Project Proposal Feasibility Study

Team 04: Desiccated

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Executive Summary

Individuals and families spend much of their income on energy for heating and cooling of their homes. Extra energy is allocated towards laundering facilities, especially the clothes dryer. Considering the economic state of society as a whole, energy efficiency and savings are important and crucial to sustainability. Energy efficiency is a growing trend, for economic as well as sustainability reasons.

Team Desiccated’s goal is to make a heating, ventilation and air conditioning (HVAC) clothes dryer that uses the air from the home’s heating and cooling system to dry clothes, treats the air for humidity, and releases it back into the main circulatory system. Targeting the European market, this design will reduce a family’s annual energy consumption by an average of $240 as well as reduce their carbon footprint. Since HVAC systems are already in use, our design harnesses a home’s energy in these systems and uses it to eliminate another.
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1 Introduction

1.1 Background
Calvin College is a Christian Liberal Arts institution located in Grand Rapids, Michigan. It is an ABET accredited school that integrates Christian values and the Liberal Arts into engineering. Calvin’s program has a strong reputation for producing thoughtful and well-rounded engineers. As a capstone to the engineering program, students participate in a senior design class. This class is a yearlong project where the students get to work on a project of their interest and incorporate all that they have learned.

1.2 Team Members

1.2.1 Jon Wilgus
Jon was born in Painesville, Ohio before moving to Rochester Hills, Michigan. He graduated from Avondale High School in Auburn Hills Michigan. Jon is a senior mechanical engineering student. In addition to engineering at Calvin College he is also involved with the ROTC program at Western Michigan University. In his spare time he can be found at the gym or playing Xbox. Upon graduation he will be commissioned as a second lieutenant in the United States Army to serve as a Field Artillery officer.

1.2.2 Stephen Kraft
Stephen Kraft was born in Vienna, Virginia to Jim and Mary Jeane Kraft. He was homeschooled and attended Ivy Tech Community College in Ft. Wayne, Indiana during high school. Stephen has a passion for math, science, and athletics and in high school he was very involved on the swim team as a captain.

At Calvin, with his interest of math and science he chose to follow the path of mechanical engineering. He also continued his passion for swimming by joining the varsity swim team and receiving a MIAA award sophomore year. He studied abroad after his sophomore year in Germany during the summer of 2011 and is now a Senior Mechanical Engineer.

1.2.3 Drew Reyelts
Born and raised in Grand Rapids, Michigan, Drew attended Forest Hills Eastern High School, graduating Summa Cum Laude, in the top 4 in his class. Drew attends Hope College, and is currently a guest student at Calvin College, taking Senior Design to complete requirements for his Bachelor’s degree in Mechanical Engineering. While at Hope College, Drew played hockey and lacrosse, and is a member of the Fraternal Society (Omicron Kappa Epsilon). Drew works at Integrated Architecture as a Mechanical Engineering Intern, and hopes to continue in the HVAC industry after college. Drew is an avid outdoorsman, enjoying fishing, hiking, camping, rock climbing, snowboarding and whatever else comes his way. Drew also loves playing hockey, whether it is men’s league, pick-up games, or pond hockey.

1.2.4 Amanda Doyle
Amanda Doyle is graduating in May 2013 with a B.S.E, mechanical concentration, and physics minor. She currently works as a manufacturing engineer intern at Benteler Automotive and as a physics tutor for Calvin Academic Services. Along with engineering, she is the president of the Renewable Energy Organization (REO) at Calvin, and is quite involved with music both at her church and at Calvin. A trained vocalist, she sings with the Capella of Calvin College, works as a volunteer vocalist at her church, and has performed in concert tours to China, the Philippines,
Singapore, and Italy. In her spare time, Amanda enjoys singing, listening to music, running, and playing volleyball.

1.3 Problem Statement
The average family household spends roughly $220 a year on drying clothes (see section 9.4.1). Tumble clothes dryers use lots of electricity, which comes mainly from coal power plants. These power plants are adding large quantities of CO2 to the atmosphere. Our project seeks to find a reasonable alternative to the standard tumble dryer which is environmentally friendly, cost effective, and efficient.

2 Constraints

2.1 Requirements
The HVAC clothes dryer must completely dry the clothes while not damaging the clothes in any way. In order for it to be a reasonable alternative, it must use less electricity and cost less than a standard tumble dryer. The dryer must also not place any harmful products on the clothes or into the air in order that the design is safe for users. Our design must also be easily accessible for those with limited technical experience. We plan to design the interface for the dryer with the same complexity level as standard household appliances such as stoves, dishwashers, or tumble dryers.

2.2 Objectives
Our objective is to make our design a comparable alternative to the standard dryer in terms of dry time, load capabilities, and quality. Assuming that the average user does two loads of laundry at a time, the clothes dryer must be able to dry the clothes in a comparable time and be large enough to hold two loads worth of clothes. Without the extreme heat and tumble action of standard clothes dryers, our HVAC powered dryer will most likely take longer. However, our objective will be to minimize that time in order that our dryer will still be a reasonable replacement for traditional tumble dryers. Our clothes dryer should produce a product that is comparable to that of the standard dryer. If the clothes come out stiff, dusty, or with a bad odor, then our dryer will not be able to compete.

3 Design Norms

3.1 Stewardship
Stewardship of the planet our Creator gave us is at the heart of our project. It is our goal to design an alternative that is energy and cost efficient. As reformed Christians, creation, fall, and redemption are at the heart of everything we do, even in our design. We are called as Christians to be responsible stewards of God’s creation. Our dryer will lower energy usage and therefore lower energy production and carbon emissions. We are also called to be stewards in the traditional sense. God has entrusted each of us with money, which we are supposed to use responsibly. Our dryer will save people money, enabling users to be responsible stewards of their money.
3.2 Transparency
Our product will be transparent. We have worked through the project to ensure that the user is able to understand how to operate our dryer and how it works. We felt that an over complicated design would stifle the user. It was also our desire to be upfront and honest about all experimental results and assumptions.

3.3 Trust and Integrity
We want our user to be able to trust the product that we have designed. We want our users to know that their clothes will be dried to the same quality as a standard dryer so we have made many of our design decisions with integrity. We have used the design norm of integrity such that the form and function of our design will perform up to the standards we have set, and provide stated energy savings.

4 Project Management

All four members of this team are well versed in the technical work required to complete this project adequately and on time. Each member is responsible for his/her work individually and is expected to contribute his/her expertise in whatever area they can. Organization plays a big role in outcome of this project; several tools that we implemented were a detailed gantt chart, weekly meetings, and a detailed budget.

4.1 Meetings
We held regular meetings on Thursday afternoons and throughout the week, as deadlines required. Meetings consisted of discussing milestones accomplished and goals for the coming week. Every week the tasks that had been accomplished and the tasks that needed to be done were discussed in detail.

4.2 Schedule
We created a Work Breakdown Schedule (WBS) at the beginning of the semester with all of the foreseen tasks the project required. This was updated weekly to reflect the project’s status. Each task was broken down into small sub-tasks that were manageable in a short period of time. This allowed us to maintain a broad understanding of the schedule as a whole while the sub tasks allowed us to focus on individual tasks.

4.3 Budget
Our team was given a five hundred dollar budget for the project. If we had a need to go over the budget, we had to provide good reason for why we needed the product. As a result, we realized we needed to keep an updated document, which contained all of the purchases that had been made for the project. Whenever a product was ordered, our budget was updated and sent to our project advisor along with the product order form.

5 Method of Approach

5.1 Design
The design process for our project involved four steps: preliminary design, experimentation, redesign and prototyping. The first step of our project was to design an experimental unit which...
would help with our design process. The next step was to figure out what might be the biggest issues of the project by building an experimental unit. Our experimental unit consisted of what we thought our design might look like, but a lot of the minor details and aesthetics were not considered when building it. After we find out what our problems are, our plan is to redesign and make modifications, which will help fix those issues.

Lastly, when all of the new designs and modifications have been resolved the final design step will be initiated. When building the final product, it is inevitable that we will find small problems with our design so it will be crucial that we are careful when putting the final product together so that we can allow for problems to be fixed.

5.2 Team Communication
Weekly team meetings and emails are crucial in maintaining lines of communication between team members. Using Dropbox and the shared drive at Calvin College and Google Docs allowed for easy flow and modification of important documents between team members. All of this was in keeping with our desire to maintain transparency in our project, both among team members and our customers.

5.3 Library Research
Research was done for the project, primarily regarding the desiccant material that would be used for drying the air. It was necessary to do research on the desiccant because there are several materials on the market that are capable of drying the air. We wanted to ensure that we bought the right material on the first order such that we would not have to waste time and money ordering and testing different desiccant materials.

Research was also done with the aid of Mr. Glen Remelts of the Heckman Library, on similar pre-existing patents. However, we only found one patent on a similar product, which we did not find to be very helpful with our project.

5.3.1 Dying Textiles
In order to ensure that our project was feasible and that our method of approaching the project was a reasonable one, our team did research into drying methods and times of different fabrics. In the article “How to Dry Textiles without Over-Drying”\(^1\), different methods of drying textiles are explored in order to find the best way to dry clothes without damaging the materials. It is mentioned that two different kinds of energy, heat and airflow, are necessary to dry textiles. The heat is needed to evaporate the water in the textile, and the airflow is needed to remove the moisture from the textiles. It is stated that textiles contain moisture corresponding to the relative humidity in the air. For example, when the air temperature is 20 °C and the relative humidity is 50%, a given piece of textile will contain about 9% moisture in the fibers. The article says that in order to not damage the clothes, this moisture that is in the clothes should not be removed, or the fibers will become deformed. It is only the water surrounding the fibers that should be removed.

\(^{1}\) http://www.conservationphysics.org/wetstuff/wetstuff.pdf
This same article presents results from experiment performed on drying textiles. Three methods were used to dry a piece of cotton in this experiment: drying the clothes with a hot plate and fan, drying the clothes with a hot plate and without a fan, and drying the clothes on a cold plate with a fan.

