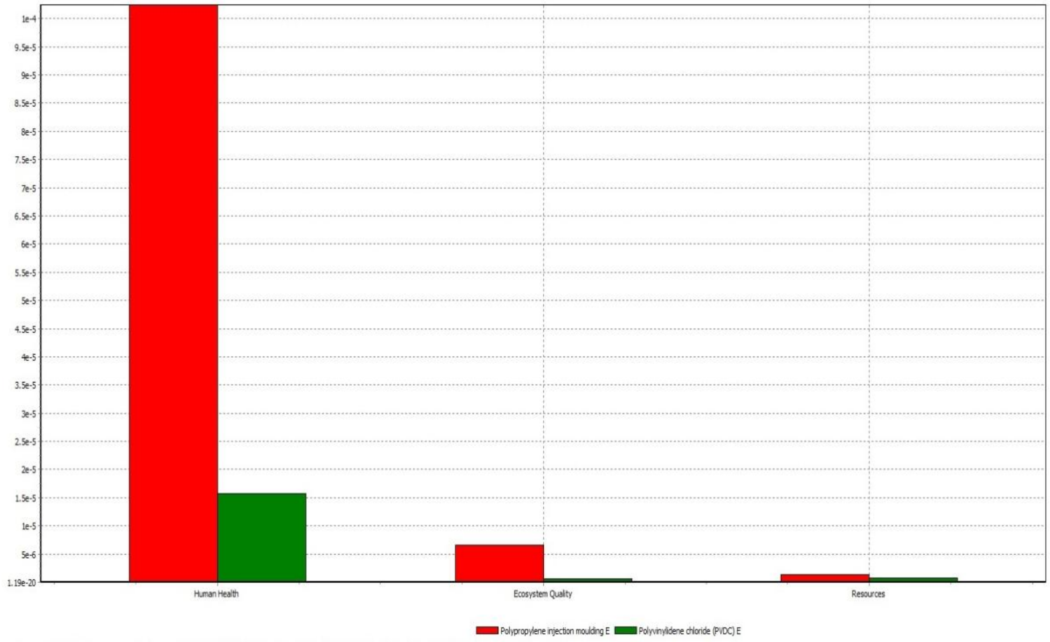


b. Relative Impacts in Disaggregated Damage Categories



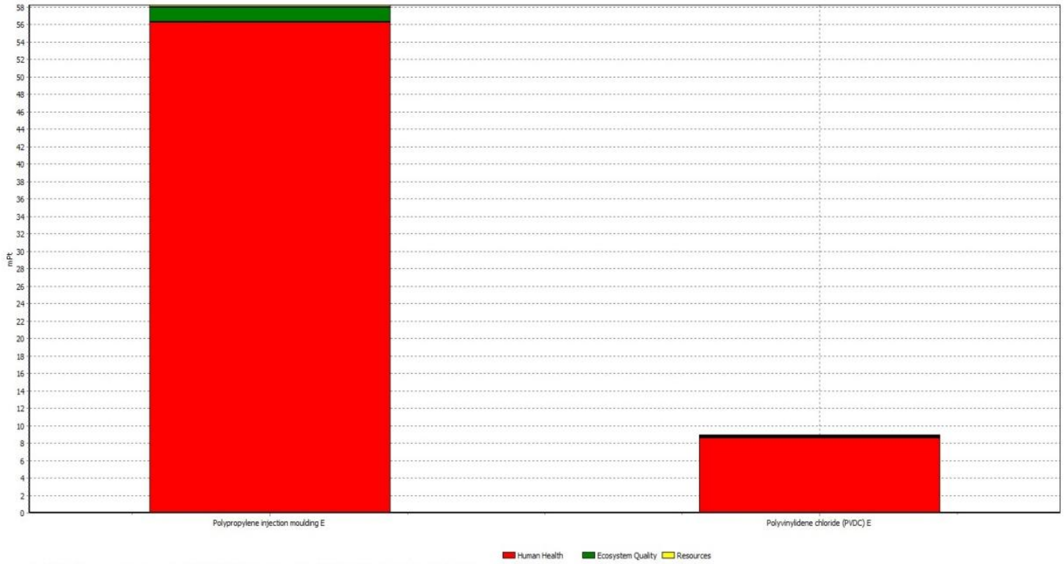
Comparing 0.471 kg 'Polypropylene injection moulding E' with 0.0324 kg 'Polyvinylidene chloride (PVDC) E'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / damage assessment

c. Normalized Score in Human Health, Eco- Toxicity, and Resource Categories



Comparing 0.471 kg 'Polypropylene injection moulding E' with 0.0324 kg 'Polyvinylidene chloride (PVDC) E'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

d. Single Score Comparison in "Points"



Comparing 0.471 kg 'Polypropylene injection moulding E' with 0.0324 kg 'Polyvinylidene chloride (PVDC) E'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

6. Environmental Impact
   a. Air: The Polypropylene Injection Molding for the ducts will cause more environmental impact.
   b. Raw: The Polypropylene Injection Molding for the ducts will cause more environmental impact.
   c. Waste: The Polypropylene Injection Molding for the ducts will cause more environmental impact.
   d. Water: The Polyvinylidene Chloride(PVDC) for the hoses will cause more environmental impact.

7. Damage Assessment
    a. The damage assessment for the Polypropylene Injection Moulding will impact the Human Health, Ecosystem Quality, and Resourses equally.
    b. The damage assessment for the Polyvinylidene Chloride(PVDC) will impact the Resourses most.
8. Life time Impact
    a. The Polypropylene Injection Molding has a higher EcoIndicator 99 point value. Over the Life Cycle of the vehicle the Polypropylene will have more of an impact on the various environmental aspects such as human health, resources, ecosystem quality…etc than the PVDC.

C.3 Manufacturing Process Selection Assignment

Ducts

1. One of the more popular mid size sedans in the US is the Toyota Camry. They sold 386,000 units in 2008. This is a reasonable estimation if fuel cell cars are mass produced in the near future.
2. To make the ducting for our system from the PP(65-70% barium sulfate)- Polypropylene, we will have to use the polymer extrusion process. This process lets us make a constant diameter tube at different lengths from a polymer type composition. There is very little waste; the process in CES says that it uses up to 99% of the material. Since we need to produce a large volume, production time is important. This process is the fastest way to make these parts compared to other processes.

Hoses

1. Again using the Toyota Camry model we predict that if this project becomes popular and is mass produced, we would make around 386,000 units of hoses for the air intake system.
2. Making the hoses would require the same process as the ducting, polymer extrusion, because this also is a high volume production of a polymer into a constant diameter circular cross section.

APPENDIX D: QUALITY FUNCTION DEPLOYMENT

System QFD

++ Strong Positive Correlation
\+ Positive Correlation
\- Negative Correlation
-- Strong Negative Correlation

1															
2	Air Flow (50 L/s)	++													
3	Temperature (85 ºC)	-	++												
4	Humidity(100% RH)	-	++	++											
5	Pressure(2.5 Bar)	-	--		++										
6	SO_2(< 100 ppb)	-			-	++									
7	H_2S(< 100 ppb)	-			-		++								
8	CO(< 20 ppm)	-			-			++							
9	NO_2(< 500 ppb)	-			-				++						
10	NO(< 500 ppb)	-			-					++					
11	Noise(< 65 dBA)	--			--						++				
12	Lifetime(>4000 h)		--	--	--	++	++	++	++	++		++			
13	Cost(< $400)		--	-	--	-	-	-	-	-	-	-	++		
14	Dust Filter(> 98 %)	-			-							-	-	++	
15	Packageing (m^3)		--	-	-	-	-	-	-	-	--			-	++
16															
17															
18															
19															
20															

				Technical Requirements													
	Customer Needs	**Customer Weights**	**Kano Type**	Air Flow (50 L/s)	Temperature (85 ºC)	Humidity(100% RH)	Pressure(2.5 Bar)	SO_2(<100 ppb)	H_2S(< 100 ppb)	CO(< 20 ppm)	NO_2(< 500 ppb)	NO(< 500 ppb)	Noise(<65 dBA)	Lifetime(> 4000 h)	Cost(< $400)	Dust Filter(> 98 %)	Packaging(m^3)
1	Quiet	3		9			9						9		3		3
2	Long Lifetime of fuel cell	9		1	9	9	3	9	9	3	9	9		9	3	3	
3	Long Lifetime of intake	9			3	3	9							9	3		
4	Ease of Maintanance	3												9			3
5	Cost	9			9	3	9	3	3	3	3	3	1	3	9	1	1
6	Aesthetic	1											3		1	1	9
7	Light Weight	1			9	3	9									1	
8	Eco-Friendly	3												1			
9	Performance	9		9	9	9	9	9	9	9	9	9				1	1
10	Packaging	3			9	3	3						3			3	9
11	Ease of Manufacturing	3			1		3						3	1	9		9
12																	
13																	
14																	
15																	
16																	
		Raw score		117	309	228	324	189	189	135	189	189	57	222	172	56	99
		Scaled		0.361	0.954	0.704	1	0.583	0.583	0.417	0.583	0.583	0.176	0.685	0.531	0.173	0.306
		Relative Weight		5%	12%	9%	13%	8%	8%	5%	8%	8%	2%	9%	7%	2%	4%
		Rank		11	2	3	1	5	5	10	5	5	13	4	9	14	12
	Technical Requirement Units			L/s	C	%RH	Bar	ppb	ppb	ppm	ppb	ppb	dB	h	$	%	m^3
	Technical Requriement Targets			50	85	100	2.5	<100	<100	<20	<500	<500	<65	4000	<400	98%	0.8
	Technical Requriement USL			65	90	100	3	100	100	20	500	500	65	5000	400	100	1
	Technical Requriement LSL			35	80	90	2	0	0	0	0	0	0	3000	0	95	0.6

