Final Design Report

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 clothes dryer that attaches to a heating, ventilation and air conditioning (HVAC) system and uses the air from that system to dry clothes. Targeting the Eastern European market, this design will reduce a family’s annual energy consumption by an average of €265 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 decrease total energy consumption.

The result of our design work is a product which dries clothes in a reasonable time compared to a tumble dryer. The results for different seasons and load sizes can be seen in the table below.

Drying Times

<table>
<thead>
<tr>
<th>Season</th>
<th>Theory</th>
<th>Test (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>Summer</td>
<td>58</td>
<td>-</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>65</td>
<td>74</td>
</tr>
</tbody>
</table>

Also important to the practicality of our project is the cost and pay back periods for the dryer which can also be seen in the tables below.

Material and Market Cost

<table>
<thead>
<tr>
<th></th>
<th>Cost of Fan</th>
<th>Cost of Sheet Metal</th>
<th>Cost of Duct Work</th>
<th>Labor Cost</th>
<th>Total Manufacturing Costs</th>
<th>Market Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€ 200</td>
<td>€ 150</td>
<td>€ 40</td>
<td>€ 60</td>
<td>€ 450</td>
<td>€ 675</td>
</tr>
<tr>
<td></td>
<td>$260</td>
<td>$200</td>
<td>$50</td>
<td>$80</td>
<td>$590</td>
<td>$885</td>
</tr>
</tbody>
</table>

Savings with Payback Periods

<table>
<thead>
<tr>
<th></th>
<th>Replacement</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous Dryer</td>
<td>HVAC</td>
<td>Drying Cabinet</td>
<td></td>
</tr>
<tr>
<td>Electric Tumble Dryer</td>
<td>2.5</td>
<td>Never</td>
<td></td>
</tr>
<tr>
<td>Gas Tumble Dryer</td>
<td>12.80</td>
<td>Never</td>
<td></td>
</tr>
</tbody>
</table>
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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 a member 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 as both a chorister and soloist in concert
tours to China, the Philippines, Singapore, and Italy. In her spare time, Amanda enjoys singing, listening to music, running, and playing volleyball.

2 Constraints

2.1 Problem Definition
The average family household spends roughly $190 a year on drying clothes (see section 8.4.1). Tumble clothes dryers use lots of electricity and gas, 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.

2.2 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 usable for those with limited technical experience. We planned to design the interface for the dryer with the less complexity level as standard household appliances such as stoves, dishwashers, or tumble dryers.

2.3 Objectives
Our objective is to make our design a comparable alternative to the standard dryer in terms of dry time, load capabilities, and quality of fabric (see section 7.1.2.1). 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 time objective was to dry the clothes in about one hour per load, which is similar to that of a tumble dryer. Another goal for our clothes dryer was to produce a dried product that is comparable to that of the standard dryer. If the clothes came out stiff, dusty, or with a bad odor, then our dryer would 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 drying source 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 decisions. 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
We made several design decisions to make our design transparent. We have worked through the project to ensure that the user would be 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 Method of Approach

4.1 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 determine 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. We built the experimental unit using materials that we found in the engineering building. The unit was built big enough that it would be appropriate for drying a few garments of clothes but not big enough that the building would take too long. See section 6.1.5 for exact dimensions of the experimental unit. After we found out what our problems were, our plan was to redesign and make modifications that would help fix those issues.

Lastly, when all of the new designs and modifications had been resolved the final design step was initiated. When building the final product, it was inevitable that we would find small problems with our design so it was crucial that we were careful when putting the final product together so that we could allow for problems to be fixed.

4.2 Library Research
Research was done for the project, primarily regarding the desiccant material that could 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. The results of this research can be seen in section 5.3.1.

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.

4.2.1 Dying Textiles
In order to ensure that our project was feasible and that our method of approaching the project was reasonable, our team did research into drying methods and times of different fabrics. In the
article “How to Dry Textile without Over-Drying”\textsuperscript{1}, different methods of drying textiles are explored in order to find the best way to dry clothes without damaging the materials. 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. 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. In order to not damage the clothes, this moisture that is in the clothes should not be removed, or the fibers will become deformed. Only the water surrounding the fibers should be removed.

This 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.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Percent H2O with Time}
\end{figure}

This figure shows that the fastest way to remove water from textile is with both heat and airflow. When the airflow is removed, the drying time for the textile increased 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 ambient air is being supplied to the house as long as airflow is being provided for the drying process.

Another article, which addresses the drying time of different materials, is “Rate of Drying Fabric”\textsuperscript{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

\begin{flushleft}
\textsuperscript{1} \url{http://www.conservationphysics.org/wetstuff/wetstuff.pdf}
\textsuperscript{2} \url{http://trj.sagepub.com/content/21/1/26}
\end{flushleft}
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 and 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 are 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.

Table 1: Fabric Description Chart

<table>
<thead>
<tr>
<th>Fabric Code</th>
<th>Structure</th>
<th>Fiber Content (%)</th>
<th>Yarns/stitches per 10 mm</th>
<th>thickness</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>
<td>267</td>
</tr>
<tr>
<td>KSD</td>
<td>knit single jersey</td>
<td>100 m. wool</td>
<td>16x51</td>
<td>0.8</td>
<td>197</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>
<td>172</td>
</tr>
<tr>
<td>KIA</td>
<td>knit interlock</td>
<td>100 m. wool</td>
<td>15x16</td>
<td>1.15</td>
<td>231</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>
<td>296</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>
<td>187</td>
</tr>
<tr>
<td>WWA</td>
<td>woven plain</td>
<td>100 wool</td>
<td>27x23</td>
<td>0.34</td>
<td>128</td>
</tr>
<tr>
<td>WWC</td>
<td>woven plain</td>
<td>100 wool</td>
<td>na, raised</td>
<td>1.67</td>
<td>350</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>
<td>402</td>
</tr>
<tr>
<td>NWA</td>
<td>n-woven</td>
<td>100 wool</td>
<td>na, raised</td>
<td>4.64</td>
<td>275</td>
</tr>
<tr>
<td>NWB</td>
<td>n-woven</td>
<td>100 wool</td>
<td>na, raised</td>
<td>2.94</td>
<td>296</td>
</tr>
</tbody>
</table>

3 “Determining Drying of Apparel Fabrics”. Laing, Wilson, Gore, Carr, Niven. 2007
Table 2: Drying Time for Different Materials

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Line Drying</th>
<th>Simulated On-skin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Time</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>
</tbody>
</table>

These different drying times, in the tables above, 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 Design Evaluation

5.1 Weather Conditions

5.1.1 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% 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. We were aware that many homes in Eastern Europe may not have air conditioning, and we address this situation in section 7.5.5.