Figure 5.3.1: Percent H2O with time

This graph shows that the fastest way to remove water from textile is with both heat and airflow. When the airflow is removed, the time for the textile dropped considerably. The dry time for the cool temperature with a fan was noticeably faster than the experiment with just the heat. This means that our design should still work in the summer when cool air is being supplied to the house as long as airflow is being provided for the drying process.

Another article, which talks about the drying time of different materials, is titled “Rate of Drying Fabric”\(^2\). This article explains that materials, specifically materials used in exercise clothes, get wet under circumstances like rain and sweating and that it is necessary to know the drying time of different materials in order that improvements can be made upon the materials in order to keep the user dry. Two different experiments were run in order to test the drying time of the different materials. The materials were dried on a line, as well as, dried in a simulated on-skin method. For the on-skin simulation the textile was placed near a hot plate which was kept at 35 °C. In the first table below the mean drying time for each of the different types of materials can be seen. Also seen below is the standard deviation (SD), minimum, and maximum drying time for each of the different fabrics. In the second table, each of the different fabrics is described in detail.

\(^2\) [http://trj.sagepub.com/content/21/1/26](http://trj.sagepub.com/content/21/1/26)
### Table 5.3.1.1: Drying time for different materials

"Determining Drying of Apparel Fabrics". Laing, Wilson, Gore, Carr, Niven. 2007

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Line Drying</th>
<th>Simulated On-skin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Time (m)</td>
<td>SD (m)</td>
</tr>
<tr>
<td>KSB</td>
<td>157</td>
<td>24.9</td>
</tr>
<tr>
<td>KSD</td>
<td>107</td>
<td>31.14</td>
</tr>
<tr>
<td>KRB</td>
<td>112</td>
<td>16.05</td>
</tr>
<tr>
<td>KIA</td>
<td>132</td>
<td>11.51</td>
</tr>
<tr>
<td>KPA</td>
<td>112</td>
<td>38.18</td>
</tr>
<tr>
<td>WPC</td>
<td>69</td>
<td>8.22</td>
</tr>
<tr>
<td>WWA</td>
<td>21</td>
<td>5.48</td>
</tr>
<tr>
<td>WWC</td>
<td>153</td>
<td>52.87</td>
</tr>
<tr>
<td>NPA</td>
<td>154</td>
<td>42.34</td>
</tr>
<tr>
<td>NWA</td>
<td>240</td>
<td>123.29</td>
</tr>
<tr>
<td>NWB</td>
<td>184</td>
<td>71.27</td>
</tr>
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### Table 5.3.1.2: Fabric Description Chart

The chart below describes the fabrics in Table 5.3.1.1

"Determining Drying of Apparel Fabrics". Laing, Wilson, Gore, Carr, Niven. 2007

<table>
<thead>
<tr>
<th>Fabric Code</th>
<th>Structure</th>
<th>Fiber Content (%)</th>
<th>Yarns/Stitches per 10 mm</th>
<th>Mass per Unit Area (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSB</td>
<td>knit single jersey</td>
<td>100 m.wool</td>
<td>11x10</td>
<td>1.18</td>
</tr>
<tr>
<td>KSD</td>
<td>knit single jersey</td>
<td>100 m.wool</td>
<td>16x51</td>
<td>0.8</td>
</tr>
<tr>
<td>KRB</td>
<td>knit 1 x 1 rib</td>
<td>100 m.wool</td>
<td>11x91</td>
<td>0.91</td>
</tr>
<tr>
<td>KIA</td>
<td>knit interlock</td>
<td>100 m.wool</td>
<td>15x16</td>
<td>1.15</td>
</tr>
<tr>
<td>KPA</td>
<td>knit eyelet, 2 layers</td>
<td>62/38 m.wool/polyester</td>
<td>3x2</td>
<td>1.53</td>
</tr>
<tr>
<td>WPC</td>
<td>woven 3/1 twill</td>
<td>65/35 polyester/cotton</td>
<td>46x23</td>
<td>0.44</td>
</tr>
<tr>
<td>WWA</td>
<td>woven plain</td>
<td>100 wool</td>
<td>27x23</td>
<td>0.34</td>
</tr>
<tr>
<td>WWB</td>
<td>woven plain</td>
<td>100 wool</td>
<td>na, raised</td>
<td>1.67</td>
</tr>
<tr>
<td>NPA</td>
<td>knit laminated double layer</td>
<td>95/5 polyester/polyurethane</td>
<td>na, raised</td>
<td>3.29</td>
</tr>
<tr>
<td>NWA</td>
<td>n-woven</td>
<td>100 wool</td>
<td>na, raised</td>
<td>4.64</td>
</tr>
<tr>
<td>NWB</td>
<td>n-woven</td>
<td>100 wool</td>
<td>2.94</td>
<td>296</td>
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</table>
These different drying times, in the tables below, from the experiments mentioned in the article “Determining Drying Time of Apparel Fabrics” will help us compare the drying time from our design to other methods.

5.4 Industrial Consultation

To help with our design process our team met with a chemical engineer, Randy Elenbaas, in order make sure our design was feasible and to make sure we were on track to have a complete design at the end of the semester and a finished product at the end of the year.

In our meeting we talked about several experiments and ideas that would help our project. The first was putting together a block flow diagram to model the flow of air and moisture through the system (see appendix E). This was to help us visualize what heating and cooling requirements needed to dry the clothes. It will also help determine where to install the desiccant.

Next, we considered an experiment that would help us determine how much water we would have to remove to dry the clothes. He suggested weighing the clothes after they came out of the washing machine then again after they come out of the dryer. This experiment would give us the mass of water we would have to remove in an average load of laundry and allow us to start on some basic calculations on drying time for our model.

We also talked about many of the factors we would have to consider if we were to put a desiccant into the system. One of the things we would have to consider is where the desiccant filter would be located in the system. Another consideration would be how much desiccant would be needed and what kind of desiccant would be needed. We would also have to consider whether the desiccant would be dried in the system itself or in an oven outside of the system.

In this meeting we also discussed whether a lint trap would be necessary for the dryer. We decided that it would not be necessary since the clothes are not being tumbled and are not being dried at extreme heats. The lint trap would also cause a large pressure drop, which would slow down the drying time for our clothes.

Lastly, our industrial consultant encouraged us to put costs together for building the unit. We also discussed that our main competition will be standard dryers and that we needed to know how they compare to the cost of a standard dryer. He suggested that our target market would be homes built in the last twenty years, where the ventilation system already includes return air. He also noted that our market would be fully developed countries because less developed countries don’t have central air in the average home.

6 Design Evaluation

6.1 Desiccant

In order to dry the clothes as fast as possible it is helpful that the air entering the dryer has as little moisture as possible. In order to achieve this goal we investigated the idea of using a desiccant.
6.1.1 **Silica Gel**
When doing our research we first found a blue indicating silica gel that is a naturally occurring mineral silicon dioxide that is purified and processed into smooth beaded form. These beads are saturated with a moisture indicating solution that gives them a deep blue color when dry, but then changes color when the silica gel has absorbed all the moisture it can hold. The pores of this desiccant have a diameter 20 to 30 Å, which is ideal for absorbing moisture in the air. This desiccant works best in conditions from 70-90°F and 60-90% relative humidity and has the ability to absorb up to 20% of its weight. In order for this product to be reused this product needs to be regenerated by placing in an oven at high temperatures for approximately an hour.³

6.1.2 **Molecular Sieve**
A molecular sieve is made with the same idea as a silica gel. The molecular sieve claims to be the most effective option for removing water from liquids and gases and can get the job done with more pure results than silica gel and activated alumina. When a gas or liquid is passed through, the sieve absorbs the smaller molecules while larger molecules pass through. Since water has very small molecules, the water is caught and retained in the pores of the sieve. This desiccant can hold approximately 22% of its weight in water; however, it needs to be regenerated by heating it to temperatures between 130°C to 250°C.⁴

We determined that this desiccant is good for eliminating moisture on a smaller scale in the air such that air with an already relatively low moisture level, would have very small water content after passing through the sieve. Due to the fact that our needs for a desiccant call for a larger scale of water absorption we decided that this desiccant would not be the best choice. Also, the desiccant would need to be regenerated often due to the fact that it cannot hold much water and is meant for smaller scale water removal.

6.1.3 **Activated Alumina**
Activated alumina works to absorb moisture because it is a highly porous form of aluminum oxide. This desiccant was the least expensive of the three considered and seemed to be the most effective as it could absorb up to 35% of its weight and could be restored. This desiccant is very good at retaining its form in any condition, which means that it could still absorb a lot of water in the conditions that we needed it to. It can also be regenerated by heating to any temperature from 350° to 600°F.⁵

This desiccant comes with many different pore and bead sizes. The best pore size for our project would be 13 Å. This size is normally recommended for vapor phase dehydration applications where pressure drop minimization is required but high absorption is needed.⁶ Also to help with pressure drop we decided that the largest bead size, one-quarter inch, was needed so that we could decrease the pressure drop over the desiccant cylinder.

6.1.4 Decision
We have decided that the desiccant would not be feasible for our design because the goal of our design is to provide the user with a more energy efficient way of drying clothes. If the user will have to use an external source of energy in order to dry the desiccant, this takes away from the efficiency of the system and makes the design infeasible.

The activated alumina was used in an experiment, which can be seen in section 8.2 below. This experiment showed us that there is a significant pressure drop when the filter is added to the system. This pressure drop decreased the airflow and dry time significantly such that we have decided that the desiccant filter would not be feasible in our design.

After running tests without desiccant, we saw dry times around 30 min. Since the dryer works without it, there is no reason to inconvenience the user with desiccant. See section 8 for more experimental results.