APPENDIX E: FUEL CELL STACK POWER IN CURRENT FUEL CELL VEHICLES

Table E.1 Hybrid Fuel Cell Vehicles (Battery and Fuel Cell Stack)

Car	**Year**	**Power**
A2	2004	66
Move FCV-KII	2001	30
EcoVoyager	2008	45
F600 Hygenius	2005	60
F-Cell	2008	85
Necar 5.2	2001	85
Batrium T&C	2001	54
Jeep Commander 2	2000	50
Explorere	2006	60
Focus FCV	2002	85
Provoq	2008	88
HydroGen4	2007	93
Equinox FCEV	2006	93
Sequel	2005	73
HydroGen1	2000	80
FCX	2002	85
Borrego FCEV	2008	115
Gradnis FCV	2003	68
X-Trail(SUV)	2002	75
Peugeot Fuel Cell Cab	2001	55
Scenic FCB H2	2008	90
Highlander	2002	90
Passat Lingyu	2008	55
Space up Blue	2007	45
Touran Hymotion	2007	80
HyPower	2002	40
	Average Fuel Cell Stack Power	70.96154

Table E.2 Fuel Cell Engine Vehicles

Car	**Year**	**Power**
Sprinter Van	2001	85
Necar 4	2000	85
Necar 5	2000	85
Necar 4	1999	70
Necar 2	1996	50
Panda	2007	60
Focus FCV	2000	85
Think FC5	2000	85
P2000	1999	75
Hy-Wire	2002	94
Advanced HydroGen3	2002	94
HydroGen3	2001	94
FCX Clarity	2007	100
Tucson	2004	80
Santa Fe SUV	2001	75
Sportage	2004	80
Premacy FV-EV	2001	85
Shanghai	2007	60
Chao Yue III	2005	50
SX4-FCV	2008	80
Wagon R FCV	2003	50
MR Wagon	2003	80
HyMotion	2000	75
	Average Fuel Cell Stack Power	77.26087

APPENDIX F: COMPONENT CONCEPT GENERATION

Table F.1 Scoop Concept Generation

	Name	Description
1	NACA Ducts	Ducts that bring in air without disturbing airflow
2	Whale Mouth	Large Curved shape opening
3	Mailbox	Use large cross sectional area similar to a mailbox
4	Multi Scoop	Have many inlets that combine to one
5	Roof Scoop	Air inlet on the roof of the car
6	Hood Scoop	Air inlet on the hood of the car
7	Ground Scoop	Air inlet near the bottom of the front of the car
8	Variable Duct Opening	Scoop Varies Cross Sectional Area with Seed
9	Compressed Tank	Air comes directly from a stored oxygen tank
10	Direct Compressor	Air is taken in directly by a compressor
11	Propeller/Fan	Add fans behind duct entrance to force air in
12	Hose	Use air hoses and lines instead of ductwork
13	Duct Sizing	Start with large cross section and finish with small cross section for ductwork

Table F.2 Filter Concept Generation

	Name	Description
1	Combination Filter	Have both chemical and dust filters in one filter
2	Mesh Screen	Have screen at duct opening to block large objects from entering ductwork
3	Many Filters	Place many separate filters in ductwork (each specializing in removing one substance)
4	Platinum Filter	Platinum attracts metal ion
5	Advanced Carbon Filter	Chemical filter coated with potassium hydroxide
6	Membrane Filter	Filters water ions in air
7	Ionic Breeze Filter	Charge air and help remove impurities
8	Donaldson Chemical Filter	Already made chemical/dust filter or fuel cell application
9	Water Filter	Remove harmful elements through water

Table F.3 Compressor Concept Generation

	Name	Description
1	Scroll Compressor	Compresses air by trapping it and spooling it to the center
2	Screw Compressor	Compresses air by using screws
3	Centrifugal Compressor	Compresses air by spinning
4	Lobe/Roots Compressor	Compresses air by rotating lobes
5	Exhaust Turbocharger	Use fuel cell exhaust pressure to drive a turbo
6	Compressed Oxygen Tank	Air is stored in a compressed oxygen tank for use
7	Self Driven	Driven by its own battery pack and alternator
8	Fuel Cell Driven	Driven by the power generated from the fuel cell
9	No Compressor	Use temperature-pressure relationship and valves to create airflow from heating

Table F.4 Humidifier Concept Generation

	Name	Description
1	Liquid Water Injection	Inject water into air stream during compression
2	Water Tank	Use water tank as storage and to control temperature of water
3	Recycle Exhaust Water	Use water created in the fuel cell and recycle it to water tank
4	Collect Rain Water	Have system that collects water from rain to store in tank
5	Spray Mist	Have airflow travel through mist to increase humidity
6	Radial Nafion® Membrane	Have airflow travel along radial membrane around duct with heated water on other side
7	Linear Nafion® Membrane	Have airflow enter a chamber similar to fuel cell with membrane and have heated water on other side
8	Boiler	Boil water and have air travel through it