4 “Determining Drying of Apparel Fabrics”. Laing, Wilson, Gore, Carr, Niven. 2007
5 http://inspectapedia.com/aircond/aircond09.htm
5.1.2 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. The added humidity in the exiting airstream goes back into the main duct and is recirculated and therefore re-treated, eliminating the concern of added humidity in the home.

5.1.3 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. On warmer days, the air conditioner will be turned on, just as the furnace will be turned on during cooler days. On days when the temperature and humidity of the surroundings (outside) are comfortable, the HVAC system will not be used.

5.2 Clothes Condition

5.2.1 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 6.1.2, 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 7.3.3.4 and 7.4.8.

5.2.2 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 in the experimental unit we found that clothes came out slightly more stiff and wrinkle than a tumble dryer. However we feel that added stiffness and wrinkles are acceptable tradeoffs for the energy savings.

5.3 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 bed, which would contain a material which could adsorb moisture from the air prior to entering the dryer.

5.3.1 Desiccant Materials
Several different materials were researched for our system in order to find the material that would work in our system. In order for the material to work in our system, the material must be
able to adsorb moisture from air at temperatures ranging between 55-130°F, which is the temperature the HVAC system will be placing the air into the system. The desiccant should also be able to adsorb as much moisture as possible such that the material will decrease the relative humidity a significant amount as well as be able to adsorb a large amount of moisture without being replaced or regenerated. The desiccant must also be able adsorb moisture in a very short amount of time because of the high velocity of air flow over the desiccant bed.

5.3.1.1 Silica Gel
Blue indicating silica gel, sold for a price of $18/lb 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 adsorbed all the moisture it can hold. The pores of this desiccant have a diameter 20 to 30 Å, which is ideal for adsorbing moisture in the air. This desiccant works best in conditions from 70-90°F and 60-90% relative humidity and has the ability to adsorb 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.6

5.3.1.2 Molecular Sieve
A molecular sieve, which can be bought for $20/lb, 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 lower resulting RH% than silica gel and activated alumina. When a gas or liquid is passed through, the sieve adsorb the smaller molecules while larger molecules pass through. Since water is a molecule, 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.7

We determined that this desiccant is good for eliminating moisture at a low level 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 removing the water from a high humidity of 50% to 30% rather than from a lower humidity of 30% to 15%, 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.

5.3.1.3 Activated Alumina
Activated alumina works to adsorb moisture because it is a highly porous form of aluminum oxide. This desiccant was the least expensive, at $5/lb, of the three considered and seemed to be the most effective as it could adsorb up to 35% of its weight and could be regenerated. Many desiccant materials tend to break down and fall apart at higher temperatures, however, this desiccant is very good at retaining its form in any condition, which means that it could still adsorb a lot of water in the conditions that we needed it to. It can also be regenerated by heating to any temperature from 350°F to 600°F.8

6 http://www.deltaadsorbents.com/silica-gel-desiccant.html
7 http://www.deltaadsorbents.com/molecular-sieve-desiccants.html
8 http://www.deltaadsorbents.com/activated-alumina.html
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 adsorption is needed. 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 bed.

5.3.2 Desiccant Testing

5.3.2.1 Procedure

The purpose for this experiment was to determine the effects of the desiccant on the clothes and the airflow. We purchased the ¼” diameter activated alumina that was chosen as our best material. In our testing the desiccant material was placed in a mesh with a 4” diameter PVC pipe to create a desiccant bed. We connected our desiccant bed in-line with our vertical supply air duct, located directly above our drying chamber. We ran three different tests with the experimental unit. The first test was without the desiccant bed and measured how much airflow the system was getting. Next, the bed with the mesh was placed in the system without any desiccant and the airflow was measured again. The activated alumina was then placed in the bed and the airflow was measured.

5.3.2.2 Results

The desiccant bed with all of its components created a significant pressure drop in our airflow. We measured the airflow in terms of air changes in the drying chamber. The number of air changes is how many times all of the air in the drying is replaced per unit of time. The results from the three different tests can be seen in the figure below:

![Figure 2: The Air Changes in Experimental Unit with Desiccant](image)

The bed reduced our air changes per hour from 2937 to 368. This pressure drop the bed created was too much for our fan to handle, greatly reducing its effectiveness. Because of the pressure drop when the filter and desiccant were in the duct, the flow rate decreased from 254 ft³/min to 32 ft³/min. This large decrease in airflow would have increased the dry time of the clothes.

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significantly since it greatly reduced the flow rate. When we found out that the bed increased the pressure drop greatly, this prompted our team to do a more in depth analysis on the pressure drop which can be seen below.

### 5.3.3 Pressure Drop

When placing the desiccant bed into the system, the desiccant impedes the air flowing through the supply air ducts. This results in a pressure drop which slows the air velocity entering the dryer. The Ergun equation helped our team decide whether or not the desiccant bed is going to decrease our drying time by lowering the water content in the air or whether the bed is going to slow down the airflow and therefore increase the drying time. The equation calculates the pressure drop over a porous material using particle diameter of the material, velocity of the input airflow, and porosity of the material. The equation to determine the pressure difference over the bed is below:\(^\text{10}\):

\[
\frac{\Delta P}{L} = \frac{150 \mu (1-\epsilon)^2 v_2}{\epsilon^3 d_p^3} + \frac{1.75(1-\epsilon) \rho v_2^2}{\epsilon^3 d_p}
\]

Equation 1

where:

- \(\Delta P\) = pressure drop
- \(L\) = length of the bed
- \(\mu\) = the fluid viscosity
- \(\epsilon\) = void space of the bed
- \(V_2\) = 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 0.1 m according to a preliminary design. This length greatly affects the pressure drop and desiccant exposure which greatly affects the results of the desiccant bed. When choosing an original length, decreasing the pressure drop was the main concern so a short length was chosen. The density of the input air at a temperature of 54 °C was used. The superficial velocity of the fluid entering the system, which was measured by our anemometer, was found to be about 20 ft/s. The diameter of the particle used was the maximum available which was \(\frac{1}{4}\) inch. The pressure difference for the experimental unit was calculated to be approximately 7 kPa. This pressure drop causes a dramatic decrease in airflow 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.