6.2 Ergun Equation
The Ergun equation will help our team decide whether or not the desiccant bed is going to help our drying time decrease or whether the bed is going to slow down the airflow and therefore the drying time. The equation calculates the pressure drop over a porous material using area of the porous material, velocity of the input airflow, and porosity of the material. The equation to determine the pressure difference over the bed can be seen below:

\[
\frac{\Delta P}{L} = \frac{150\mu(1 - \varepsilon)^2\mu_0}{\varepsilon^3 d^2_p} + \frac{1.75(1 - \varepsilon)\rho\mu_0^2}{\varepsilon^3 d_p}
\]

where:

- \(\Delta P\) = pressure drop
- \(L\) = length of the bed
- \(\mu\) = the fluid viscosity
- \(\varepsilon\) = void space of the bed
- \(\mu_0\) = superficial velocity
- \(d_p\) = particle diameter
- \(\rho\) = fluid density

For this equation it was assumed that the void space of the bed was 0.45 due to recommendation by the team advisor. The length of the bed of desiccant was assumed to be approximately 0.05 m according to a preliminary design, and the density of the input air at a temperature at 54 °C was used. The diameter of the particle used was the diameter of the desiccant ordered for testing which was ¼ inch. The pressure difference for the experimental unit was calculated to be approximately 3.3 kPa or 0.5 psi. This pressure drop causes a dramatic decrease in airflow.

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7http://faculty.washington.edu/finlayso/Fluidized_Bed/FBR_Fluid_Mech/packed_beds_scroll.htm
through the chamber where the clothes are being dried. This means that there will be fewer air changes and less water removed from the system and clothes per unit of time.

6.3 Weather Conditions

6.3.1 Summer

In the summer the air outside is hot and humid. This problem is typically solved in buildings with air conditioning units which use a condenser to cool the air and pull out water. This cool dry air is then circulated throughout the house to provide a comfortable living environment. For this situation, conditioned air at 55°F with a relative humidity of 50%\(^8\) will be pulled through the clothes drying apparatus, taking water out of the clothes, and will exit and be re-routed back to the central air system for retreatment.

6.3.2 Winter

In the winter the air outside is cold and dry. This problem is solved by heating the air in a furnace then circulating this hot dry air throughout the house. The hot air comes from the furnace at a temperature of 130°F and a relative humidity of 40%. The dryness of the air is a typically accepted problem although many home furnaces have a built in humidifier which helps to alleviate the problem. This hot dry air is perfect for drying clothes.

6.3.3 Spring/Autumn

During the spring and autumn seasons, air at temperatures and relative humidity in between the outside conditions of summer and winter are treated and circulated through the house. Usually this treatment is a humidification (autumn) or a dehumidification (spring). This air would be pulled into the HVAC clothes dryer with an average temperature of 70°F and a comfortable relative humidity of 40%, drying the clothes, and then put back into the central air system for retreatment.

6.4 Clothes Condition

6.4.1 Odor

One potential problem is a bad odor developing in the clothes. If there is an odor in the air circulating through the house’s HVAC system then this odor could be transferred to the clothes as they dry. As seen in the Lithuanian design described in section 7.1.1 below, if the clothes take too long to dry they could start to develop an odor as a result of mildew which could occur in the rest of the house. However, after running experiments we found that an odor does not develop in the clothes. For more information see section 8.

6.4.2 Stiffness

Another potential problem is the stiffness/fluffiness of the clothes. One of the main advantages of a tumble dryer is that the clothes come out soft and fluffy, ideal for blankets, soft sheets and warm sweatshirts. However when something is hung out to dry, the clothes can end up hard and stiff. Hard and stiff clothes are undesirable; however, it may be a trade off the customer is willing to make. After running experiments we found that clothes came out slightly more stiff and wrinkly than a tumble dryer. However we feel that added stiffness and wrinkles are expectable tradeoffs for the energy savings.

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\(^8\)http://inspectapedia.com/aircond/aircond09.htm
7 System Architecture

7.1 Different Designs

7.1.1 Lithuanian Design
The idea for this project was based off an existing HVAC clothes dryer that Jon Wilgus used during his trip to Lithuania at the Lithuanian Military Academy. Lithuania, a poor former Soviet state, buys much of its natural gas and fossil fuels from Russia. As a result Lithuania has a vested interest in alternative energy and energy efficient projects as a matter of their national security. It featured a large metal cabinet in which clothes were hung. An air duct above it brought in treated air before it was returned to the system. The system was very basic and needed improvements. Among the problems with the Lithuanian design were the long dry times and stiff clothes with bad odors.

7.1.1.1 Problems with the Lithuanian Design
The clothes took about two days to dry. When they did dry the odor was terrible and were very stiff. This could have been because there was not a fan to force the air through the drying cabinet. The cabinet just used the flow that was already flowing through the HVAC system. This air had a relatively low speed. With few air changes the clothes could not dry quickly, allowing for bacteria to grow and for the clothes to become significantly stiffer than when clothes came out of a tumble dryer.

7.1.2 Original Concept
The original concept was going to use a metal office storage cabinet. A duct would bring in air from the top and that air would be pushed downwards by a fan. The treated air from the AC/furnace would then flow over the clothes before being returned to the duct system of the home. During the spring and fall, when the air is not being treated as it would be in the winter and summer, the air would still follow the original concept and bring the air from the HVAC system into the drying unit. The original design tapped into an air duct itself.

7.1.3 Design Modifications
We have made several improvements to the original design. First, we decided to place the fan on the outside of the apparatus, giving us more space for clothing. Our next decision was to decide if the fan should blow air through the box or pull air through. We chose to pull air through the box to maintain even, laminar airflow. With the fan pulling air, we know exactly how much air will be drawn through the apparatus. To push air through, backflows from pressure differentials are possible. Also, the furnace is pushing air into our apparatus, and adding a fan in the same place would be redundant. Placing the fan near the bottom of our box ensures air is drawn through from top, where the air enters, to the bottom of the box where it exists.

We also decided that it would be best to reroute the air instead of tapping into the ducts. This was done in order to get the full airflow, instead of just part of it.

7.1.4 Experimental Unit
Design choices for the experimental unit were based on time, availability of materials, and available prefabricated components. The body of the dryer was found from pervious projects as was the fan. Since the fan had two air intakes, we utilized both to make full use of the fan’s potential. As a result we were able to pull air more evenly though the air cavity. For the air
outtake we used ribbed plastic tube. The ribs cause a minor head loss, however they allowed the tubes to be bent easily in a 180° loop. Using smooth aluminum or PVC ducts with elbows would eliminate the minor head losses. To reduce pressure drop, we built the hood to smoothly narrow the wide opening at the top of the box down to the size of our ducts. The hood also acted to expand the airflow for an even flow distribution. Air in the supply duct has a high velocity flow. When the air exists the duct and enters the hood, velocity decreases because there is now a greater area for the same amount of air. With this velocity drop, the pressure of the air also decreases. This pressure reduction allows the air to be evenly distributed across the box’s cross sectional area, resulting in even air distribution for the box. We fabricated the hood and the ducts out of Aluminum because it is the industry standard for air ducts used in applications where there is a potential condensation or other forms of moisture. This is because aluminum is much more resistant to rust than stainless steel. Aluminum is also lighter in weight than other metals, and is more convenient for homeowners to move. To save time and preserve the furnace and duct work at our test site, we decided not to return the air into the HVAC system in the house. For a dimensioned drawing see Appendix E.

![Image](image.png)

Fig 7.1.4: The figure above is a scale model of the experimental unit modeled in Autodesk Inventor. This model was used to aid in the building process and for graphical communication.

### 7.1.5 Final Prototype

The final design will incorporate all the lessons learned from the experimental unit. The dryer will need to be large enough to hold one to two loads of laundry. The drying cavity will roughly be 4 feet wide, 3 feet deep and 5 feet tall. Inside will be rails for hanging clothes and a grate for smaller articles like socks. The entire system will be aluminum or painted steel to prevent rust. Air will be pulled though the cavity using a fan. Routing all the air though the apparatus will be impractical so we are only taking a portion of the air coming from the furnace. As a result we will have to tap into the duct instead. The final design will feature a single air intake through the top with a hood to encourage airflow expansion. The air will be sucked out through two outtake...
ducts and returned to the air ducts to be dispersed throughout the house giving off a fresh laundry smell.

7.1.5.1 Final Prototype Size

For the final design our team decided to size the chamber such that the user would be able to hang and/or place two loads of laundry in the chamber at a time. The dimensions of the chamber for the final design are 3 feet deep, 4 feet wide and 6 feet tall. The design of the chamber needed to be 3 feet deep in order that the chamber would be able to comfortably hold clothes on a hanger. The chamber needed to be 4 feet wide in order that the amount of clothes equivalent to two tumble dryer loads could be hung in the chamber. It was also necessary for the chamber to be 6 feet tall in order that the user would be able to dry sheets or comforters up to 10 feet long by hanging them over the rack inside of the chamber which is 1 foot underneath the roof of the chamber.

The total area in our chamber totals to 72 ft$^3$, which is much larger than a standard dryer. The average tumble dryer is approximately 9.8 ft$^3$ with a 2.5 ft diameter and is 2 ft deep. The design of our chamber needs to be much larger due to the fact that the clothes are hanging in the chamber as opposed to being tumbled in a machine.

7.1.5.2 The Hood

Air in the supply duct has a high velocity. When the air exists the duct and enters the hood, velocity decreases because there is now a greater area for the same amount of air. With this velocity drop, the pressure of the air also decreases. This pressure reduction allows the air to be evenly distributed across the box’s cross sectional area, resulting in even air distribution for the box.

7.1.5.3 Routing Air

All of the air from the HVAC will not be pulled into the dryer because this would be impractical. The fan on the dryer will only pull a fraction of the air from the HVAC system such that the dryer gets the air that it needs to dry the clothes, and the house is still getting enough air in order to keep the house at its normal conditions. If the dryer were to pull all of the air from the HVAC system, the house would cease to receive the air conditioning or heating it needed to stay at the desired conditions.