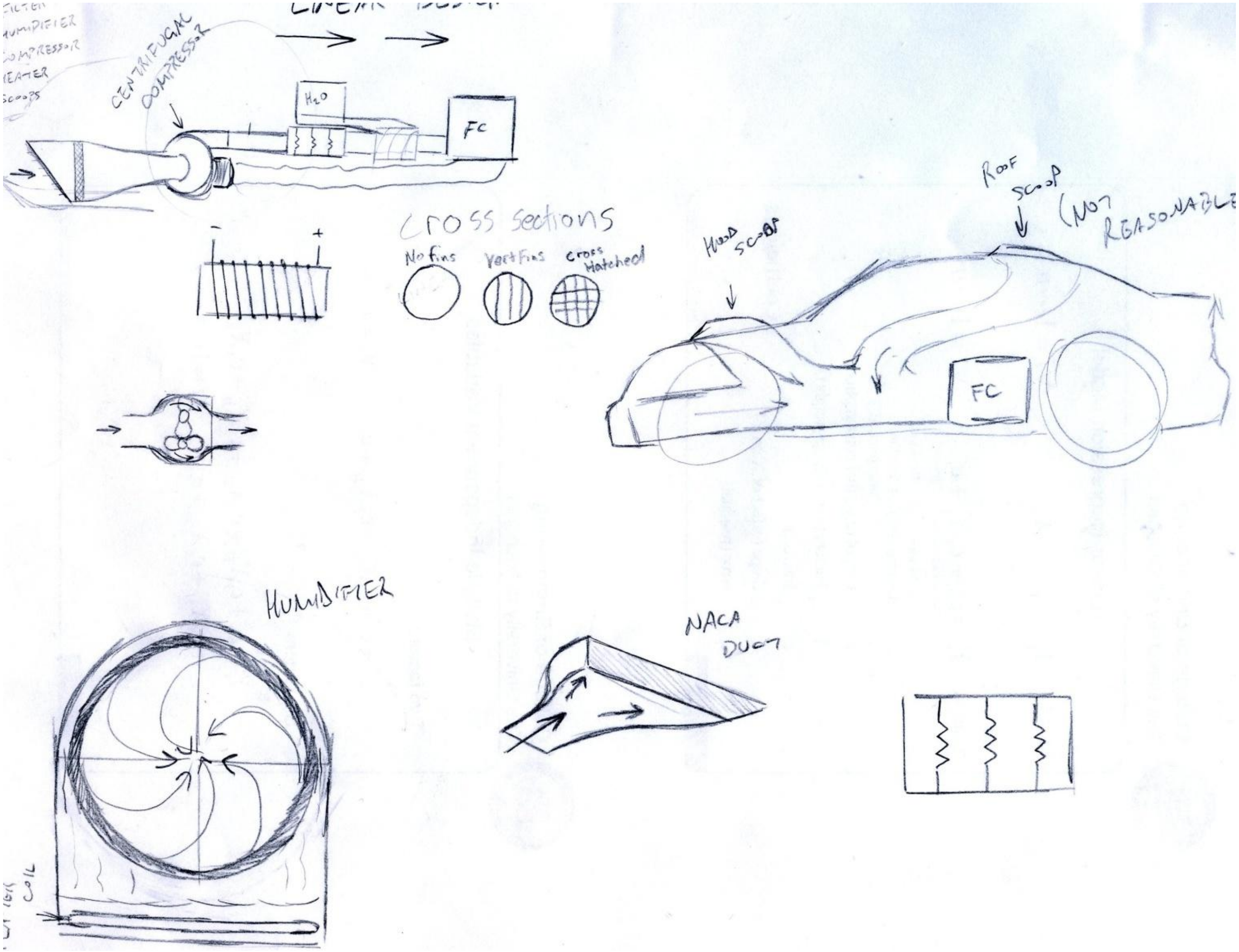
Table F.5 Cooler Concept Generation

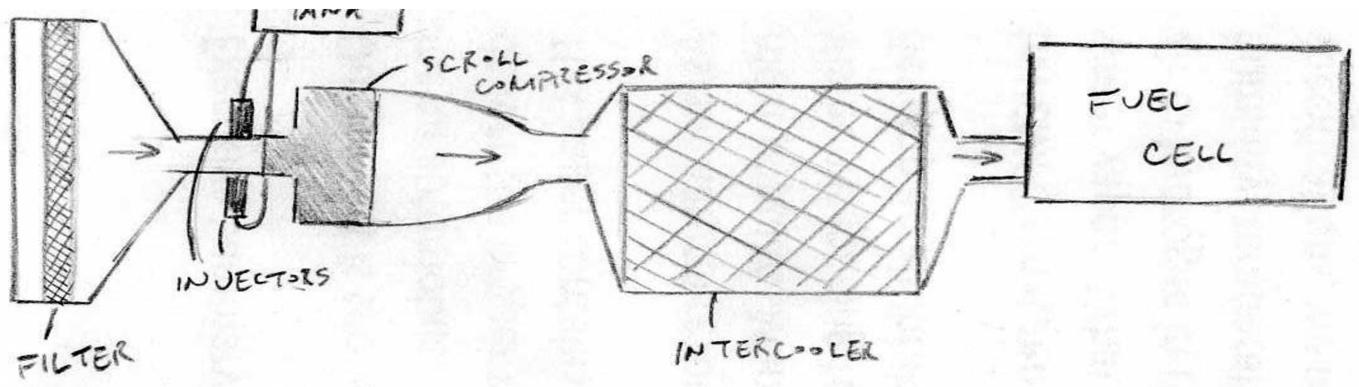
	Name	Description
1	Intercooler	Cool air using heat exchanger between hot and cold air
2	Refrigeration System	Create a full refrigeration system like for air conditioning to cool air
3	Water Injection	Use water injection humidifier to help cool air

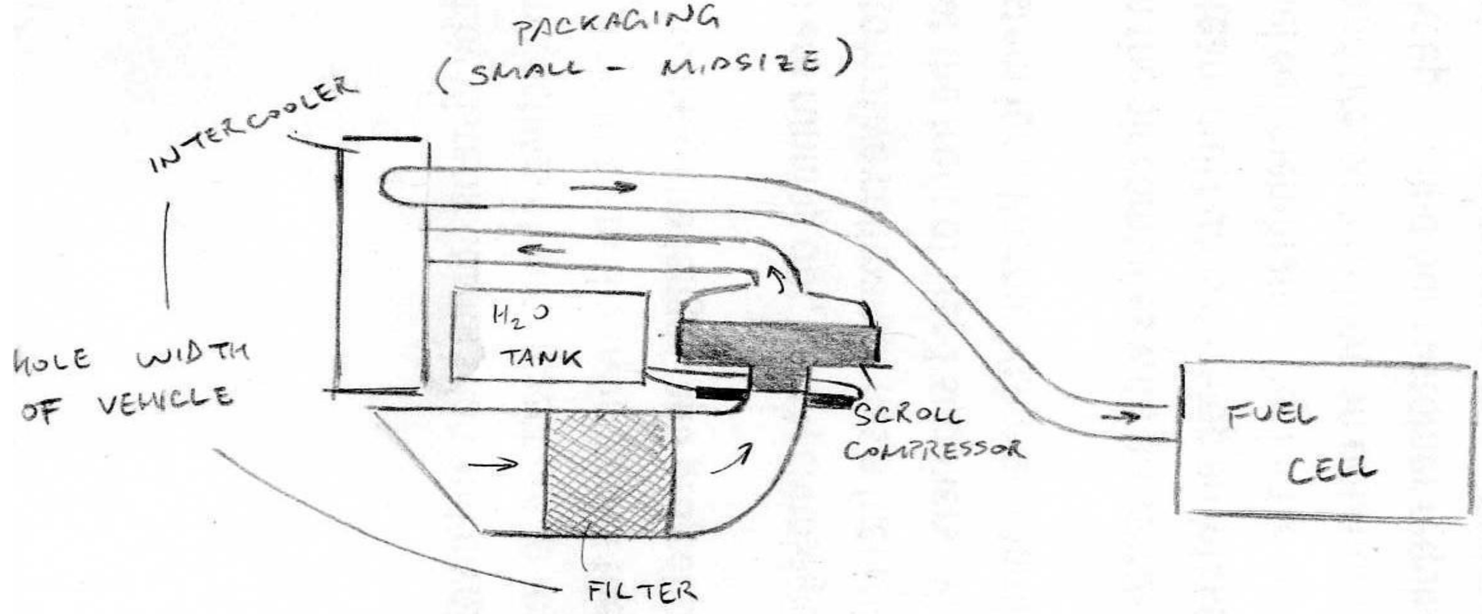
Table F.6 Noise Concept Generation

	Name	Description
1	Helmholtz Resonator	Attenuates different frequencies
2	Quarter Wave Resonator	Cancels out equal frequencies

APPENDIX G: CONCEPT GENERATION




SCROLL COMPRESSOR
FUEL CELL
INJECTORS
FILTER
INTERCOOLER


PACKAGING
(SMALL - MIDSIZE)
INTERCOOLER
H_2O TANK
HOLE WIDTH OF VEHICLE
SCROLL COMPRESSOR
FUEL CELL
FILTER

Appendix H: Pugh Charts

Table H.1 Scoop Pugh Chart

		Concept A		Concept B		Concept C		Concept D		Concept E	
Selection Criteria	**Weight**	**Whale Mouth**		**NACA Ducts**		**Ground Ducts and Inlets**		**Multi Scoop System**		**Variable Duct Opening**	
		Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
High Volume Air Intake	0.25	5	1.25	2	0.5	4	1	5	1.25	5	1.25
Maintaining Pressure (2 - 3atm)	0.1	3	0.3	3	0.3	4	0.4	3	0.3	5	0.5
High Efficiency	0.15	5	0.75	4	0.6	5	0.75	5	0.75	5	0.75
Structurally Sound	0.1	4	0.4	5	0.5	5	0.5	3	0.3	3	0.3
Low Cost	0.15	2	0.3	4	0.6	4	0.6	1	0.15	2	0.3
Last Lifetime of Car 5 years	0.05	5	0.25	5	0.25	5	0.25	4	0.2	3	0.15
Low Noise	0.1	5	0.5	5	0.5	5	0.5	3	0.3	3	0.3
Packaging ability	0.1	2	0.2	5	0.5	4	0.4	2	0.2	3	0.3
Total Score	1		3.95		3.75		4.4		3.45		3.85
Rank			2		4		1		5		3

Table H.2 Filter Pugh Chart

		Concept A		Concept B		Concept C		Concept D	
Selection Criteria	**Weight**	**Visteon Dust Filter**		**Activated Carbon Filters**		**Membrane Filter**		**Donaldson Chemical Filter**	
		Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
Low Restriction	0.15	3	0.45	4	0.6	3	0.45	3	0.45
Large Surface Area	0.07	4	0.28	3	0.21	3	0.21	4	0.28
High Efficiency	0.2	3	0.6	5	1	3	0.6	4	0.8
Low Cost	0.1	2	0.2	3	0.3	3	0.3	2	0.2
Lifetime of Dust Filter	0.1	3	0.3	4	0.4	3	0.3	4	0.4
Lifetime of Chemical Filter	0.1	3	0.3	2	0.2	3	0.3	4	0.4
Low Noise	0.05	3	0.15	3	0.15	3	0.15	3	0.15
Replaceable	0.18	2	0.36	4	0.72	3	0.54	2	0.36
Small Size	0.05	2	0.1	3	0.15	3	0.15	3	0.15
Total Score	1		2.74		3.73		3		3.19
Rank			4		1		3		2