\(^{10}\)http://faculty.washington.edu/finlayso/Fluidized_Bed/FBR_Fluid_Mech/packed Beds_scroll.htm
5.3.3.1 Desiccant Bead Diameter

In order to decrease the pressure drop a simulation was performed with the Ergun equation. First the diameter of the desiccant material was increased. When this dimension is increased the pressure drop declines very quickly as can be seen in the figure below.

![Figure 3: Pressure Drop vs Diameter of the Desiccant Material](image)

The diameter of the desiccant material has a large impact on the pressure drop over the desiccant bed and therefore the velocity into the dryer. However, several manufacturers of activated alumina were contacted and the largest bead that can be manufactured is 6.3 mm or (1/4 in). Beads start to fall apart when the diameter was increased above 7 mm so manufacturers are limited to producing activated alumina beads with a maximum diameter of 6.3 mm.

5.3.3.2 Desiccant Bed Diameter

The next test performed to see if the pressure drop over the desiccant bed could be decreased was changing the diameter of the desiccant bed. This dimensional change would result in a velocity decrease as the air entered the desiccant bed. The velocity would increase again as the air left the desiccant bed where the diameter would decrease to its original diameter of 4 inches. A diagram of dimensions that were changed in the desiccant bed can be seen in the figure below.
The result of the increase in desiccant bed diameter is a significant decrease in the velocity through the bed as well as a decrease in pressure drop over the desiccant bed. These results can be seen in the figures below.
These figures show that the velocity entering the desiccant bed and the pressure drop over the desiccant bed do decrease a significant amount as the diameter of the bed increases. This is a result of conservation of volumetric flow which is explained in the equations below.

\[ Q_1 = Q_2 \quad \text{Equation 2} \]

or

\[ v_1 A_1 = v_2 A_2 \quad \text{Equation 3} \]

where

- \( v_1 \) = velocity before air enters desiccant bed
- \( A_1 \) = cross sectional area of duct work prior to desiccant bed
- \( v_2 \) = velocity in the desiccant bed
- \( A_2 \) = cross sectional area of desiccant bed

Since the area of the bed and duct work is a circle, the area can be replaced to make the following equation

\[ v_1 \frac{\pi}{4} D_{duct}^2 = v_2 \frac{\pi}{4} D_{bed}^2 \quad \text{Equation 4} \]

The above equation shows that when the diameter of the bed is increased, the velocity in the bed has to decrease. This decrease in velocity affects the pressure drop over the bed because of the velocity term in equation one seen above.
5.3.3.3 Desiccant Bed Volume

To see if the pressure drop over the bed would decrease quicker, both the length and diameter were increased. The results can be seen in the graph below.

![Graph showing Volume of Desiccant Bed vs Pressure Drop](image)

**Figure 7: Volume of Desiccant Bed vs Pressure Drop**

The pressure drop first increases when the volume is increasing but then decreases quickly. This is because increasing length term in the Ergun equation makes the pressure increase. However, the decreasing velocity term is a more dominant factor in the equation and quickly causes the pressure drop to decrease. While decreasing the length of the bed would decrease the pressure drop, we did not want to decrease the length of the bed more than 0.1 m due to the affect it has on the exposure time which can be seen below. The pressure drop can be decreased enough for the desiccant bed to be a feasible option for our system. However, the pressure drop is not the only problem that the desiccant bed proposed.

5.3.4 Exposure Time

Most desiccant materials need an exposure time of approximately 20 seconds. When the air is not exposed to the desiccant material for 20 seconds, the amount of moisture that is adsorbed by the desiccant is significantly decreased. To determine if enough exposure time to have moisture adsorbed, the velocity of the air entering the bed and the length of the bed were used to calculate an exposure time. With the original bed design of a diameter of 0.1016 m (4 in) and a length of 0.1 m the exposure time was calculated to be 0.016 seconds.

In order to try to increase this exposure time both the length of the bed was changed as well as the diameter of the bed. A graph of the exposure time when the length was changed can be seen below.
Figure 8: Exposure Time of the Air to the Desiccant vs Length of the Bed

It can be seen in this figure that the exposure time is linearly proportional to the length of the desiccant bed. It can also be seen that the exposure time does not come close to the exposure time that the desiccant needs to be able to adsorb moisture. Next, the diameter of the bed was changed and the length of the bed was held constant. As the diameter of the bed is increased, the velocity through the bed decreases thus increasing the exposure time. This can be seen in the figure below.

Figure 9: Exposure Time vs Diameter of the Desiccant Bed

The increasing diameter of the bed evidently allows the exposure time to increase dramatically as the diameter of the bed approaches one meter. The volume of the desiccant bed was increased by increasing the length and the diameter of the bed simultaneously. The results can be seen in the figure below.
This figure shows that if the length and diameter are increased a significant amount, the exposure time would increase to an acceptable level and the desiccant would be able to adsorb moisture. However, a desiccant bed this large could not fit into a conventional oven where the desiccant bed would be regenerated. General dimensions of a conventional oven are 0.61 m wide by 0.41 m tall by 0.41 m deep. In order for the air to have enough exposure time the diameter would have to be larger than 1.0 m and the length would have to exceed 0.4 m which would be too large. The lines on the figure show the approximate volume of a conventional oven and the corresponding exposure time for that volume.

5.3.5 Regeneration

5.3.5.1 Regeneration Frequency

Activated alumina, the desiccant material that was chosen, needs to be regenerated when the material has adsorbed its full capacity of water. In order for the desiccant bed to be feasible for the system, the user should not have to regenerate the bed very frequently. The bed should not have to be regenerated more frequently than tumble dryers need to have its lint trap cleaned. In order for a tumble dryer to work at its high efficiency and to refrain from fire hazards, it needs to have its lint trap cleaned every time the dryer is used, which means out desiccant bed should not have to be regenerated more than once per use.

In order to get the regeneration frequency it was necessary to determine how fast the activated alumina adsorbed moisture. Activated alumina adsorbs moisture at a rate of 0.03 kg/m²s \(^{11}\) where the kg is the amount of moisture adsorbed and m² is the surface area of the desiccant. Another important factor in determining the regeneration frequency is the maximum amount of moisture that activated alumina can adsorb. Activated alumina can adsorb up to 20% of its weight when the exposure time is about 20 seconds. Using this number a mass of water that

could be adsorbed by the activated alumina was calculated based on the volume of the bed and how much desiccant was in the bed. Assuming that the user used the dryer once a day for 45 minutes, the desiccant bed would need to be regenerated 11 times a year, which is much less than a lint trap needs to be cleaned for a tumble dryer.