7.1.5.4 Fan

Our fan, donated by Marshall and Wells Co, is a 10” centrifugal duct fan rated at 589 CFM. This is a standard exhaust fan used in the HVAC industry, priced at $225. Bill VanDyken, our contact at Marshall and Wells Co., was able to donate this fan because it is a commonly fan sold, and there were extras in the Grand Rapids warehouse that were not already sold, so it was available for us to have.

With a variable speed controller, we are able to dial down the air flow as desired. We wanted a fan that would provide adequate air changes to dry our clothes in the project dry time of 2 hours (for 2 loads of laundry that will fit into our drying apparatus). With our final design, with a volume of 72 cubic feet, this exhaust fan will give 490 air changes per hour: 589 ft$^3$/ min*60 min/hr / 72 ft$^3$ = 490 air changes per hour.
7.2 Process
Air is initially heated by the furnace burner, and is discharged upwards through a humidifier. Here the hot dry air absorbs moisture so that the supply air to the home is not dry and uncomfortable. This also cuts down on static electricity in the home.

Next, a small fraction of the supply air (SA) is drawn from the main supply duct. This air will be our supply for drying clothes. The air enters our drying chamber through an air hood which helps distribute the air such that the velocity of the air in the chamber is the same.

The hot supply air passes through our drying chamber, where it absorbs moisture from the wet clothing and heats the clothing to stimulate evaporation. Some moisture from the clothing will drip to the bottom of the chamber, where it is drained and taken outside of the house, but most moisture is carried out of the chamber by the hot air.

The air is drawn through the ductwork and the drying chamber by an exhaust fan, located outside the chamber. The air passing through the fan is both cooler and wetter than the supply air entering the chamber. This slightly cooler, wetter air is then pushed through more ductwork back into the main supply duct for the house, where it mixes with the supply air from the furnace and is distributed throughout the home through the ductwork.

Overall, the supply air for the home experiences negligible effects from diverting a small fraction of its supply air through our drying apparatus and back into the main supply duct.

This same process of winter is the same for summer, fall, and spring conditions, except that the air coming from the furnace is cooler and drier than the air from the winter conditions. This air will still go through the process of being pulled into the ductwork, through an air plenum, and into the drying chamber. The air will still dry the clothes since the summer, fall, and spring air conditions have drier air coming from the furnace and this air can therefore hold more water. The air then leaves the drying chamber as cool, passes through the fan, and is pushed back into the supply air from the furnace where it is distributed into the house.

8 Testing

8.1 Process Experiments
To design a well-suited drying apparatus, we needed to determine certain variables that would impact the efficiency of our design. First, we needed to obtain airflows going into and coming out of our unit. The airflow determines the air changes over a given period of time, which is the number of times the volume of our dryer is completely replaced by fresh air. The higher the air speed, the greater the airflow, and thus the more air changes per hour. The more air changes per hour, the faster our clothes would dry. The next set of variables we needed to obtain were air temperature and humidity, so we could determine the effectiveness of the air to absorb moisture from the clothes, through psychrometrics. The warmer and dryer the air, the faster clothes will dry. Ultimately, our goal was to establish accurate data as to how long it would take our clothes to dry given these variables. Through these values, we can extrapolate accurate data for a full sized drying apparatus, focusing on maintaining the number of air changes because the other variables, temperature and humidity, are constants.
8.2 Water in Laundry
It is important to know the amount of water that must be removed from the laundry. This water is either added to humidity in the air drained by gravity. To determine the amount of water in the laundry we weighed laundry before and after drying. The wet laundry is weighed after a spin cycle in the washing machine and the dry laundry is weighed after being removed from a tumble dryer. Data that was taken yielded that laundry holds approximately half its weight in water. For example, 8 lbs of laundry holds 4 lbs of water. The data gathered is shown below in Table 1. Further measurements need to be taken for more accuracy.

Table 8.2: Water in Laundry

<table>
<thead>
<tr>
<th>Load</th>
<th>Before Wash</th>
<th>After Wash</th>
<th>After dry</th>
<th>Water</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.9</td>
<td>22.4</td>
<td>14.8</td>
<td>7.6</td>
<td>51%</td>
</tr>
<tr>
<td>2</td>
<td>16.8</td>
<td>24.6</td>
<td>16.8</td>
<td>7.8</td>
<td>46%</td>
</tr>
</tbody>
</table>

The ratio column is the ratio the weight before drying to after drying. All numbers except the ratios are given in pounds. The average and standard deviation are also given.

8.3 Experimental Unit
8.3.1 Purpose
We have anticipated many problems with our design project. The purpose of this experiment was to answer several of the questions, which we thought might be a problem. This experiment is also the first part of our design process and helped us figure out what challenges we have to overcome.

One of the problems that we thought might be issues before we ran tests on the experimental unit include wet air coming out of the dryer. This would be a problem due to the fact that this wet air could leave behind water in the ducts, which could cause sweating of the ducts. This would cause the ducts to leak water and make the system unacceptable.

A buildup of lint could pose a potential fire hazard. All conventional clothes dryers have a filter, which collects lint from the clothes over time. Our main possible problem with the lint is that it would possibly cause a large pressure drop, reducing the number of air changes and therefore increasing drying time.

We also speculate that the clothes will come out of the dryer stiff and with an unpleasant odor. The design that was seen in Lithuania had a dry time of a couple days and caused the clothes to come out with a strong odor and stiff complexion. If the clothes come out stiff when the user wishes her clothes to be soft then our dryer does not provide a realistic alternative to a traditional tumble dryer. On the same hand if the clothes smell bad then this will be an unacceptable alternative.

We also want to get a good idea of the time that it would take for the clothes to dry. Being that this is the key constraint of our design we wanted to make sure that we based our design
decisions on how long the clothes dried. If the dryer takes too long then this design is no longer feasible.

We know that the air coming out of the dryer will have more moisture than the incoming air. What we don’t know is how much more and if that moisture is a problem. In winter months, air tends to be drier, so additional moisture could be beneficial. In summer months, extremely moist air is undesirable. During springtime and autumn, the moisture in the air usually varies more than it does during the summer and the winter. Ultimately, a range of 25%-60% relative humidity is comfortable for the home and everyone who lives in it, and so it is important to maintain a somewhat constant humidity.  

We would also like to get some base numbers for calculations. We need to know how long it will take to dry sample load of laundry. If the time frame is too long, the clothes may develop an odor. If a washing machine takes about 30min, and the averages user has two loads then the dryer should either be able to dry clothes in 30min or have the capacity for two loads. Increasing or decreasing the flow rates will have an effect on dry time but by how much?

8.3.2 Procedure
Experiments were conducted in a real home. We used the home of one of our group members, Drew Reyelts. Clothes were hung in the drying chamber. With an anemometer, Figure 2, we planned to measure the flow rates of the air, temperature, and humidity of the air.

![Anemometer](image)

Figure 8.3.2: Anemometer used to measure properties at inlet and outlet of dryer.

8.3.3 Anemometer Problems
The anemometer we used to conduct our experiments had a defective humidity sensor, so the data we collected was 99% relative humidity. This would make the air fully saturated, and is obviously incorrect. It has been sent back to the manufacturer to be replaced. Because we could not get accurate relative humidity readings, we based our calculations on 40% RH, which is the [9 http://www.buildingscience.com/documents/reports/rr-0203-relative-humidity](http://www.buildingscience.com/documents/reports/rr-0203-relative-humidity)
humidity setting of the furnace. Although this Rh value may be incorrect, it gives us much more practical data than using the 99% Rh value from the broken anemometer.

8.3.4 Results

Using the anemometer, we were able to obtain air speeds. The air speed entering our drying system was 11.7 m/s. This air speed delivers 254 cubic feet per minute (CFM) of air through a 4.5” diameter duct. The volume of our drying box is 5.2 cubic feet, and 254 CFM of air yields approximately 2937 air changes per hour.

With 2937 air changes per hour, the sample clothes that were dried—a pair of socks, 2 cotton shirts, and a hand towel—were sufficiently dry in 40 minutes. The quality of the dry was comparable to clothes dried on a clothes line which are favorable results.

We ran numerous experiments with our clothes dryer, using different garment types and amounts of water weight. We found that as long as the clothes fit inside the drying apparatus (without bunching at the bottom) the clothes dry in approximately 30 minutes.

We were expecting that the more clothes (and thus the more water needed to be taken out) we put in, the longer it would take the clothes to dry. However, our findings indicate that if it fits, it dries (in 30 min). These are great results, which leads us to believe that our design in is fact feasible on a larger scale. The key variable in our process is the amount of airflow. If we maintain a consistent airflow to volume ratio in a larger model, clothes should also dry in 30 minutes.

Another important variable is that the clothes cannot be bunched up. Pants tended to dry completely where they were fully vertical in our drying apparatus, but where they bunched at the bottom did not dry very well. This is an important finding that we need to incorporate into our full size design, so that we can have large garments, such as pants, towels, and even bed sheets be able to hang freely in our apparatus so that there is not bunching. From running experiments we found that the main focus of our design needs to be sizing for the clothes to fit without bunching not mass of clothes. If the clothes are bunched the air will not be able to flow over them and it will take much longer for the clothes to dry.

Another question we wanted to answer was the rate at which the clothes dried; do the clothes dry quicker in the early stages of the drying process and slower towards the end? We ran two tests to answer this question. The first test used 1.38 lbs of water weight in a pair of jeans, a heavy cotton long sleaved shirt, and a pair of sweat pants. Our second test consisted of 0.44 lbs of water in a pair of wool socks, a polyester t-shirt, two pairs of boxers, and a fleece jacket. These results are shown below in Figure 8.3.4. For experimental data see appendix F.
The clothing dried quickest in both loads in the first 5 minutes of the drying process, and slowed as time progressed. Test 1 was unable to remove all the water because the clothes were too large for our experimental unit, and bunched at the bottom, where water was not removed fully.