Table H.3 Compressor Pugh Chart

		Concept A		Concept B		Concept C		Concept D		Concept E	
Selection Criteria	**Weight**	**Scroll Compressor**		**Screw Compressor**		**Centrifugal Compressor**		**Lobe Compressor**		**Compressed Oxygen Tank**	
		Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
High Pressure (2-3 atm)	0.25	4	1	5	1.25	3	0.75	4	1	4	1
High Efficiency (mass flow rate)	0.15	1	0.15	5	0.75	3	0.45	5	0.75	3	0.45
Low Power Requirement	0.1	4	0.4	4	0.4	4	0.4	5	0.5	5	0.5
Low Cost	0.15	3	0.45	2	0.3	4	0.6	3	0.45	4	0.6
Last Lifetime of Car 5 years	0.05	4	0.2	5	0.25	5	0.25	2	0.1	1	0.05
Low Noise	0.1	5	0.5	3	0.3	4	0.4	5	0.5	4	0.4
Small Size	0.05	3	0.15	2	0.1	5	0.25	4	0.2	2	0.1
Pressure Ripple below 200 mbar	0.05	3	0.15	4	0.2	3	0.15	3	0.15	3	0.15
No Oil Mixing	0.05	5	0.25	3	0.15	2	0.1	5	0.25	5	0.25
Low Weight	0.05	3	0.15	2	0.1	5	0.25	3	0.15	5	0.25
Total Score	1		3.4		3.8		3.6		3.5		3.25
Rank			4		1		2		3		5

Table H.4 Humidifier Pugh Chart

		Concept A		Concept B		Concept C		Concept D		Concept E	
Selection Criteria	**Weight**	**Liquid Spray In Compressor**		**Linear NAFION Membrane**		**Exhaust Exchanger**		**Carbon Foam**		**Radial NAFION Membrane**	
		Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
100% Relative Humidity	0.2	5	1	4	0.8	3	0.6	3	0.6	4	0.8
High Efficiency	0.13	5	0.65	3	0.39	3	0.39	3	0.39	3	0.39
Low Power Requirement	0.1	5	0.5	5	0.5	5	0.5	3	0.3	5	0.5
Low Cost	0.1	5	0.5	4	0.4	4	0.4	3	0.3	4	0.4
Last Lifetime of Car 5 years	0.1	5	0.5	5	0.5	5	0.5	3	0.3	5	0.5
Small Size	0.15	5	0.75	2	0.3	4	0.6	3	0.45	3	0.45
Operating	0.05	5	0.25	4	0.2	5	0.25	3	0.15	4	0.2

Temperature											
Reservoir Size	0.02	3	0.06	3	0.06	5	0.1	3	0.06	3	0.06
Low Air Flow Restriction	0.15	5	0.75	5	0.75	3	0.45	3	0.45	5	0.75
Total Score	1		4.96		3.09		3.79		3		3.04
Rank			4		1		2		3		4

APPENDIX J: MATHEMATICAL MODEL OF SYSTEM

To determine the relationship between the pressure, temperature and humidity of our system, our team has developed a mathematical model of our system. First, we determined that there are four key states:

<u>State 1:</u> the ambient conditions of air being taken into the system
<u>State 2:</u> the conditions of the air immediately after the compressor
<u>State 3:</u> the conditions of the air after the water injector
<u>State 4:</u> the final conditions of the air after the intercooler

A visual representation of these states in the system can be seen in Figure I.1 below

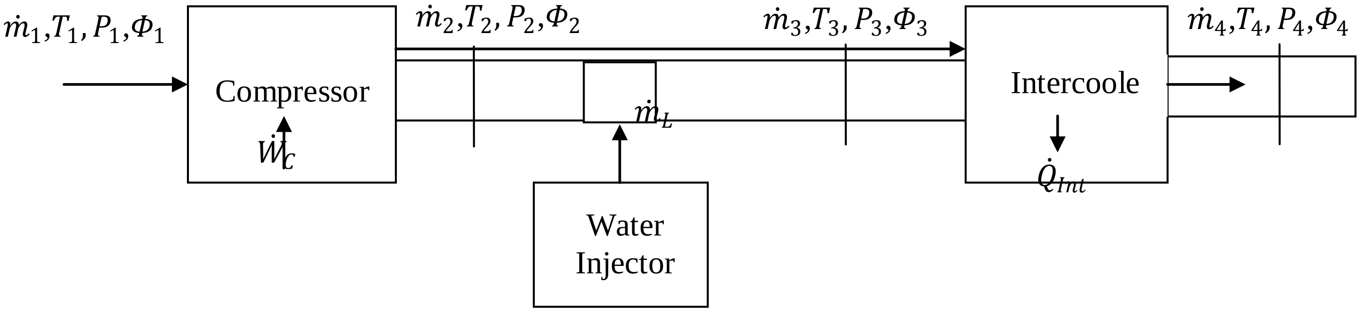


Figure J.1: Simplified visual of key states in the system

After determining the location of the four key states in our system, our team made assumptions about our system necessary to complete the needed calculations. These assumptions are as follows:

1. Isentropic compression (constant entropy)
2. Pressure remains constant after the compressor
3. Our assembly/ducting is ideally insulated (zero heat loss through ducts)

Calculations for compressors are often assumed to be ideal, pressure ripples throughout the system may occur but should not be large, and losses through the ducting should not be significant. For these reasons, we feel that these assumptions are valid for the purpose of our project.

Next our team has identified certain known variables for our system. These known variables are the mass airflow rate $\dot{m}_1$, temperature T_1, pressure P_1 and relative humidity Φ_1 of the air at the inlet of the compressor and the relative humidity of state 2 Φ_2 . These variables will be measured. Our team will also set our desired final variables temperature T_4, pressure P_4 and relative humidity Φ_4 (=1 or 100% relative humidity). Lastly, we will set the pressure after the compressor P_2, and since we assumed constant pressure after the compressor, we also know P_3 and P_4.

Model

<u>Mass Flow Rate of Liquid Injected ($\dot{m}_L$)</u>

The first calculations performed were to determine the amount of water to inject into the system based on the known variables at state 1 and our desired variables at state 4. We used the mass continuity equation to develop Equations J.1, J.2, and J.3.

$\dot{m}_1$=$\dot{m}_2$ (Eq. J.1) $\dot{m}_3$=$\dot{m}_4$ (Eq. J.2) $\dot{m}_3$=$\dot{m}_2 + \dot{m}_L$ (Eq. J.3)

Where $\dot{m}_\#$ the mass air flow rate at is different sections of our assembly seen in Figure J.1, and $\dot{m}_L$is the mass flow rate of water being injected into the system.

Through substitution, we obtained Equation J.4 which relates the mass flow of our final state, initial state and the amount of water injected.

$$\dot{m}_4=\dot{m}_1 + \dot{m}_L \text{ (Eq. J.4)}$$

Using Equation J.4, we then related the molar fractions of vapor between the states in Equation J.5

$$\dot{m}_1 y_{v1} + \dot{m}_L = \dot{m}_4 y_{v4} \text{ (Eq. J.5)}$$

Where y_{v1} is the MOLE fraction of vapor at the inlet state and y_{v4} the MOLE fraction of vapor at the final state. $\dot{m}_L$ has a molar fraction of one because it is liquid.

The equations for the molar fractions for state 1 and state 4 can be seen below in Equations J.6 and J.7.

$$y_{v1}=\frac{\Phi_1 * P_{g1}}{P_1} \quad \text{(Eq. J.6)} \qquad y_{v4}=\frac{P_{g4}}{P_4} \quad \text{(Eq. J.7)}$$

Where Φ_1 is the relative humidity at state 1, $P_1$is the pressure at state 1, P_{g1} is the saturation pressure at T_1, P_4 is the pressure at state 4 and P_{g4} is the saturation pressure at T_4

Lastly, we combined Eqs.J.4, J.5, J.6, and J.7 into one equation and solved for the mass flow of water necessary for the system (Equation J.8).

$$\dot{m}_L=\frac{\dot{m}_1(y_{v4}-y_{v1})}{1-y_{v4}}=\frac{\dot{m}_1(\frac{P_{g4}}{P_4}-\frac{\Phi_1 * P_{g1}}{P_1})}{1-\frac{P_{g4}}{P_4}} \quad \text{(Eq. J.8)}$$

<u>Amount of cooling per kilogram dry air ($\frac{\dot{Q}_{Int}}{\dot{m}_a}$)</u>

The next set of calculations performed determine the amount of cooling in the intercooler necessary to achieve our desired final temperature. First, we calculated the temperature rise across the compressor in Equation J.9.

$$T_2=\frac{P_2 T_1}{P_1} * (\frac{P_1}{P_2})^{1/k} \quad \text{(Eq. J.9)}$$

where k=1.4 for air during an isentropic process, T_1 is the temperature at state 1, P_1 is the pressure at state 1, and P_2 is the pressure at state 2.