5.3.5.2 Regeneration Cost
For the desiccant to be regenerated the bed needs to be placed in an oven at a temperature above 350°F. This requires extra energy and cost outside of what our system uses. In order to determine the time and cost of the regeneration, the energy needed to heat the water from room temperature to boiling temperature and to evaporate the water. The energy provided by a standard oven is 2 kWh per hour\[^{12}\]. This value was used to calculate how long it would take the oven to provide the energy needed to evaporate the water in the desiccant. Based on an electricity cost of $0.16 a kWh\[^{13}\] the cost of regenerating the desiccant bed a year was also calculated. The larger the desiccant bed is the longer it takes the activated alumina to regenerate and the more costly the regeneration. These results are in the figure below.

![Figure 11: Regeneration Time and Cost vs The Volume of the Desiccant Bed](image)

5.3.6 Exposure
When the activated alumina was purchased we also received a Material Safety Data Sheet (MSDS). Prolonged exposure can cause skin irritation and the particles from activated alumina are harmful to breathe in. Considering that the desiccant bed would be in the air intake, some of the activated alumina could get on the clothes and cause skin irritation. Then, as the contaminated air is circulated through the house the user would be breathing it. Using activated aluminum goes against our design norm of trust.

\[^{12}\] http://www.bestbuy.com/site/Appliances-Promotions/How-much-energy-does-the-average-range/oven-use%3F-/pcmcat160300050011.c?id=pcmcat160300050011

\[^{13}\] http://www.bestbuy.com/site/Appliances-Promotions/How-much-energy-does-the-average-range/oven-use%3F-/pcmcat160300050011.c?id=pcmcat160300050011
5.3.7 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. At this point we know that adding a desiccant bed to our system would not improve the drying time due to the fact that it would decrease the airflow rate. We also know that the activated alumina will not adsorb very much moisture prior to the air entering the system due to the low exposure time. Lastly, while we know that the cost of regeneration is low; our desire is for the system to be user friendly and energy efficient as possible. If we added the desiccant bed to the system, even though the effect on the energy usage is minimal and low compared to the savings, our user would have to use the outside source of energy of an oven to regenerate the desiccant.

The fan that has been chosen for our system is not the largest fan that could work with our system which means that there is a possibility that a larger fan could help increase the air flow into our dryer. However, increasing the velocity of the air flow over the desiccant bed decreases the exposure time of the air to the desiccant which is our main issue with the desiccant bed. Getting a larger fan also does not change the fact that activated alumina can cause skin irritation.

6 System Architecture

6.1 Different Designs
6.1.1 Preexisting Designs
In America, there are some products that are similar to our product but have some key differences that make our product unique. In the picture below is the Staber Model DCV-3000 which has a high cost of $1400.

![Drying Cabinet – Staber Model DCV 3000](http://www.greenbuildingadvisor.com/blogs/dept/musings/alternatives-clothes-dryers)

Figure 12: Drying Cabinet – Staber Model DCV 3000

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14 http://www.greenbuildingadvisor.com/blogs/dept/musings/alternatives-clothes-dryers
In this product, air is circulated evenly throughout the cabinet and around the items to be dried. This model, along with others, is used only in conjunction with a tumble dryer as the clothes take a long time to dry. Also, this model does not have very much space for clothes to be placed into the cabinet.

Another drying cabinet product can be seen below. This product works the same as the Staber seen above but has a different configuration.

![Drying Cabinet](image)

**Figure 13: Drying Cabinet**

This product also has similar problems as the Staber in that it is used in conjunction with a tumble dryer and takes a long time to dry the clothes. Both of the products above remove the moisture by condensing the water in the exit airflow of the cabinet and draining the water from the system. This keeps the system from having to run the moist air outside of the building or house the system is in. The drying cabinets in combination with dryers are more energy efficient than using just a tumble dryer. However, due to the costs and life expectancy of the dryers this energy efficiency is not enough for the user to gain any monetary benefits from the efficiency as can be seen below in the cost analysis section. Our product allows the user to save the user both money and energy which makes it a better option for drying.

Another similar product made in America is drying rooms used at ski resorts, which can be seen in the picture below.

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This product is used by skiers to dry their wet gear and provides plenty of space to do so. The drying room has the ventilation and heating rates higher than an average closet or room in order to dry the clothes quicker than if they were just hanging in a closet.

6.1.2 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 in Vilnius. 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.

6.1.2.1 Problems with the Lithuanian Design

The clothes took about two days to dry. The dried clothes had a terrible odor 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 though the HVAC system. This air had a relatively low flow rate. 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.

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16 http://www.greenbuildingadvisor.com/blogs/dept/musings/alternatives-clothes-dryers
6.1.3 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.

6.1.4 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 whether 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, even though there may be leaks. This is because our dryer is negatively pressured, so any leaks will result in air being pulled into the dryer and through the fan on the fan. If our fan was located on the supply side of our dryer, air would be forced out of our dryer through leaks, and the overall pressurization of our dryer would be positive.

To push air through, backflows from pressure differentials are possible, but by drawing air through our dryer, we have greater control of the air leaving our system. 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 tap into the duct instead of rerouting all the supply air.

6.1.5 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 previous projects as was the fan. Since the fan had two air intakes, we utilized both to make full use of the fans potential. A CAD drawing of the experimental unit can be seen below.

![Experimental Unit CAD Drawing](image)

Figure 15: Experimental Unit CAD Drawing
As a result of the two intakes, 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 exits 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 that 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 the figure below.

Figure 16: Experimental Unit Dimensions

6.1.6 Prototype Design 1
The first prototype design incorporated all the lessons learned from the experimental unit. The dryer needed to be large enough to hold two loads of laundry. The drying cavity was roughly 4 feet wide, 3 feet deep and 5 feet tall. Inside were rails for hanging clothes and a grate for smaller articles like socks. The entire system was to be aluminum or painted steel to prevent rust. Air will be pulled though the cavity using a fan. Because routing all the air though the apparatus will
be impractical, we are only taking a portion of the air coming from the furnace. As a result we would have to tap into the duct. This first design featured a single air intake through the top with a hood to encourage airflow expansion. The air would 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.

6.1.6.1 Prototype Size
For the first prototype design we decided to size the chamber so 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 were 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 was 1 foot underneath the roof of the chamber. A schematic of the described design can be seen in the figure below.