8.4 Desiccant Testing

8.4.1 Purpose
Because the relative humidity of the supply air from the furnace was very high, we thought of using a desiccant material to remove some of this moisture, so the air was dryer when it reached the wet clothes, thus increasing its effectiveness. The purpose for this experiment was to determine the absorptive capacity of the desiccant.

8.4.2 Desiccant Testing
The first desiccant that we thought about using was calcium chloride. Calcium chloride came in small particle sizes so it would require a fine mesh to retain. The main problem with the calcium was that when it became saturated it turned into a liquid. This is unacceptable within our dryer.

We decided to use ¼” diameter activated alumina pellets as our desiccant material with a mesh within a 4” diameter PVC pipe to create a desiccant filter. We connected our desiccant filter in-line with our vertical supply air duct, located directly above our drying box.

A significant problem with activated aluminum is that prolonged exposure can cause skin irritation and it is harmful to breathe in. Considering that it would dry the air intake, some of the activated aluminum could get on the clothes and cause skin irritation. Then as this now contaminated air is circulated through the house the user would be breathing it in. Using activated aluminum goes against our design norms.
8.4.3 Results
Although the desiccant was able to absorb some moisture from the supply air, the desiccant filter with all of its components created a significant pressure drop in our air flow. The filter reduced our air changes per hour from 3055 to 368. The pressure drop the filter created was also too much for our exhaust fan to handle, greatly reducing its effectiveness. This large decrease in airflow increased the dry time of the clothes. Because of this, we decided as a group to remove the desiccant filter and dry the clothes at full airflow, but with no humidity reduction. The idea of using a desiccant is currently being abandoned, however, may be revisited at a later point.

![Air Changes](image)

Figure 8.4.3: The drop in air changes based on desiccant and filter use compared to no obstruction in the duct

8.5 Theoretical Simulations
There were three (3) simulations: a summer case, winter case, and a spring/autumn case. Each simulation involved calculations of mass flow rates, the temperature of the air coming out of the dryer, wet bulb temperature, incoming air velocity, and the absolute humidity of the air flowing in and out of the dryer; the calculations were carried out using the computer program Engineering Equation Solver (EES). The results of these simulations are listed in Table 8.5.2.2 as well as later in this chapter. Fig. 8.5 shows the control volume used for analyzing this system:
8.5.1 Assumptions

Several assumptions were made in order to simplify the calculations. The first assumption was that drying the clothes is a steady state process; this means that the rate of drying does not change with respect to time or dampness of the clothes. We know from research and experiments on drying (5.2.1), this process is not constant with respect to time.

Another assumption made was that air is incompressible. This makes the calculations simpler by allowing the pressure of the air flowing out of the dryer to be equal to the pressure of the air coming in.

The third assumption made was that all of the water would be removed from the clothes. This may not seem like a pressing issue, but after talking to both Professors Ned Nielsen and Aubrey Sykes, it was determined that if all of the moisture is removed from clothes, they become dry and stiff. This can happen when clothes are line-dried instead of tumble-dried, and for simulation simplicity, we modeled the clothes as losing all of the moisture gained from the washing machine. This was assumed to be 8 pounds of water from two medium-sized loads of 16 pounds of clothes. The assumption came from experimental results shown in Table 8.2.

The fourth and final assumption made about the system as a whole is that “perfect” evaporation is taking place inside the dryer. That is, the wet bulb temperature of the air stays the same throughout the evaporation process, making it possible to correlate on a psychometrics chart (Appendix E) to find the outgoing dry bulb temperature.

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10 Source: http://housekeeping.about.com/od/laundry/f/fullload.htm
### 8.5.2 Summer, Winter, and Spring/Autumn Condition Calculations

The following inputs were used for each case:

Table 8.5.2.1: The inputs for the conditions of the air as well as the amount of water leaving the system in the exit stream

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Area [ft²]</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>T drybulb in [°F]</td>
<td>130</td>
<td>100</td>
<td>55</td>
</tr>
<tr>
<td>Pressure [psia]</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
</tr>
<tr>
<td>Relative humidity in [-]</td>
<td>0.40</td>
<td>0.40</td>
<td>0.15</td>
</tr>
<tr>
<td>Relative humidity out [-]</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>m_dot_water [lb/s]</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>Time [s]</td>
<td>5400</td>
<td>5400</td>
<td>5400</td>
</tr>
</tbody>
</table>

The pressure was assumed to be atmospheric pressure, and the relative humidity of the air going in and coming out were specified so that the incoming air was relatively dry and the outgoing air was mostly saturated, but not fully saturated so as to avoid condensation on the ductwork. The same amount of water must be removed from the clothing regardless of the season, and this mass flow rate was found by dividing the amount of water that must be removed from the clothes by the time specified in our problem statement (that is, the clothes must be dried in 1.5 hours).

From these inputs, the wet bulb temperature of the air was found as a function of the dry bulb temperature, the pressure, and the relative humidity of the air. The absolute humidity of the air was found as a function of wet bulb and dry bulb temperatures, and the pressure. Then, using the input of the mass flow rate of the water coming out of the system, a mass balance was carried out on the control volume (see Fig. 8.5):\[ \dot{m}_{air,in} + \dot{m}_{water} = \dot{m}_{air,out} \] Eqn (8.5.2.1)

Then, the difference of the absolute humidity from the two state points was used in conjunction with Eqn. (8.5.2.1), yielding: \[ \omega_{out} - \omega_{in} = \Delta \omega = \dot{m}_{air,out} - \dot{m}_{air,in} \] Eqn (8.5.2.2)

Once the absolute humidity of the exiting air was found, the dry bulb temperature was found at statepoint 2 as a function of the wet bulb temperature, pressure, and absolute humidity.

The outputs are shown in the table below:
Table 8.5.2.2: The outputs of the condition of the air coming out of the dryer as well as the absolute humidity of the air coming in

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density [lb/ft^3]</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>T wetbulb [F]</td>
<td>103</td>
<td>79</td>
<td>39</td>
</tr>
<tr>
<td>T drybulb out [F]</td>
<td>109</td>
<td>84</td>
<td>41</td>
</tr>
<tr>
<td>Absolute humidity in [-]</td>
<td>0.040</td>
<td>0.017</td>
<td>0.001</td>
</tr>
<tr>
<td>Absolute humidity out [-]</td>
<td>0.045</td>
<td>0.020</td>
<td>0.004</td>
</tr>
<tr>
<td>m_dot_in [lb/s]</td>
<td>0.2861</td>
<td>0.3954</td>
<td>0.4881</td>
</tr>
<tr>
<td>m_dot_out [lb/s]</td>
<td>0.2876</td>
<td>0.3969</td>
<td>0.4896</td>
</tr>
<tr>
<td>Air velocity in [ft/s]</td>
<td>48.6</td>
<td>63.7</td>
<td>72.4</td>
</tr>
</tbody>
</table>

The air velocities were calculated so as to give us a better idea of what kind of fan system this clothes dryer needs to support these drying results. The supporting calculations done in EES can be found in Appendix E.

8.5.3 Summer Case Oddity
An interesting result came from the summer case; even though the air coming in was cool and dry, the air coming out of the dryer was yet cooler. After talking to Drs. Matthew Heun, Aubrey Sykes, and Wayne Wentzheimer, we came to the conclusion that the effect of the evaporation process was greater than the heat exchange of the clothes with the flowing air (which are at the house’s ambient temperature when they first enter the dryer).

8.5.4 Conclusions
According to the values obtained in Table 8.5.2.2, drying the specified two loads of laundry in 1.5 hours is feasible regardless of the season. All of those velocities are obtainable with the fan systems we currently have, and fans we have deemed as compatible with this apparatus. During the summer, there is less electrical input from the fan to pull air through the apparatus to meet the demands that we’ve put on the system. During the winter, we need the most electrical input into the fan. This makes sense realistically because in the winter, cool and dry air is flowing through the system from the air conditioner. Evaporation uses energy, and there is less energy available from cold air as there is from hot air.

9 Business Plan

9.1 Marketing Strategy
9.1.1 Target Market
We are planning on targeting our market towards European countries, because they do not often use tumble dryers due to higher energy costs. Also, we are more likely to be able to sell our product to people who have HVAC systems in their homes, who have the money to buy our product, and who wish to be environmentally conscious with their clothes washing/drying.

Key countries to target, and the percentage of homes with central heating, are Austria (92%), Belgium (83%), Czech Republic (82%), Denmark (98%), Finland (92%), France (93%), Germany (92%), Italy (95%), Lithuania (74%), Luxembourg (73%), Netherlands (94%), Poland (78%), Slovakia (79%), Sweden (100%), the United Kingdom (94%)

(79%), and Turkey (100%)\textsuperscript{12}. These countries have a high potential for our product to be used in homes because HVAC are in place and can easily be converted to use our clothes dryer.

One more important point is that there are similar products on the market in Europe, that are called "drying cabinets." These units do not use HVAC but offer better energy savings than traditional tumble dryers, which is why there is a market for them. Our design will be more energy efficient than these “drying cabinets” because we will be using conditioned air (heating in winter, and dehumidified in summer) from the home’s HVAC system, as opposed to the drying cabinet’s need for supplemental heat and air.

9.1.2 Customer’s Motivational Factors
With the energy crisis looming, more of the European population is becoming aware of the need to conserve energy and to “green” already existing processes. By lowering the amount of energy input for a household, a household also saves money on energy consumption. After asking some family members, friends, and environmentally-minded acquaintances, the significant motivational factors are:

9.1.2.1 Giving customer high quality
Even though the clothes are not heated or moved around with electrical energy, the customer still deserves the same quality of dry clothes as one would obtain with a household tumble dryer while receiving the benefits of a smaller energy input.

9.1.2.2 Energy cost savings
It takes extra energy to run a clothes dryer. If a household can go without using that extra energy, it ends up saving money on energy consumption in the long run.