Next, we used Equation J.10 to obtain the partial vapor pressure of state 2. This was then used to determine the humidity ratio seen in Equation J.11.

$$P_{v2} = y_{v2} * P_2 = \Phi_2 * P_{g2} \quad \text{(Eq.J.10)} \qquad \omega_2=.622*(\frac{P_{v2}}{P_2-P_{v2}})= .622*(\frac{\Phi_2 * P_{g2}}{P_2-\Phi_2 * P_{g2}}) \quad \text{(Eq. J.11)}$$

Where P_{v2} is the partial vapor pressure at state 2, y_{v2} is the MOLE fraction of vapor at state 2, Φ_2 is the relative humidity at state 2, P_{g2} is the saturation pressure of state 2 as a function of T_2, and ω_2 is the humidity ratio of state 2.

We then used conservation of energy in our system between states 2 and 3 to develop Equation J.12.

$$\dot{m}_3 h_3=\dot{m}_2 h_2 + \dot{m}_L h_L \quad \text{(Eq. J.12)}$$

Where h_3 is the specific enthalpy of state 3 is, h_2 is the specific enthalpy of state 2 which is a function of P_2 and T_2, and h_L is the specific enthalpy of the water which is a function of its temperature and pressure.

Rearranging Equation J.12 and substituting Equations J.1, J.3, & J.8 into it, we obtained Equation J.13.

$$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_L h_L}{\dot{m}_1 + \dot{m}_L} = \frac{h_1 + \frac{(\frac{P_{g4}}{P_4} - \frac{\Phi_1 * P_{g1}}{P_1})}{1 - \frac{P_{g4}}{P_4}} * h_L}{1 + \frac{(\frac{P_{g4}}{P_4} - \frac{\Phi_1 * P_{g1}}{P_1})}{1 - \frac{P_{g4}}{P_4}}} \qquad \text{(Eq. J.13)}$$

From the enthalpy at state 3, we can determine the temperature of state 3 (T_3) as it is a function of h_3 and P_3. We can then solve for the humidity ratio of state 3 using Equation J.14.

$$\omega_3 = \frac{\omega_2 * (h_{v2} - h_L) - 1.004 * [T_2 - T_3]}{h_{fg3}} \qquad \text{(Eq. J.14)}$$

Where ω_3 is the humidity ratio of state 3, h_{v2} is the partial vapor enthalpy of state 2 which for our case is the saturation vapor enthalpy h_{g2} which is a function of T_2, and h_{fg3} is the evaporation enthalpy of state 3 which is a function of T_3.

Next, we calculated the humidity ratio of state 4, seen in Equation J.15.

$$\omega_4 = .622 * (\frac{P_{g4}}{P_4 - P_{g4}}) \qquad \text{(Eq. J.15)}$$

Where ω_4 the humidity ratio of state 4, P_{g4} is the saturation vapor pressure of state 4, and P_4 is the pressure at state 4.

Lastly, we were able to calculate the amount of cooling necessary in the intercooler per kilogram air, seen in Equation J.16. Equation J.17 was then created by substituting Equations J.11, J.14, and J.15 into Equation J.16.

$$\frac{\dot{Q}_{Int}}{\dot{m}_a} = h_{a4} - h_{a3} + \omega_4 * h_{v4} - \omega_3 * h_{v3} = 1.004 * [T_4 - T_3] + \omega_4 * h_{v4} - \omega_3 * h_{v3} \qquad \text{(Eq. J.16)}$$

$$\frac{\dot{Q}_{Int}}{\dot{m}_a} = 1.004 * [T_4 - T_3] + .622 * (\frac{P_{g4}}{P_4 - P_{g4}}) * h_{v4} - \frac{.622 * (\frac{\Phi_2 * P_{g2}}{P_2 - \Phi_2 * P_{g2}}) * (h_{v2} - h_L - 1.004 * \left[\frac{P_2 T_1}{P_1} * (\frac{P_1}{P_2})^{\frac{1}{k}} - T_3\right])}{h_{fg3}} * h_{v3}$$

(Eq. J.17)

Where $\frac{\dot{Q}_{Int}}{\dot{m}_a}$ is the amount of cooling necessary in the intercooler per kilogram of air, h_{a3} is the partial enthalpy of air at state 3, h_{v3} is the partial vapor enthalpy at state 3, h_{a4} is the partial enthalpy of air at state 4, and h_{v4} is the partial vapor enthalpy at state 4 which is equal to the saturation enthalpy at state 4, h_{g4}.

Compressor Power

The final input calculated was the power required to run the compressor seen in Equation J.18.

$\dot{W}_C = \dot{m}_1 (h_2 - h_1) = \dot{m}_1 * 1.004 * [T_2 - T_1]$ (Eq. J.18)

Where $\dot{W}_C$ is the power required to run the compressor, and $\dot{m}_1$, h_1, and T_1 are the mass air flow, enthalpy, and temperature, respectively, of the air at the inlet of the compressor, h_2 and T_2 are the enthalpy and temperature of air after the compressor.

APPENDIX K: AIR INTAKE SYSTEM FLOW CHARACTERISTICS

K.1- Initial Mass Flow

For our project no specific fuel cell power requirement was given to our team For this reason our team calculated the necessary mass flow at the air intake in order to satisfy fuel cell power requirements ranging from 10-100 kW. These flow rates can be seen in Table K.1 using the equation seen below. A list of different fuel cell vehicles and their power requirements can be seen in Appendix E.

Table K.1: Mass flow rates necessary for different fuel cell power requirements

Fuel cell Power (kW)	Mass flow at the intake (kg/s)
10	0.011
20	0.022
30	0.033
40	0.044
50	0.055
60	0.066
70	0.077
80	0.088
90	0.099
100	0.110

$$AirUsage = \left(3.57x10^{-7}\right) \times (\lambda) \times \left(\frac{P_e}{V_C}\right) \qquad \text{(Eq. K.1)}$$

where λ is the stoichiometric multiple(=2 to ensure proper airflow), P_e is the power output of the fuel cell stack in watts, and V_c is the average voltage of each cell.

K.2 Liquid Injection Mass Flow

To properly regulate the humidity of our system, our team needed to know the amount of water to inject into the system based on the input and output characteristics. Using Equation J.8 obtained from the calculation of our thermodynamic model in Appendix J, our team created Figure K.1 Figure K.2 below. Figure K.1 shows the amount of water that needs to be injected into our final design for different powers requirements (initial mass flow rates), at different ambient temperatures, and different ambient humilities. We used our desired characteristics of our final design 85°C, 2.5 bar, and 100% relative humidity for the final state in Equation J.8 in the equation. Figure K.2 shows the amount of water that needs to be injected into our prototype for different powers requirements (initial mass flow rates), at different ambient temperatures, and different ambient humidity. We used our desired characteristics of our prototype 40°C, 1.35 bar, and 100% relative humidity for the final state in Equation J.8.