![Figure 17: Prototype Design 1 Dimensions](image)

The total area in this design was 72 ft$^3$, which was 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 and that our system needs to hold two loads of laundry.
6.1.6.2 Routing Air

All of the air from the HVAC will not flow 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.

6.1.6.3 Fan

Our fan, donated by Marshall and Wells Co, is a 10” centrifugal duct fan rated at 589 CFM, 400 CFM with static pressure in our design. 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 sold fan, and there were extras in the Grand Rapids warehouse that were not already sold, so it was available for us to use.

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 first prototype design, with a volume of 72 cubic feet, this exhaust fan will give 490 air changes per hour: $589 \text{ ft}^3/\text{min} \times 60 \text{ min/hr} / 72 \text{ ft}^3 = 490 \text{ air changes per hour}.

We looked at a larger fan, capable of 940 CFM, 550 CFM with static pressure. This fan is priced at $325 and would improve the dry times of our dryer. Although we could have chosen this fan for our final design, we did not; there is a trade-off between faster dry times and dryer price. Since the less expensive fan that is rated at 589 CFM supplies the needed air velocities for each season, even in worst case scenarios, it is against our design norm of stewardship to have the more inexpensive fan in the final design. Therefore we have determined that the 10” centrifugal duct fan rated at 589 CFM will be used for our final design.

6.1.6.4 Material of Prototype

The dryer was made of Aluminum because it is durable, easy to work with, and doesn’t rust. Common engineering materials that could have reasonably been used for this application are steel, aluminum, and plastics. The problem with steel is that it is heavy and has a tendency to rust. Considering that we are building a cavity that will be holding wet clothes and wet air, it was determined that steel would be a poor choice. Stainless steel is rust resistant, but not rust proof and will rust over time. Any surface starness (from drilling, cutting, and bending) would ruin the surface finish and cause rust. While the option of painting the surface did exist, paint chips over time and would shorten the design life of our product and increase maintenance costs. Plastics were never a real consideration because of the limited facilities at Calvin College. Calvin possesses a full metal shop, but very limited ability to work with polymers. If the ability to use plastics became available it might be worth the consideration, however, plastics are often times more costly than metals. Aluminum was the best choice because it is a common engineering material that can be ordered in sheets; it cannot rust, is easy to work with, and is reasonably priced. While aluminum is not as strong as steel, we don’t have high strength requirements and aluminum is strong enough for our application.
6.1.7  Prototype Design 2
Several changes were made from the first final design because of some realizations during the building of the prototype. These realizations include the size of the prototype, air distribution changes, duct work size, and clothes position.

6.1.7.1  Prototype size
The first consideration for our prototype design was overall size. We wanted to be able to dry multiple loads of laundry at once. To maximize the amount of clothes while keeping our design small enough to fit comfortably into a room with duct access to a home’s furnace, we designed our dryer to have the following dimensions: 5 feet tall by 4 feet wide by 2.5 feet deep. This gives us a total volume of 50 ft³.

![Prototype design 2](image)

Figure 18: Prototype design 2

Another factor we took into account was that the drying cabinet needed to fit through a door way to be brought into the home. This was an oversight for our initial design, which was 3 feet deep, but this dimension was too large to fit through our test site’s (the Reyelts’ home) doorway. So we needed to cut down on the smallest dimension (depth) so the dryer could be brought into the home.

The height of 5 feet was used so that the dryer would have enough room to hang bed sheets, pants to their full extension, and any other large garments. Four feet of width gives adequate space to fit two or more full loads along the cross bar at top of the dryer.

6.1.7.2  Airflow distribution
6.1.7.2.1  Fan position
Our next design decision was how to maintain evenly distributed air flow throughout our entire drying cabinet. We wanted to supply air at the top of the drying cabinet, and return air at the
bottom, traveling past the larger, wetter garments, first, and then past the smaller garments with less moisture content next.

With the location of our dryer in the home with respect to the furnace, we needed approximately 10 feet of ductwork on both the supply and return sides. The air flow through our drying cabinet without supplemental air flow would not be enough to dry the clothes in our targeted dry time (45 min per load). Thus, we needed to incorporate a fan in-line with the ductwork to achieve enough air flow. If we were to connect a fan on the supply side of the drying cabinet, therefore pushing air into our cabinet, air would not be evenly distributed. This is because of static pressure build-up at the bottom of our drying cabinet. We would be unable to control air flow once it entered our cabinet, and we would simply have to “go with the flow” on where the air decided to travel on its path back to the central air system.

With this in mind, we decided to connect a fan on the return side of the system. This draws the air through the cabinet and, pushes the air back into the central system where we were not concerned about flow distribution because the air has already passed through the clothing and our drying system. Having a fan that draws air through our system gives us maximum control of air flow through our drying cabinet.

6.1.7.2.2 Air Distributor
Air in the supply duct has a high velocity. When the air exits 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.

To assist with even air distribution, we designed our cabinet to have a distribution hood on the top where the supply duct connects, as well as a supply air diffuser. We tried three different air diffusers in our design. The first design was a square diffuser. This diffuser design worked too well for our system and caused the air flow to have a large dead space in the middle so we modified it by removing the center piece.

![Image: Diffuser Designs](image-url)
The result of removing the center piece from the square design worked well however we felt that better air distribution was still needed so we tried using a circular diffuser.

The circular diffuser worked better then both of the square diffuser designs so this was the design that was kept for our prototype design. The results of the air distribution testing can be seen in section 7.4.7.

The combination of these two components slows the air velocity and distributes it as evenly as possible across the entire cross-sectional area of our drying cabinet. At the bottom of the cabinet, return grilles are used to draw air evenly from the bottom, with a consistent static pressure. From there, air enters duct work where it travels out the back of the drying cabinet, into return ducting and through the fan.