9.1.3 Market Size and Trends
9.1.3.1 How large is the market?
Since the awareness of the energy crisis is spreading in North America, people are looking for more ways to cut down energy consumption. Other appliances such as dishwashers, refrigerators, furnaces, and clothes washers are being made so that they are an “ENERGY STAR Qualified” product and consumers are buying them in an attempt to save money via tax credits and exemptions. The HVAC clothes dryer will be able to follow this trend of energy efficiency and interest the same customers who own at least one (1) other “green” appliance or those who are thinking of owning a “green” appliance.

9.1.3.2 Market Growth
There are a few companies, such as GE, that sell “ENERGY STAR Qualified” appliances, but none of these companies sell anything similar to the HVAC clothes dryer. Because of the state of the economy, people will be looking for more ways to save money, and decreasing energy consumption is one way of doing this. Since the targeted customers are already familiar with “green” technology, the demand for the HVAC clothes dryer is most likely to increase; hence, the targeted market is growing.

9.1.4 Advertisement and Promotion
The main medium of advertisement depends on the targeted customers. This section describes the different advertisement mediums that will be used as well as promotional materials.

\textsuperscript{12} http://www.environ.ie/en/Publications/DevelopmentandHousing/Housing/FileDownload,2453,en.pdf
9.1.4.1 Media to be used
Both offline and online advertisement media will be used. Online advertisement will be the main medium because of the smaller upfront cost, as well as less paper being used in the process (saving energy in the advertisement process).

9.1.4.1.1 Online Promotion
Website: Most of the maturing population knows how to look subjects up on the internet. A website for the company will be put up in order to reach a large number of potential customers, and to be available as information to others who are just browsing or interested.

9.1.4.1.2 Offline Promotion
Brochures: The brochures would mainly be advertisement for the HVAC clothes dryer (and any other device the company would develop along the way). An updated brochure would be distributed annually, noting any changes and improvements with the clothes dryer including: design changes, functionality, and cost.

9.1.4.2 Frequency of Usage
Since the main advertisement for the company is going to be through the website, the website will be kept up regularly. Magazines will be used monthly and brochures will be distributed annually (as mentioned before).

9.2 Business Strategy
9.2.1 Desired Image and Position in the Market
We would like to stand out in the dryer market throughout service and product reliability. We want our product to have quick and easy installment and very low maintenance requirements. We also hope to create a positive public image of our company by providing quality service and a green money saving product.

9.2.2 Company Goals and Objectives
9.2.2.1 Operational
We believe that because the product we are providing to our customers is energy efficient, we as a company, should also be energy and time efficient. Time efficiency will consisted of hiring employees and training them to quickly assemble and install our products. Energy efficiency will consist of order large quantities of supplies at a time to cut down on shipping costs and reduce fuel usage to haul our material to our warehouse. We will assemble products here so that there are no secondary shipment in between raw materials coming in and a final product going out to the consumer.

9.2.2.2 Financial
The same principle can be applied to our financial objectives. We hope to be efficient with our money and also aim to only purchase what our company needs. We will allocate the money in order to prosper and grow instead of buying unnecessary machinery or human resources.

9.3 Competitor Analysis
9.3.1 Existing Competitors
Our major competitors are Whirlpool, Maytag, LG, GE and Haeir. Maytag was bought by Whirlpool and is now their subsidiary. LG is a corporation based out of Korea that deals in electronics, appliances, amongst other things. Haeir is a Chinese appliance company based out of Qingdao, China.
9.3.1.1 **Strengths**
The strengths of our competitors are their size. They all are well established and can make use of economies of scale. They are also diversified with a wide range of products from refrigerators to furnaces. Our competitors are also well established already; they have the entire necessary infrastructure and have worked through all the ‘kinks’ of starting and maintaining a large company.

9.3.1.2 **Weaknesses**
Our competitor’s weaknesses are their inflexibility and inability to adapt to the changing market. They are unwilling or unable to be innovative with new products and ideas. The only driving forces for change are Energy Star requirements, whereas we will exceed all federal energy regulations. Commitment to energy efficiency is our priority, unlike large companies that create products that just meet these energy requirements. We are able to think past the traditional methods and look into the future with new ideas. Our lack of infrastructure allows us to rethink the traditional and encourage ingenuity.

9.3.2 **Potential Competitors**
Once our product is on the market it will attract the attention of those already existing in the industry. If we start to attract too much attention and take up too much of the market share we can expect our competitors to react. They will either try to buy us out and shut us down or copy our product and introduce it to their production line. If they start to produce our clothes dryer before we can perfect our system, they will potentially be able to manufacture, market, and distribute our product better than we could. Therefore developing a solid, lean manufacturing, advertising, and distribution process is vital to our business’s early and continuing success.

9.4 **Cost Estimates**
The cost to run a clothes dryer, even a high efficiency (HE) dryer, is one of the greatest energy expenses for a family. With a HE gas dryer, if a family dries a single hour’s load of laundry a day, it will cost them about $117 per year to run. If a family has a HE electric dryer, and doing the same volume of laundry, it will cost about $335 a year. These calculations were based on the prices of electricity and natural gas in Lithuania, a choice country in Eastern Europe. The prices were given in Euros, and those were converted using Google’s currency conversion calculator.

Our HVAC clothes dryer will greatly reduce energy costs. The only extra energy that our design uses, that is not already being used in the home, is to power the exhaust fan. For our full sized prototype, the fan has a 1/5 hp motor. This fan will cost $15.76 annually to run for one hour a day. The results of the cost analyses are shown in the table below:

---

13 [http://www.energy.eu/#Domestic-Gas](http://www.energy.eu/#Domestic-Gas)
9.4.1 Cost of Production

To fabricate our 6’x4’x3’ drying apparatus and 20’ of ductwork, the cost of sheet metal is approximately $150, and the exhaust fan costs approximately $200. This yields a total of $350 for raw materials. Labor costs are estimated to be 5 hours at $20/hr, totaling $100 per unit. To produce one unit, it will cost $450 for materials and labor.

10 Conclusion

After performing theoretical calculations, conducting research, and running tests on our experimental unit, team 04 has determined that the apparatus does dry the clothes in a timely manner in the winter. Through our theoretical calculations we believe that this dryer will also dry clothes in the fall, spring, and summer seasons as well. This drying process also saves on energy costs for a household by decreasing the energy consumption. Therefore, we believe that this dryer is a feasible design. By the end of the spring semester, team 04 will have the final design of the dryer complete and will have performed tests on the dryer in all of the different seasonal conditions to ensure that our theoretical calculations match with data gathered from those tests. Through this project, we hope to create an energy efficient alternative to tumble clothes dryers for the customers who wish to save money on energy consumption as well as help stabilize the environment. We believe that this HVAC clothes dryer will have a positive impact not only on

Table 2: Energy Cost Savings

<table>
<thead>
<tr>
<th>Electricity Cost [$/kWh]</th>
<th>Unit</th>
<th>Energy Use [kW]</th>
<th>Yearly Use [hrs]</th>
<th>Annual Unit Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>Fan</td>
<td>0.254</td>
<td>365</td>
<td>15.7607</td>
</tr>
</tbody>
</table>

High Efficiency Tumble Dryer (Gas)

<table>
<thead>
<tr>
<th>Gas Cost [$/kWh]</th>
<th>Unit</th>
<th>Energy Use [kW]</th>
<th>Yearly Use [hrs]</th>
<th>Annual Unit Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>Dryer</td>
<td>6.45</td>
<td>365</td>
<td>117.7125</td>
</tr>
</tbody>
</table>

High Efficiency Tumble Dryer (Electric)

<table>
<thead>
<tr>
<th>Electricity Cost [$/kWh]</th>
<th>Unit</th>
<th>Energy Use [kW]</th>
<th>Yearly Use [hrs]</th>
<th>Annual Unit Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>Dryer</td>
<td>5.4</td>
<td>365</td>
<td>335.07</td>
</tr>
</tbody>
</table>
the users and the environment, but also to future generations who will inherit the world that we live in.
11 Acknowledgements

Dr. Wayne Wertheimer
Professor Wentzheimer was the faculty adviser for Team 04: Desiccated. Weekly advising meeting with Professor Wentzheimer guided and directed Team 04 to explore new ideas and feasibility guidance. Team 04 gained valuable knowledge and greatly appreciates his time and efforts over the Fall ’12 semester.

Randy Elenbaas
Randy Elenbass is a process engineer for Vertellus, operating out of Zeeland, MI. He was the industrial consultant for Team 04. He assisted Team 04 with several design issues, including desiccant materials, lint collection, and total water removal. With his help in these areas, Team 04 was able to accomplish several key design criterion for their experimental model.

Ned Nielsen
Professor Nielsen is a professor at Calvin and has been very instrumental in our project. He helped with critiquing the PPFS as well as provided advice from a mechanical point of view. Professor Nielsen also has experience in the clothes dryer and marketing industry so his advice was very valuable.

Matthew Heun
Professor Heun helped our project in a very critical manner. He assisted the team along with Professor Wentzheimer with the theoretical simulations especially with the psychrometric analysis.

Marshall & Wells Co.
Team 04 received a donation of an exhaust fan and speed control from Marshall & Wells Co. in Grand Rapids, MI. Team 04 would like to thanks Bill VanDyken, sales associate at Marshall & Wells Co., for coordinating this donation with Team 04.
12 Appendices

Appendix A: Bibliography
Appendix B: Industrial Consultant
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Appendix D: Pressure Drop Calculations
Appendix E: Sketches of Potential Designs
Appendix F: Experimental Data
Appendix G: Gantt Chart
Appendix A: Bibliography


Appendix B: Industrial Consultant Brief

Team 4: Desiccated

Project Description:
HVAC clothes dryer; our project is designing and building a clothes drying system that uses heated air from a home’s ducts to heat clothes, eliminating (or worst case, reducing) a family’s need for a standard tumble dryer, which uses a lot of energy. We hope to help the user reduce energy costs and offer a more environmentally conscious way to do laundry.