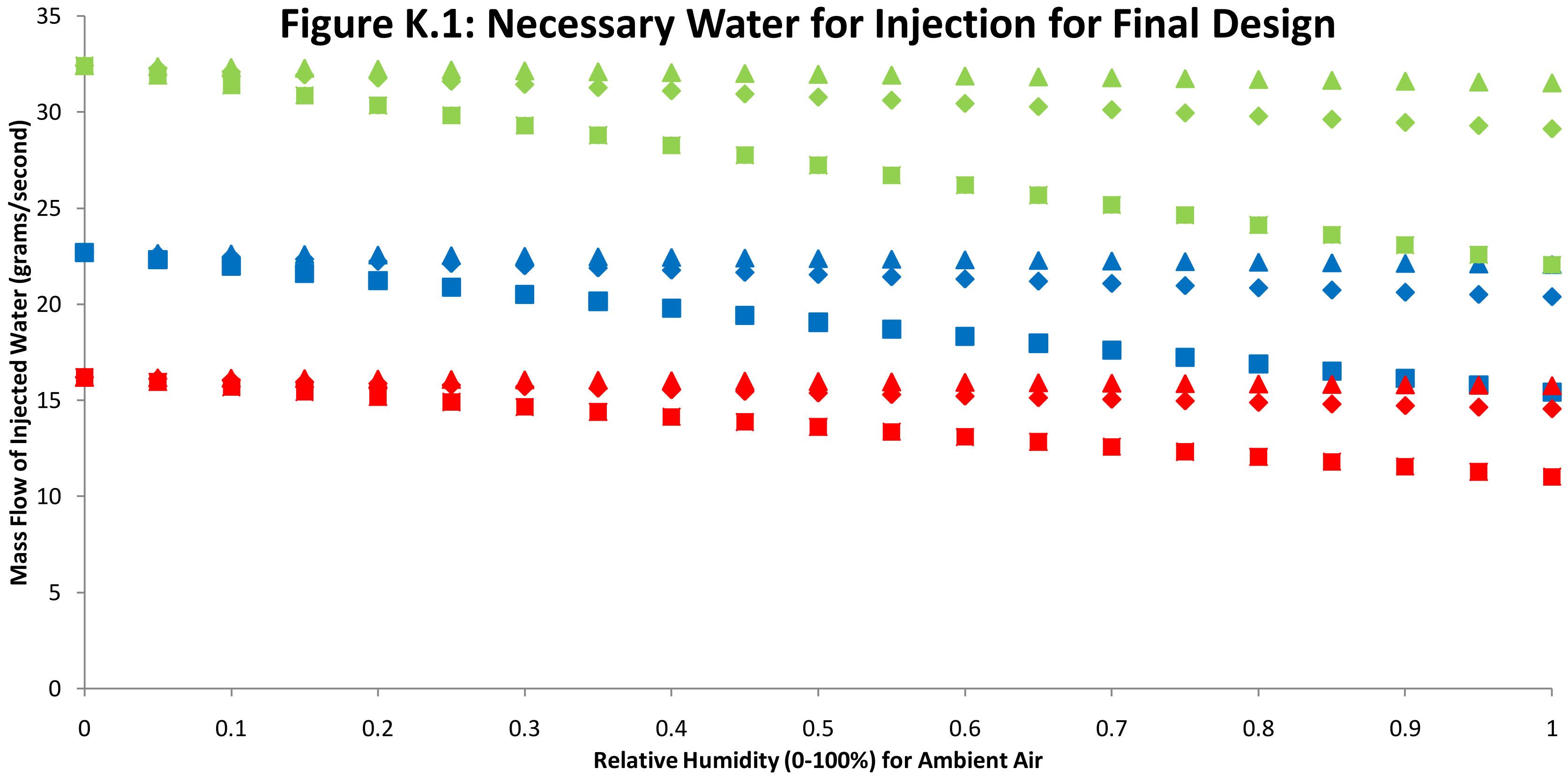


Figure K.1: Necessary Water for Injection for Final Design

△ = Ambient Temperature is 0°C

◇ = Ambient Temperature is 20°C

□ = Ambient Temperature is 40°C

🟩 = 100 kW Fuel Cell (Initial Mass Flow into Compressor is $0.110\frac{kg}{sec}$)

🟦 = 70 kW Fuel Cell (Initial Mass Flow into Compressor is $0.077\frac{kg}{sec}$)

🟥 = 50 kW Fuel Cell (Initial Mass Flow into Compressor is $0.055\frac{kg}{sec}$)

Calculations were performed using:
1. Final gauge pressure 2.5 bar
2. Final temperature of 85°C at the outlet of the prototype
3. Final relative humidity of 100%
4. Initial pressure was atmospheric (1 bar)

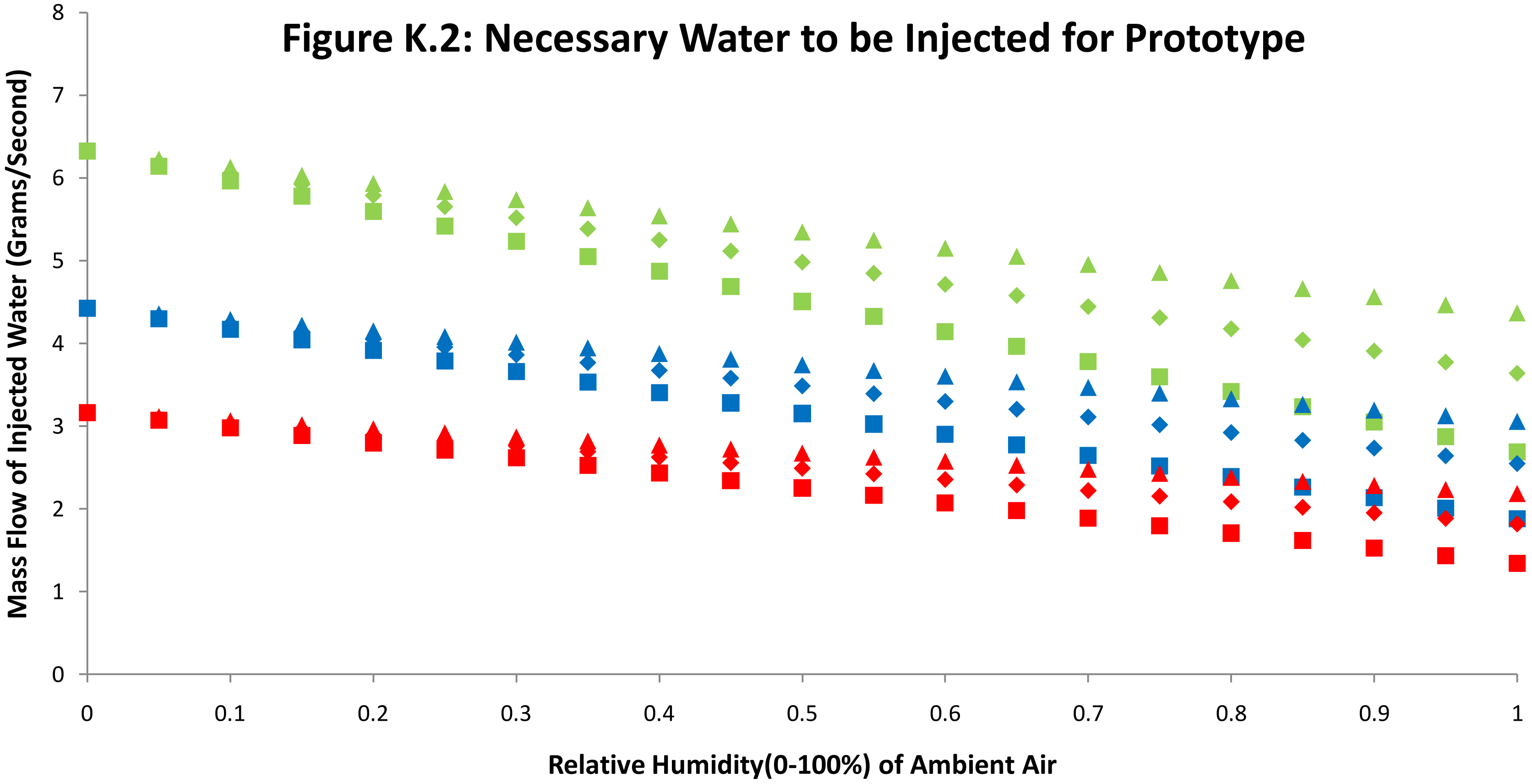


Figure K.2: Necessary Water to be Injected for Prototype

△ = Ambient Temperature is 0°C

◇ = Ambient Temperature is 20°C

□ = Ambient Temperature is 40°C

🟩 = 100 kW Fuel Cell (Initial Mass Flow into Compressor is 0.110$\frac{kg}{sec}$)

🟦 = 70 kW Fuel Cell (Initial Mass Flow into Compressor is 0.077$\frac{kg}{sec}$)

🟥 = 50 kW Fuel Cell (Initial Mass Flow into Compressor is 0.055$\frac{kg}{sec}$)

Calculations were performed using:

1. Final pressure 1.35 bar (135.8 kPa)
2. Final temperature of 40°C at the outlet of the prototype
3. Final Relative humidity is 100%
4. Initial pressure was atmospheric (1 bar)