6.1.7.2.3 Return Air Grill

Not only did we want even air distribution for the air entering our dryer, we also for the air leaving the dryer. For this, we designed a return air plenum box 18” high from the bottom of the dryer, and 6” in depth. The plenum box runs along the sides and back of the prototype. Along the bottom of the plenum box, return air grilles are located. The grilles are 2” in height and 22” in length on the sides of the dryer, and 34” in length along the back of the dryer. The total opening size of the return grilles is 1.0833 ft$^2$. However, are grille screen, with free area of 55%, covers the grilles, so our overall free area of the return air grilles is 0.6 ft$^2$. With 400 CFM of air flowing through our dryer, the return air leaving the dryer has a velocity of 670 fpm through the return air grilles. The return air fan, located outside the dryer, is connected by a 6” duct to the middle of the back of our dryer plenum box.
6.1.7.2.4 Computational Flow Dynamics
To help with air flow distribution we attempted to perform a computational flow dynamics (CFD) analysis. This analysis would tell us where we could expect low air velocities in the dryer and would help with our design of a diffuser for our system. However, we knew that most CFD programs cannot accurately simulate turbulent flow. We know we have turbulent flow due to the calculation of the Reynolds number seen below.
\[ Re = \frac{\rho v D_H}{\mu} \]  
Equation 5

\[ D_H = \frac{4A}{P} \]  
Equation 6

where

\[ \rho = \text{density of the fluid} \]

\[ v = \text{velocity between the fluid and the object} \]

\[ D_H = \text{hydraulic diameter} \]

\[ \mu = \text{dynamic viscosity} \]

\[ A = \text{cross sectional area} \]

\[ P = \text{wetted perimeter} \]

The results of calculating the Reynolds number in the dryer can be seen in the table below.

<table>
<thead>
<tr>
<th>Temperature (F)</th>
<th>Velocity (ft/min)</th>
<th>50</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>300</td>
<td>100,000</td>
<td>90,000</td>
</tr>
<tr>
<td>Minimum</td>
<td>80</td>
<td>26,000</td>
<td>24,000</td>
</tr>
</tbody>
</table>

Because all of the Reynolds numbers are over 4000 which is the threshold for the transition from laminar to turbulent flow, we know that the air flow in our design would always be turbulent.

With the help of Jacob Vriesema, an engineer at Koops Inc. and a Calvin graduate, we successfully simulated airflow over a sphere with initial summer and winter starting temperatures of 55°F and 130°F, respectively. The results are shown below:
Figure 23: CFD over Sphere at 55°F
Figure 24: CFD over a Sphere at 130 °F
From these results, it was obvious that the software (SolidWorks) did not take into account that the velocities obtained constituted a turbulent flow situation; the graphics clearly indicate a laminar flow situation. After discussing matters with Dr. Rich DeJong, we were told that we could not model turbulent flow situations accurately with any existing software.

6.1.7.3 Duct Work Size

The ductwork was sized based on an air flow of 2000 feet per minute through 6 inch diameter ducts. This velocity of 2000 fpm is a relatively high velocity for air flow, but we wanted to minimize ductwork size based on tight spaces where our prototype was installed. Had we used 8” or even 10” ducts, our velocity would have been slower, but there simply was not enough room for ducts this large. Our fan, which was donated to us by Marshall Wells Co., is a 10” inline FG10x1 Fantech fan, rated at 590 CFM (cubic feet per minute) at 0” of static pressure.

We were able to determine the static pressure of our system (duct work, dryer assembly, fan, etc.) by measuring return air velocities at the furnace when our dryer was empty, filled 33%, filled 66%, and completely full. These velocities are, respectively: 2400 fpm, 2100 fpm, 2000 fpm, and 1900 fpm through a 6” duct. From these velocities, CFM values can be calculated and are, respectively: 471 CFM, 412 CFM, 393 CFM, and 373 CFM. From these CFM values, were able to determine static pressure levels using the fan curve graph below.

Our system has approximately 0.8” wc of static pressure when the dryer is empty. When our dryer had 2 full loads of laundry our system experiences approximately 1.25” wc of static pressure, and our fan is able to draw 400 CFM or air through our dryer.

![Figure 25: Power curve of prototype fan](http://residential.fantech.net/residential-products/inline-duct-fans/inline-exhaust-fans/)
Ideally, we would like to use a fan with a bit more capacity. This would be an upgrade from Fanthech’s FG10xl to an FG12xl, rated at 505 CFM with 1.25” we static pressure. Increased air flow will reduce dry time. However, for a larger fan, costs are higher. We feel that because the fan we have now, the Fantech 10xl, dries our clothes in a time frame that is acceptable, it is not necessary to increase costs ($100 more for fan upgrade) for slightly better dry times.

6.1.7.4 Clothes Position

Our design also utilized drying grates that can be easily removed, to lay smaller garments on, such as socks and underwear. These grates are located at a height of 1.5 ft. from the bottom of our cabinet, so that air passes the larger, wetter garments first, and then past the grates, upon which are the smaller, less damp garments. This order of garments allows the driest air to absorb moisture from the wettest clothes first, so that we can minimize dry times for the wettest garments. Garments such as socks do not take as long to dry, and if the user takes all the clothing out at the same time (at the end of the drying cycle) the smaller garments will not be over-dried and stiff because air with a high humidity (after absorbing water from large garments) will be passing over them for the entire drying cycle.

6.1.7.5 Door Design

The opening for the doors was designed to be large enough to easily fit clothes. Any seem has the possibility to leak ambient air into the dryer, thus we wanted to minimize the perimeter around the doors. It was also desired for the doors to be on the same level as the drying grates. This was to allow the user needs easy access to clothes on the grates; however the user does not need easy access below them. Four inches of clearance was given on all four sides. The opening for the doors was cut to be 40” wide and 35.75” high.

The doors themselves overlap the opening by 1”. Two doors were decided upon as one door would open wider and could cause space constraints for the user. A foam gasket was placed along the perimeter of the doors in order to get a tighter seal. The doors were designed to overlap so that the right door keeps the left one closed and so that a tighter seal could be achieved.

6.2 Process

The process of our system is a relatively simple one. 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. The air is drawn though the house by a fan. This fan is only on when the furnace is on.

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 a diffuser and a hood which helps distribute the air such that the velocity of the air in the chamber relatively 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. Moisture is carried out of the chamber by the hot air.

The air is drawn through the air plenum at the bottom of the dryer. The air then enters the ductwork and the drying chamber by an exhaust fan, in line with the duct. 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 furnace. This process can be seen in the figure below.

![Block Diagram of Air Flow](image)

While the air is technically cooler after the drying process, this result is small and negligible. Thus the supply air for the home experiences negligible effects from diverting its supply air through our drying apparatus and back into the main supply duct.

The process is the same for winter as it is in the summer, except that the air coming from an air conditioner. Air conditioners cool the air causing the moisture to fall out. The dryness of this air has a great potential to absorb water.

7 Testing

7.1 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 at the inlet and exit of our system, 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 experiments, we can extrapolate to a full sized drying apparatus, focusing on maintaining the number of air changes because the other variables, temperature and humidity, are constants.