Design Criteria:
- Effectively dry an average of one load per hour (if this time is unachievable we would like to increase our load size to compensate for the time difference)
- Effectively dry clothes that are not stiff when dry cycle is complete
- Provide easy installation/use and low maintenance
- Offer an inexpensive clothes drying product that delivers a noticeable drop in energy bill
- Work in summer (air-conditioning), spring/fall (intermittent heat/ac), and winter (furnace on consistently)
- Effectively remove moisture and desiccant that lasts through several months of use

Current Status:
We are building an experimental model (not full size) to run tests to determine air flow, temperature, dry time, humidity, and the quality of the drying cycle on the clothes. We will use this information to calculate appropriate modifications needed for a full-scale prototype.

Foreseen Challenges:
- Ability to convert between heat and cooling to dry clothes effectively: lack of instrumentation devices
- Effectiveness of desiccant to remove humidity
- Reducing stiffness of clothes due to lack of movement during the drying cycle
- Obtaining accurate measurements on air flow, temperature, pressure drops, humidity levels
- Ease and effectiveness of collecting lint easy and effectively
- Applying model to full scale and not having enough fan power to dry lots of clothes
- Too much static pressure that overworks our exhaust fan and does not effectively dry clothes in an appropriate amount of time
Appendix C: EES Calculations

"(1) With no filter"
\[ V = 11.7 \text{ convert(m/s, ft/min)} \]
\[ D = 4.5 \text{ [in]} \]
\[ A = \pi(4/1)^2 \text{ convert(m}^2, \text{ ft}^2 \text{)} \]
\[ CFM = V/A \]
\[ V_{cone} = 1794.709 \text{ convert(m}^3, \text{ ft}^3 \text{)} \]
\[ V_{box} = 22.5[\text{in}^3]*10.5[\text{in}]*16.375[\text{in}] \text{ convert(m}^3, \text{ ft}^3 \text{)} \]
\[ V_{total} = V_{cone} + V_{box} \]
\[ \text{AirChange}\_\text{hour} = \frac{\text{CFM} \times V_{total}}{\text{convert(1/min, 1/hr)}} \]

"(2) Smaller diameter duct with a filter"
\[ V = 11.7 \text{ convert(m/s, ft/min)} \]
\[ D = 3 [\text{in]} \]
\[ A = \pi(3/2)^2 \text{ convert(m}^2, \text{ ft}^2 \text{)} \]
\[ CFM = V/A \]
\[ \text{AirChange}\_\text{hour} = \frac{\text{CFM} \times V_{total}}{\text{convert(1/min, 1/hr)}} \]

"Same diameter duct as #2, with a filter, with a layer of dissipation"
\[ V = 3.3 \text{ convert(m/s, ft/min)} \]
\[ CFM = V \times A \]
\[ \text{AirChange}\_\text{hour} = \frac{\text{CFM} \times V_{total}}{\text{convert(1/min, 1/hr)}} \]

"Furnace Out: Air In"
\[ V_{furnace\_on} = 7.9 \text{ convert(m/s, ft/s)} \]
\[ CFM_{furnace\_on} = A \times V_{furnace\_on} \text{ convert(m}^3/s, \text{ ft}^3/min) \]

"Speed of the air coming out of the experimental unit"
\[ V_{out} = 7.9 \text{ convert(m/s, ft/min)} \]
\[ A_{out} = 3.5 [\text{in}^2] \text{ convert(m}^2, \text{ ft}^2 \text{)} \]
\[ CFM_{out} = 2 \times A_{out} \times V_{out} \]
\[ AC_{out} = \frac{\text{CFM}_{out} \times V_{total}}{\text{convert(1/min, 1/hr)}} \]

Unit Settings: SI C kPa kJ mass deg

\[ A = 0.1104 \text{ [ft}^2\text{]} \]
\[ AC_{out} = 3055 \text{ [l/sec]} \]
\[ \text{AirChange}\_\text{hour}\_2 = 1305 \text{ [1/hr]} \]
\[ A_{out} = 0.08507 \text{ [ft}^2\text{]} \]
\[ CFM_{out} = 254.3 \text{ [l/sec]} \]
\[ D = 3 \text{ [in]} \]
\[ DF_{out} = 136.4 \text{ [ft}^3\text{/min]} \]
\[ V = 2303 \text{ [l/sec]} \]
\[ V_{furnace\_on} = 19.63 \text{ [l/sec]} \]
\[ V_{out} = 1555 \text{ [l/sec]} \]

No unit problems were detected.
Ergun Equation

\[ L = 0.05 \text{ m} \]

\[ \mu = 0.00002075 \text{ kg/m}^s \]

\[ \varepsilon = 0.45 \]

velocity = 19.69 [ft/s]

\[ \mu_0 = \text{velocity} \cdot \begin{vmatrix} 0.3048 \cdot \text{m/s} \\ \text{ft/s} \end{vmatrix} \]

\[ d = 0.25 \text{ in} \cdot \begin{vmatrix} 0.0254 \cdot \text{m} \\ \text{in} \end{vmatrix} \]

\[ \rho = 1.109 \text{ kg/m}^3 \]

\[ \frac{dP}{L} = \frac{150 \mu \left(1 - \varepsilon\right)^2 \mu_0}{\varepsilon^3 \cdot d^2} + \frac{1.75 \rho \mu_0^2}{\varepsilon^3 \cdot d} \]

\[ \Delta P_1 = dP \cdot \begin{vmatrix} 0.000145038 \cdot \text{psi} \\ \text{Pa} \end{vmatrix} \]

SOLUTION

Unit Settings: SI C kPa kJ mass deg

\[ d = 0.00635 \text{ m} \]
\[ c = 0.45 \]
\[ \mu_0 = 6.002 \text{ m/s} \]

\[ \lambda P = 3399 \text{ Pa} \]
\[ \lambda = 1.109 \text{ kg/m}^3 \]

No unit problems were detected.
Theoretical Simulations

Winter Conditions

Assume SS for all calculations

\[ \text{Area}_{\text{duct}} = 12.8 \cdot 0.00944444 \cdot \frac{\text{ft}^2}{\text{in}^2} \]

\[ \rho_{\text{air, winter}} = \rho \left[ \text{Air}^0, T = T_{\text{in, winter}}, P = P_1 \right] \]

\[ T_{\text{in, winter}} = 130 \ [\text{F}] \]

\[ T_{\text{wet, in, winter}} = \text{WB} \left[ \text{AirH}_2\text{O}^0, T = T_{\text{in, winter}}, R = \text{rh}_{\text{in, winter}}, P = P_1 \right] \]

\[ \text{rh}_{\text{in, winter}} = 0.4 \]

\[ P_1 = 14.7 \ [\text{psia}] \]

\[ \omega_{\text{in, winter}} = \omega \left[ \text{AirH}_2\text{O}^0, T = T_{\text{in, winter}}, B = T_{\text{wet, in, winter}}, P = P_1 \right] \]

\[ P_2 = P_1 \]

\[ T_{\text{wet, out, winter}} = T_{\text{wet, in, winter}} \]

\[ \text{rh}_{\text{out, winter}} = 0.8 \]

\[ \omega_{\text{out, winter}} = \omega \left[ \text{AirH}_2\text{O}^0, T = T_{\text{out, winter}}, B = T_{\text{wet, out, winter}}, P = P_2 \right] \]

About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer

\[ m_{\text{water, winter}} = \frac{8}{\text{time}} \ [\text{lb}] \]

\[ m_{\text{in, winter}} + m_{\text{water, winter}} = m_{\text{out, winter}} \]

\[ \omega_{\text{out, winter}} = \frac{m_{\text{water, winter}}}{m_{\text{in, winter}}} \]

Psychrometric chart

\[ T_{\text{out, winter}} = T \left[ \text{AirH}_2\text{O}^0, R = \text{rh}_{\text{out, winter}}, B = T_{\text{wet, out, winter}}, P = P_1 \right] \]

Summer Conditions

\[ \rho_{\text{air, summer}} = \rho \left[ \text{Air}^0, T = T_{\text{in, summer}}, P = P_1 \right] \]

\[ T_{\text{in, summer}} = 55 \ [\text{F}] \]

35
$$T_{\text{wet,summer}} = \text{WB} \left[ \text{AirH2O} \ , \ T = T_{\text{in,summer}} \ , \ R = \text{rh}_{\text{in,summer}} \ , \ P = P_1 \right]$$

$$\text{rh}_{\text{in,summer}} = 0.15$$

$$\omega_{\text{in,summer}} = \omega \left[ \text{AirH2O} \ , \ T = T_{\text{in,summer}} \ , \ B = T_{\text{wet,summer}} \ , \ P = P_1 \right]$$

$$T_{\text{wet, out, summer}} = T_{\text{wet, in, summer}}$$

$$\text{rh}_{\text{out, summer}} = 0.8$$

$$\omega_{\text{out, summer}} = \omega \left[ \text{AirH2O} \ , \ T = T_{\text{out, summer}} \ , \ B = T_{\text{wet, out, summer}} \ , \ P = P_2 \right]$$

*About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer*

$$\dot{m}_{\text{water, summer}} = \frac{8 \ [\text{lb}]}{\text{time}}$$

$$\dot{m}_{\text{in, summer}} + \dot{m}_{\text{water, summer}} = \dot{m}_{\text{out, summer}}$$

$$\omega_{\text{out, summer}} - \omega_{\text{in, summer}} = \frac{\dot{m}_{\text{water, summer}}}{\dot{m}_{\text{in, summer}}}$$

*Psychrometric chart*

$$T_{\text{out, summer}} = T \left[ \text{AirH2O} \ , \ R = \text{rh}_{\text{out, summer}} \ , \ B = T_{\text{wet, out, summer}} \ , \ P = P_1 \right]$$