APPENDIX L: FINAL DESIGN CAD PICTURES

Figure L.1: Front View of Final Design

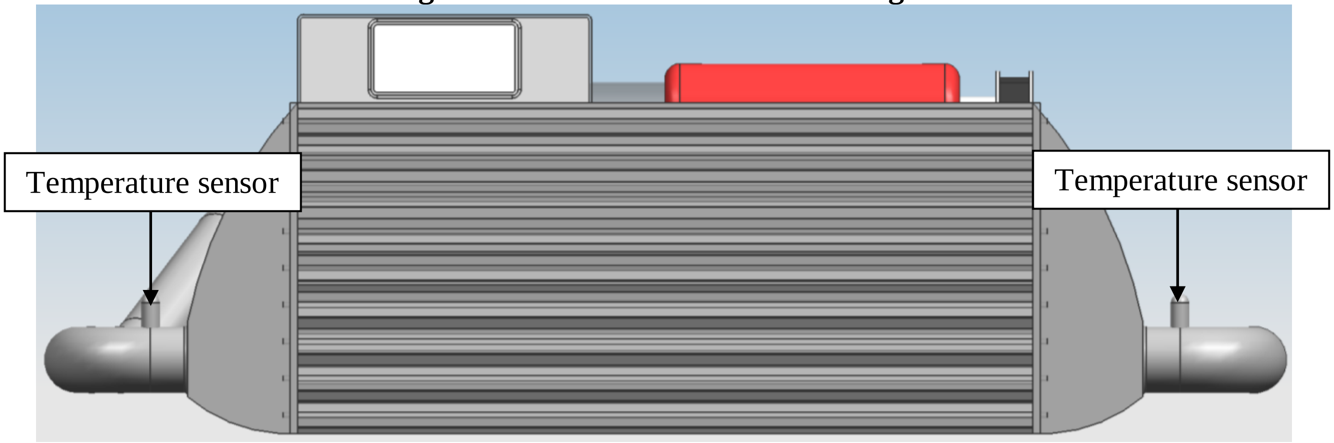


Figure L.2: Left View of Final Design

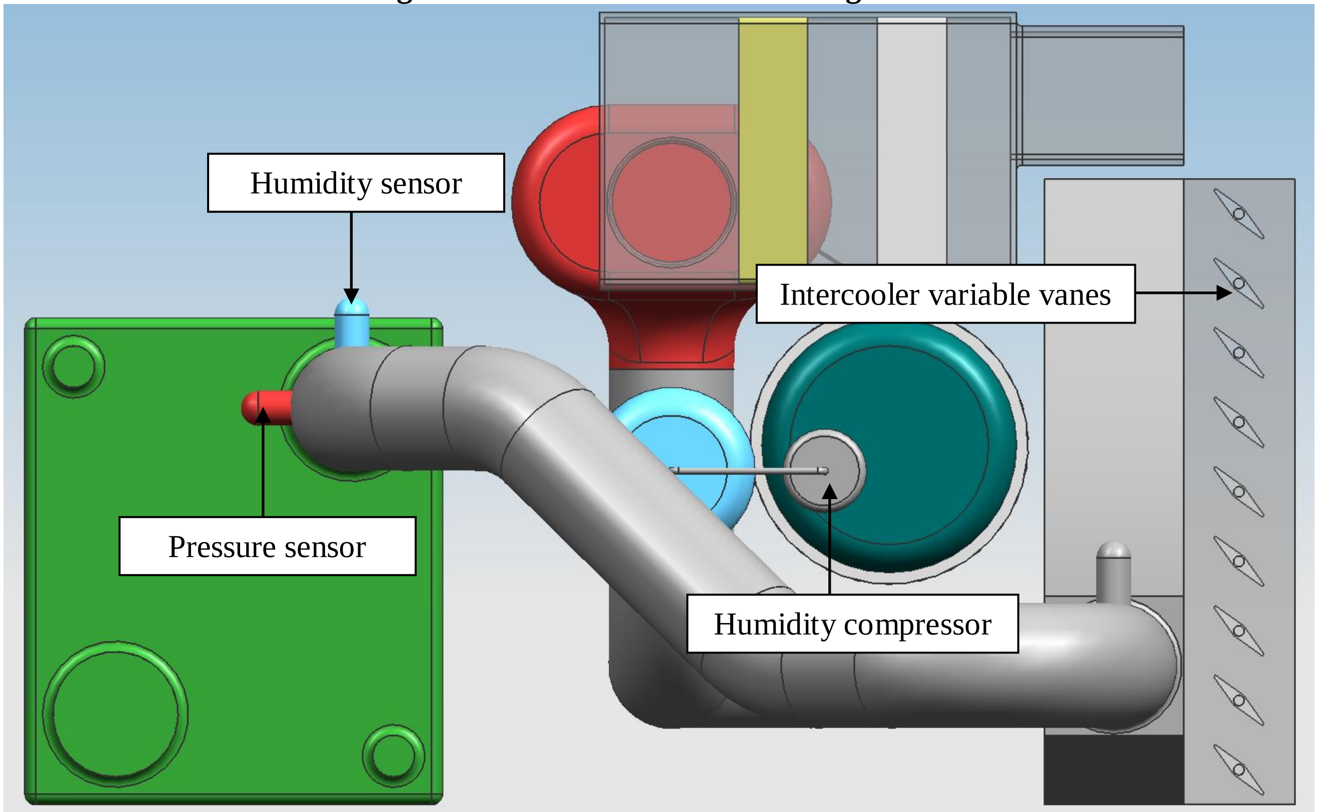


Figure L.3: Bottom View of Final Design

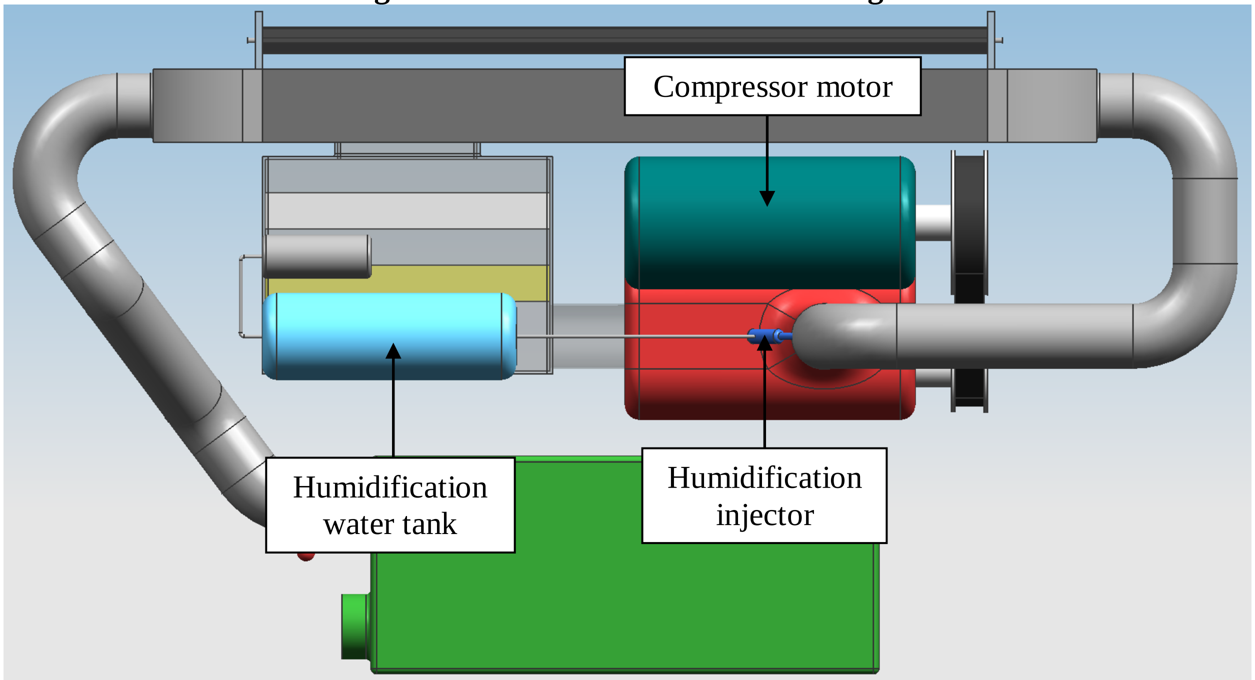
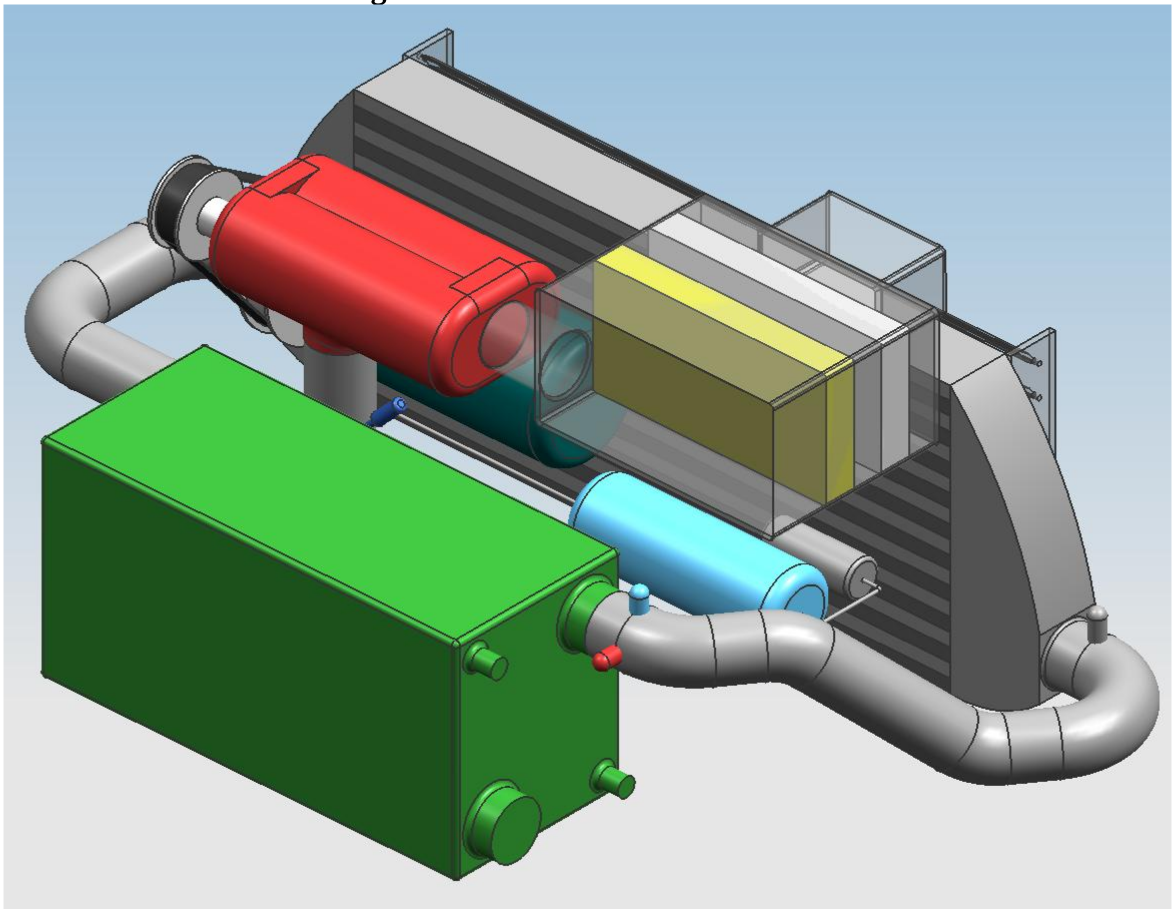