7.2 Water in Laundry
It was important to know the amount of water that must be removed from the laundry in order to estimate how long it will take to dry the clothes and the fan power that would be necessary to dry the clothes in that time. 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. The data gathered is shown below in Table 1.

Table 4: Water Weight in Laundry

<table>
<thead>
<tr>
<th>Load</th>
<th>Wet Weight (lbs)</th>
<th>Dry Weight (lbs)</th>
<th>Water Removed (lbs)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>66.67</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>7</td>
<td>4</td>
<td>57.14</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>11</td>
<td>6</td>
<td>54.55</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>66.67</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>12</td>
<td>4</td>
<td>33.33</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>50.00</td>
</tr>
<tr>
<td>7</td>
<td>22.4</td>
<td>14.8</td>
<td>7.6</td>
<td>51.35</td>
</tr>
<tr>
<td>8</td>
<td>24.6</td>
<td>16.8</td>
<td>7.8</td>
<td>46.43</td>
</tr>
<tr>
<td>AVG</td>
<td>17.6</td>
<td>11.7</td>
<td>5.9</td>
<td>50.6</td>
</tr>
</tbody>
</table>

The ratio column is the ratio the weight before drying to after drying. The average is also given.

7.3 Experimental Unit
7.3.1 Purpose
We 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 determine what challenges we would have to overcome.

One of the problems that we thought might be an issue before we ran tests on the experimental unit was saturated air coming out of the dryer. This would be a problem due to the fact that this air could leave behind water in the ducts as it cooled, 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 filter is
that it would possibly cause a large pressure drop, reducing the number of air changes and therefore increasing drying time.

We also speculated 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 his or 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 design will be an unacceptable alternative.

We also wanted to get a good idea of the time that it would take for the clothes to dry. Being that this is a 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 did not know is how much more and if that moisture is a problem. In winter months, air tends to be drier, so additional moisture would 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.\(^\text{18}\)

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 30 min, and the averages user has two loads then the dryer should either be able to dry clothes in 30 min or have the capacity for two loads. We needed to know how much increasing or decreasing the air flow rates will have an effect on dry time.

\subsection*{7.3.2 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, seen below, we planned to measure the flow rates of the air, temperature, and humidity of the air. The measurements were not able to be completed due to difficulties with the anemometer. The anemometer was fixed before the prototype was finished so measurements with the device were able to be completed during testing of the prototype.

\[^\text{18}\]http://www.buildingscience.com/documents/reports/rr-0203-relative-humidity
7.3.3 Results

7.3.3.1 Air Flow and Dry Time

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. 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 about 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 could not 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 was an important finding that incorporated 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 answered was the rate at which the water was removed and if the water removal was constant or had an decreasing exponential trend. 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-sleeved 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 the following figure.

![Figure 28: Water content versus time](image_url)

The clothing dried quickest in both loads in the first 5 minutes of the drying process, and slowed as time progressed which tells us that the water removal rate is not constant. 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. The data for these two tests can be seen in the table below.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Water Weight (lbs)</th>
<th>Time (min)</th>
<th>Water Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.375</td>
<td>0</td>
<td>0.4375</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
<td>0.3125</td>
</tr>
<tr>
<td>10</td>
<td>0.9374</td>
<td>10</td>
<td>0.125</td>
</tr>
<tr>
<td>15</td>
<td>0.75</td>
<td>15</td>
<td>0.0625</td>
</tr>
<tr>
<td>20</td>
<td>0.6875</td>
<td>20</td>
<td>0.0625</td>
</tr>
<tr>
<td>25</td>
<td>0.5625</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.375</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.375</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More tests were done with the experimental unit were done to see how long each piece of clothing would dry. The results of this test can be seen in the table below.
### 7.3.3.2 Sweating

When the tests were run on the experimental unit we did not notice any duct sweating at the exit of the dryer. This was a good result of the test due to the problems that duct sweating would cause. Calculations were also done to ensure that sweating would not occur in the ducts and can be seen in section 7.5.

### 7.3.3.3 Lint Trap

Another result of the tests on the experimental unit was that it was made clear that we would not need a lint trap on the exit of the dryer. Lint in tumble dryers is due to the clothes being heated to high temperatures and the act of the clothes being tumbled. Since the clothes in our design are not being heated to high temperature or being tumbled, a lint trap is unnecessary for our system.

### 7.3.3.4 Stiffness and Odor

The quality of the clothes was comparable to clothes dried on a clothes line which are favorable results. The clothes did not have any odor when they were taken out of the dryer and they were about as stiff as clothes that had been dried outside on a line.

### 7.4 Prototype Testing

We ran numerous tests on different amounts and types of laundry, simulation both winter and spring/fall conditions. We define “dry” clothes as both qualitatively and quantitatively. The clothes were considered dry when the clothes were dry to the touch and the relatively humidity in

![Table 6: Drying Data for Experimental Unit](image)

<table>
<thead>
<tr>
<th>Trial</th>
<th>1</th>
<th>Trial</th>
<th>2</th>
<th>Trial</th>
<th>3</th>
<th>Trial</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Weight</td>
<td>1.5</td>
<td>Wet Weight</td>
<td>3</td>
<td>Wet Weight</td>
<td>5.2</td>
<td>Wet Weight</td>
<td>4.7</td>
</tr>
<tr>
<td>Dry Weight</td>
<td>1</td>
<td>Dry Weight</td>
<td>2.5</td>
<td>Dry Weight</td>
<td>3.5</td>
<td>Dry Weight</td>
<td>4.2</td>
</tr>
<tr>
<td>Water Weight</td>
<td>0.5</td>
<td>Water Weight</td>
<td>0.5</td>
<td>Water Weight</td>
<td>1.7</td>
<td>Water Weight</td>
<td>0.5</td>
</tr>
<tr>
<td>Clothing Dry Time</td>
<td>25 min</td>
<td>Clothing Dry Time</td>
<td>30</td>
<td>Clothing Dry Time</td>
<td>35</td>
<td>Clothing Dry Time</td>
<td>35</td>
</tr>
<tr>
<td>Boxers</td>
<td>Dress Shirt</td>
<td>30</td>
<td>Dress pants</td>
<td>35</td>
<td>Dress pants</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Sweater</td>
<td>25 min</td>
<td>Sweat pants</td>
<td>30</td>
<td>Hand Towel</td>
<td>35</td>
<td>Dress</td>
<td>30</td>
</tr>
<tr>
<td>T-shirt</td>
<td>25 min</td>
<td>Pair socks</td>
<td>45</td>
<td>Boxers</td>
<td>35</td>
<td>Socks Pair</td>
<td>20</td>
</tr>
<tr>
<td>Athletic shorts</td>
<td>30</td>
<td>Fleece</td>
<td>35</td>
<td>Socks Pair</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-shirt</td>
<td>30</td>
<td>Wind breaker</td>
<td>30</td>
<td>Socks Pair</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

39
the dryer (on the return air side of the clothing) remained constant (± 5%). We took data using an anemometer, recording both temperature and relative humidity at the drying grate level, 18” from the bottom of our dryer, after the air had passed the hanging clothes. Dew point and wet bulb temperatures were calculated using psychrometric equations.