*Spring/Fall Conditions*

$$\omega_{\text{air, sf}} = \omega \left[ \text{Air} \ , \ T = T_{\text{in, sf}} \ , \ P = P_1 \right]$$

$$T_{\text{in, sf}} = 100 \ [\text{F}] \quad \text{This is temp of furnace}$$

$$T_{\text{wet, in, sf}} = \text{WB} \left[ \text{AirH2O} \ , \ T = T_{\text{in, sf}} \ , \ R = \text{rh}_{\text{in, sf}} \ , \ P = P_1 \right]$$

$$\text{rh}_{\text{in, sf}} = 0.4$$

$$\omega_{\text{in, sf}} = \omega \left[ \text{AirH2O} \ , \ T = T_{\text{in, sf}} \ , \ B = T_{\text{wet, in, sf}} \ , \ P = P_1 \right]$$

$$T_{\text{wet, out, sf}} = T_{\text{wet, in, sf}}$$

$$\text{rh}_{\text{out, sf}} = 0.8$$

$$\omega_{\text{out, sf}} = \omega \left[ \text{AirH2O} \ , \ T = T_{\text{out, sf}} \ , \ B = T_{\text{wet, out, sf}} \ , \ P = P_2 \right]$$
About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer.

\[ m_{\text{water sf}} = \frac{8}{\text{time}} \text{ [lb]} \]

\[ m_{\text{in, sf}} + m_{\text{water, sf}} = m_{\text{out, sf}} \]

\[ \psi_{\text{out, sf}} - \psi_{\text{in, sf}} = \frac{m_{\text{water, sf}}}{m_{\text{in, sf}}} \]

**Psychrometric chart**

\[ T_{\text{out, sf}} = T \left[ '\text{Air} + \text{H}_2\text{O}' \right], R = m_{\text{out, sf}}, B = T_{\text{water, sf}}, P = P_1 \]

**Time that clothes must be dried in**

\[ \text{time} = 1.5 \times 3600 \text{ s/hour} \]

\[ \Delta \psi_{\text{winter}} = \psi_{\text{out, winter}} - \psi_{\text{in, winter}} \]

\[ \Delta \psi_{\text{summer}} = \psi_{\text{out, summer}} - \psi_{\text{in, summer}} \]

\[ \Delta \psi_{\text{sf}} = \psi_{\text{out, sf}} - \psi_{\text{in, sf}} \]

\[ m_{\text{in, winter}} = \text{vel}_{\text{in, winter}} \cdot \rho_{\text{air, winter}} \cdot \text{Area}_{\text{duct}} \]

\[ m_{\text{in, summer}} = \text{vel}_{\text{in, summer}} \cdot \rho_{\text{air, summer}} \cdot \text{Area}_{\text{duct}} \]

\[ m_{\text{in, sf}} = \text{vel}_{\text{in, sf}} \cdot \rho_{\text{air, sf}} \cdot \text{Area}_{\text{duct}} \]
SOLUTION

Unit Settings: Eng F psia mass dag
Area duct = 0.0875 [ft²]

Δ summer = 0.003035
m_in, summer = 0.3954 [lb/s]
m_out, summer = 0.2861 [lb/s]

m_in, winter = 0.4881 [lb/s]
m_out, winter = 0.2875 [lb/s]

m_water, summer = 0.001481 [lb/s]

m_water, winter = 0.001481 [lb/s]

Δ winter = 0.005177

in, summer = 0.001362

out, sf = 0.02026

out, winter = 0.04527

ρ_air, summer = 0.07711 [lb/ft³]

ρ_in, sf = 0.4

ρ_out, summer = 0.8

time = 5400 [s]

T_in, summer = 55 [F]

T_out, sf = 84.1 [F]

T_out, winter = 102.2 [F]

T_wat, in, summer = 88.92 [F]

T_wat, out, sf = 78.98 [F]

T_wat, out, winter = 102.7 [F]

vel_in, summer = 72.36 [ft/s]

vel_in, winter = 48.6 [ft/s]

No unit problems were detected.

Arrays Table: Main

<table>
<thead>
<tr>
<th>P_i [psia]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
Appendix D: Pressure Drop Calculations

Table E: Duct Designer Pressure Drop Calculations

<table>
<thead>
<tr>
<th>Unit</th>
<th>Length (ft)</th>
<th>in w.c / 100 ft</th>
<th>CFM</th>
<th>Press. Drop (in w.c.)</th>
<th>Unit</th>
<th>Length (ft)</th>
<th>in w.c / 100 ft</th>
<th>CFM</th>
<th>Press. Drop (in w.c.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5&quot; duct</td>
<td>3</td>
<td>1.979</td>
<td>255</td>
<td>0.059</td>
<td>4.5&quot; duct</td>
<td>3</td>
<td>1.979</td>
<td>255</td>
<td>0.059</td>
</tr>
<tr>
<td>90 Elbow</td>
<td>--</td>
<td>--</td>
<td>255</td>
<td>0.052</td>
<td>90 Elbow</td>
<td>--</td>
<td>--</td>
<td>255</td>
<td>0.052</td>
</tr>
<tr>
<td>4.5&quot; duct</td>
<td>3</td>
<td>1.979</td>
<td>255</td>
<td>0.059</td>
<td>4.5&quot; duct</td>
<td>3</td>
<td>1.979</td>
<td>255</td>
<td>0.059</td>
</tr>
<tr>
<td>Cone</td>
<td>1.5</td>
<td>--</td>
<td>255</td>
<td>0.128</td>
<td>Cone</td>
<td>1.5</td>
<td>--</td>
<td>255</td>
<td>0.128</td>
</tr>
<tr>
<td>Dryer Box</td>
<td>1.625</td>
<td>0.005</td>
<td>255</td>
<td>0.000</td>
<td>Dryer Box</td>
<td>1.625</td>
<td>0.500</td>
<td>255</td>
<td>0.008</td>
</tr>
<tr>
<td>4.5&quot; duct</td>
<td>2</td>
<td>0.550</td>
<td>128</td>
<td>0.011</td>
<td>4.5&quot; duct</td>
<td>2</td>
<td>0.550</td>
<td>128</td>
<td>0.011</td>
</tr>
<tr>
<td>4&quot; flex 180 elbow</td>
<td>--</td>
<td>--</td>
<td>128</td>
<td>1.200</td>
<td>4&quot; flex 180 elbow</td>
<td>--</td>
<td>--</td>
<td>128</td>
<td>1.2</td>
</tr>
<tr>
<td>Fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fan</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td></td>
<td></td>
<td>1.510</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>1.518</td>
</tr>
</tbody>
</table>

This analysis shows that there is not a significant pressure drops throughout our system with no desiccant filter, which allows us to expect good performance from our exhaust fan. At 1.51 in wc of static pressure, our fan in our experimental unit should perform at approximately 250 CFM. Using our air flow meter, our fan was able to draw approximately 254 CFM of air through our system. This data from our device confirms our static pressure calculations.
Figure E: Fan curve for experimental unit fan
Appendix E: Figures and Drawings

*Experimental Unit*

Figure F1: The figure above is a drawing of the experimental unit.
Fig F2: The figure above is a drawing of the final design.
Figure F3: The figure above is a block flow of how the air will flow
Figure F4. The figure above is a psychrometric chart.
Appendix F: Experimental Data

Dry Time Trials

Trial 1:
Wet Weight: 1.5 lbs
Dry Weight: 1 lb
Water weight: .5 lbs

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Dry Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boxers</td>
<td>25 min</td>
</tr>
<tr>
<td>Sweater</td>
<td>25 min</td>
</tr>
<tr>
<td>T-shirt</td>
<td>25 min</td>
</tr>
</tbody>
</table>

Trial 2:
Wet weight: 3 lbs
Dry Weight: 2.5 lbs
Water weight: .5 lb

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Dry Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dress Shirt</td>
<td>30</td>
</tr>
<tr>
<td>Sweat pants</td>
<td>30</td>
</tr>
<tr>
<td>Pair socks</td>
<td>45</td>
</tr>
<tr>
<td>Athletic shorts</td>
<td>30</td>
</tr>
<tr>
<td>T-shirt</td>
<td>30</td>
</tr>
</tbody>
</table>

Trial 3:
Wet weight: 5.2 lbs
Dry weight: 3.5 lbs
Water weight: 1.7 lbs

<table>
<thead>
<tr>
<th>Clothes</th>
<th>Dry time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dress pants</td>
<td>35</td>
</tr>
<tr>
<td>Hand Towel</td>
<td>35 *stiff</td>
</tr>
<tr>
<td>Boxers</td>
<td>35</td>
</tr>
<tr>
<td>Fleece</td>
<td>35</td>
</tr>
</tbody>
</table>

Trial 4
Wet weight: 4.7 lbs
Dry: 4.2 lbs
Water: .5 lbs

<table>
<thead>
<tr>
<th>Clothes</th>
<th>Dry time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dress pants 1</td>
<td>30</td>
</tr>
<tr>
<td>Dress pants 2</td>
<td>30</td>
</tr>
<tr>
<td>Socks Pair 1</td>
<td>20</td>
</tr>
<tr>
<td>Socks Pair 2</td>
<td>30</td>
</tr>
<tr>
<td>Socks Pair 3</td>
<td>30</td>
</tr>
<tr>
<td>Wind breaker pants</td>
<td>20</td>
</tr>
</tbody>
</table>
## Water Weight vs Dry Time

### Test 1

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Water Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.375</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0.9374</td>
</tr>
<tr>
<td>15</td>
<td>0.75</td>
</tr>
<tr>
<td>20</td>
<td>0.6875</td>
</tr>
<tr>
<td>25</td>
<td>0.5625</td>
</tr>
<tr>
<td>30</td>
<td>0.375</td>
</tr>
<tr>
<td>40</td>
<td>0.375</td>
</tr>
</tbody>
</table>

### Test 2

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Water Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4375</td>
</tr>
<tr>
<td>5</td>
<td>0.3125</td>
</tr>
<tr>
<td>10</td>
<td>0.125</td>
</tr>
<tr>
<td>15</td>
<td>0.0625</td>
</tr>
<tr>
<td>20</td>
<td>0.0625</td>
</tr>
</tbody>
</table>
Appendix G: Gantt Chart