Figure L.4: Reverse Isometric View



APPENDIX M: GANNT CHART

Tasks	13-Jan	15-Jan	20-Jan	22-Jan	27-Jan	29-Jan	3-Feb	5-Feb	10-Feb	12-Feb	17-Feb	19-Feb	24-Feb	26-Feb
Form Project Team	🟦													
Set Team Roles	🟦													
Information Gathering	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
Meet With Sponsor			🟥											
Meet with Professor Borgnake			🟩											
Initial QFD/Problem Definition			🟥											
Meet with Professor Stefanopolou				🟦										
Create Gantt Chart				🟩	🟩									
Summarize Info Gathering				🟥	🟥	🟥								
Write Executive Summary					🟦									
Prepare DR #1 Presentation					🟦	🟦								
Design Review #1						🟦								
Meet With Sponsor						🟦								

🟩 = Individual
🟦 = Team
🟥 = Individual and Team

Team Roles Worksheet						🟩								
Tasks	13-Jan	15-Jan	20-Jan	22-Jan	27-Jan	29-Jan	3-Feb	5-Feb	10-Feb	12-Feb	17-Feb	19-Feb	24-Feb	26-Feb
Finish DR #1 Report						🟦								
Submit DR #1 Report						🟩								
Discuss Ways to make meeting more efficient/Reflect on team failures of DR #1 and how to prevent them							🟦							
Determine Fuel Cell Power Requirements							🟩							
Visit Sponsor’s Facilities							🟦							
Concept Generation							🟥	🟥	🟥	🟥				
Determine Engineering Fundamentals required to analyze system							🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Informal Presentation #1							🟦							

Prepare Functional Decompisition							🟥	🟥						
Informal Submission #1								🟥						
View Fuel Cell on Campus								🟦						
Tasks	13-Jan	15-Jan	20-Jan	22-Jan	27-Jan	29-Jan	3-Feb	5-Feb	10-Feb	12-Feb	17-Feb	19-Feb	24-Feb	26-Feb
Concept Selection								🟦						
Research Compressor Concepts								🟩	🟩					
Research Humidifier Concepts								🟩	🟩					
Research Cooler Concepts								🟩	🟩					
Research Air Intake Scoop Concepts								🟩	🟩					
Research Filter Concepts								🟩	🟩					
Create Pugh Charts for all Concepts of every Components of System								🟩	🟩					
Summarize								🟥	🟦					

Info Gathering								🟥	🟦					
Evaluate Concepts									🟦					
Discuss tradeoffs Between Components									🟦					
Choose Best Components									🟦					
Choose most efficient order of components									🟦					
Tasks	13-Jan	15-Jan	20-Jan	22-Jan	27-Jan	29-Jan	3-Feb	5-Feb	10-Feb	12-Feb	17-Feb	19-Feb	24-Feb	26-Feb
Pick Alpha Design									🟦					
Correct DR #1 Report									🟥	🟥	🟥	🟥		
Meet with Russ Pitts									🟦					
Informal Presentation #2									🟦					
Meet Professor Mousseou										🟩				
Determine length of small/ mid size vehicle										🟥				
Dimension scoops and ducts										🟥	🟥			
Create										🟥	🟥	🟥		

Engineering Drawings(CAD)										🟥	🟥	🟥		
Informal Submission #2											🟦			
Summarize Info Gathering											🟥	🟥		
Prepare DR #2 Presentation											🟥	🟥		
DR #2												🟦		
Finalize DR #2 Report												🟦		
Submit DR#2 Report												🟩		
Spring Break													🟩	🟩

Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Determine which components to purchase and which to build	🟦	🟦														
Determine important characteristics of system to demonstrate with our prototype	🟦	🟦														
Search for Compressor	🟥	🟥														

🟩 = Individual

🟦 = Team

🟥 = Individual and Team

Perform Cost Analysis	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Perform Temperature Analysis	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Perform Mass flow rate analysis	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Perform Humidity Analysis	🟥	🟥	🟥	🟥	🟥	🟥	🟥									
Visit Junkyard/Purchase Compressor			🟦													

Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Safety Review of Compressor			🟥													
Meet with Professor Oslewski				🟩												
Visit Junkyard/Purchase Fuel Injectors, Gas Pump/Tank, Air Intake/Filter,				🟦												

and Intercooler				🟦												
Safety Review of Fuel Injectors, Gas Pump/Tank, Air Intake/Filter, and Intercooler				🟥												
Design Test Rig					🟥	🟥										
Determine Other components to purchase including drill to run compressor and ducting material					🟥	🟥										
Work on Safety Review					🟥	🟥	🟥	🟥								
Meet with Sponsor						🟦										
Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Finalize Alpha Design						🟥	🟥	🟥								
Finalize Prototype						🟥	🟥	🟥								

Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Design						🟥	🟥	🟥								
Dimension Parts in CAD						🟥	🟥	🟥								
Determine Manufacturing Processes required for assembly						🟥	🟥	🟥								
Determine initial testing needed to characterize the system						🟥	🟥	🟥								
Make Corrections to DR #2 Report						🟥	🟥	🟥								
Prepare DR #3 Presentation							🟥	🟥								
Design Review #3 Presentation								🟦								
Finalize DR #3 Report								🟦								
Submit DR #3 Report								🟩								
Build Alpha Prototype								🟥	🟥	🟥	🟥	🟥	🟥	🟥		

Build Test Rig								🟥	🟥							
Manufacture Adapter Pieces in Machine Shop								🟥	🟥							
Make Rubber Gaskets								🟥	🟥							
Build compressor subassembly								🟥	🟥	🟥	🟥					
Build water Injector subassembly									🟥	🟥	🟥	🟥				
Build intercooler subassembly										🟥	🟥					
Perform compressor characterization test										🟥	🟥	🟥				
Insert pressure, temperature and humidity sensors										🟥	🟥	🟥				

🟩 = Individual
🟦 = Team
🟥 = Individual and Team

Analyze data and find appropriate speed to run compressor										🟥	🟥	🟥				
Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Perform water injector characterization test											🟥	🟥				
Assemble subassemblies with ducting											🟥	🟥				
Perform cooling characterization test											🟥	🟥				
Finalize Assembly											🟥	🟥	🟥			
Prepare DR #4 Presentation											🟥					
Design Review #4 Presentation											🟦					
Test Prototype											🟦	🟦	🟦	🟦		

Reasses plan to cool and instead show heating through hair dryers												🟥	🟥	🟥		

Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Make adjustments to amount of cooling, compressor speed, and amount of water injected												🟥	🟥	🟥		
Analyze pros/cons of our system based on performance												🟥	🟥	🟥		
Redefine prototype targets												🟥	🟥	🟥		
Prepare Poster												🟥	🟥	🟥		

Presentation												🟥	🟥	🟥		
Material Selection Assigment												🟥	🟥	🟥		
Design Expo														🟦		
Prepare Final Report														🟦	🟦	
Ethics Assignment														🟩	🟩	
Submit Final Report															🟩	
Tasks	3-Mar	5-Mar	10-Mar	12-Mar	17-Mar	19-Mar	24-Mar	26-Mar	31-Mar	2-Apr	7-Apr	9-Apr	14-Apr	16-Apr	21-Apr	23-Apr
Submit Ethics Assignment															🟩	
Meet With Sponsor and Give Presentation															🟦	
Submit Peer Evaluations															🟦	
Deliver Prototype																🟩
Clean Area																🟩
Get Reimbursed																🟩