We placed shirts, pants, shorts, boxers, and bed sheets on hangars, and smaller garments such as socks on the drying racks. An important note: pants were hung to their full extension, clamped at the waist. The waistbands of the pants were the last part of the clothing to dry because they were not exposed to direct air flow due to the method they were hung.

7.4.1 Test 1: Spring/Fall Condition with High Efficiency Spin Cycle

The first test was conducted on Sunday April 7th, 2013 between the hours of 3PM and 7PM. The first test that was run had 3 loads of laundry. Since the temperature outside was about 60°F, and the thermostat of the home was set to 70°F, the furnace was not operating at the time of this test. The house did not lose heat quickly enough to necessitate the furnace to turn on during the drying operation. Thus the clothes dried without the aid of any heated or cooled air. Data for ambient inside temperature and humidity can be seen below. This data is important because it illustrates that the Reyelts’ central air system was not on during this test. This is important because it means that there was no heating, cooling, humidification, or dehumidification of the air flowing through our prototype. The air was strictly ambient room temperature and humidity.

<table>
<thead>
<tr>
<th>Ambient Room Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°F)</td>
<td>60.4</td>
</tr>
<tr>
<td>DP (°F)</td>
<td>35.1</td>
</tr>
<tr>
<td>WB (°F)</td>
<td>47.8</td>
</tr>
<tr>
<td>%RH</td>
<td>38.7</td>
</tr>
</tbody>
</table>

The fan was running during these tests, which caused air circulation within the prototype. By looking at the ambient room temperature air and the downstream air inside the dyer we can conclude that the air circulation was aiding the drying process. The downstream air was on average 1°F cooler than the room temperature air and at most 2°F cooler. The relative humidity was also higher at the downstream. We know this because the relative humidity at the inlet in the winter was about 14%. Because this is a winter case, this is the highest the humidity would be coming into our system. Thus, we can conclude that our worst case scenario for drying is when the temperature outside is such that neither the furnace nor the air conditioner need to be used. We also concluded that air circulation does help dry the clothes based on the psychrometric differences between the ambient air and the downstream air. The psychrometric data for this test can be seen below.
### Table 8: Psychrometric Data during the First Test

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temp (°F)</th>
<th>DP (°F)</th>
<th>WB (°F)</th>
<th>%RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
<td>66.4</td>
<td>39.9</td>
<td>52.3</td>
<td>36.7</td>
</tr>
<tr>
<td>100</td>
<td>66.0</td>
<td>40.8</td>
<td>52.3</td>
<td>39.0</td>
</tr>
<tr>
<td>105</td>
<td>66.0</td>
<td>41.4</td>
<td>52.7</td>
<td>39.6</td>
</tr>
<tr>
<td>135</td>
<td>64.8</td>
<td>40.8</td>
<td>52.0</td>
<td>40.1</td>
</tr>
<tr>
<td>150</td>
<td>64.9</td>
<td>41.0</td>
<td>52.2</td>
<td>41.1</td>
</tr>
<tr>
<td>165</td>
<td>65.3</td>
<td>39.6</td>
<td>51.8</td>
<td>38.5</td>
</tr>
<tr>
<td>190</td>
<td>65.5</td>
<td>39.9</td>
<td>52.0</td>
<td>38.8</td>
</tr>
<tr>
<td>210</td>
<td>65.8</td>
<td>39.2</td>
<td>51.8</td>
<td>37.3</td>
</tr>
</tbody>
</table>

A dry time of 210 minutes (3.5 hours) for 3 loads of laundry averages out to 70 minutes per load. This dry time is higher than a conventional dryer dry time; however, because this was a worst case scenario (no air treatment, ambient conditions only), this was expected. Also, because this test included three loads of laundry the dryer was very full which affected the dry time. The drying load consisted of the following clothes: 6 pairs of boxers, 3 pairs of socks, 2 pairs of Army Combat Uniform (ACU) pants, 2 ACU coats, 3 pairs of jeans, 7 pairs of athletic shorts, 3 cotton T-shirts, 2 sweaters, 1 dress shirt, 1 under armor shirt, and 1 pair of athletic pants.

#### 7.4.2 Test 2: Winter Condition with High Efficiency Spin Cycle

The second test was conducted on Sunday April 14\(^{th}\), 2013. We wanted to simulate a winter condition, or a best case scenario, so the thermostat was set to 77°F. This was to ensure the furnace was on during the entire process, simulating winter conditions. The ambient room conditions are the same as test 1, but are not important for this test, because conditioned air from the furnace was used to dry our clothes.

After 75 minutes of drying the contents, consisting of 2 loads of laundry, was completely dry. These 2 loads consisted of the following garments: 3 pairs of dress socks, 1 pair of wool socks, 1 men’s dress shirt, 2 pillow cases, bed sheets (size: full), 1 hooded sweat shirt, 2 cotton t-shirts, and 1 pair of boxers. The average load dry time for this test is 37.5 minutes. Psychrometric data for this test is located in the table below. Note: We hung the sheet by clipping it to two hangers and allowing it to drape in the middle.

### Table 9: Psychrometric Data during Test Two

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temp (°F)</th>
<th>DP (°F)</th>
<th>WB (°F)</th>
<th>%RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>115.5</td>
<td>51.8</td>
<td>65.6</td>
<td>21.9</td>
</tr>
<tr>
<td>75</td>
<td>98.6</td>
<td>51.8</td>
<td>65.6</td>
<td>21.9</td>
</tr>
</tbody>
</table>
7.4.3 Test 3: Winter Condition-Clothes Positioning
At 25, 30, 45, 55, and 68 minutes we checked load 2 and removed clothes as they were dry. This was done to see how material and clothes positioning within our drying cabinet affected dry time. The laundry dried in this test dried completely in 1 hour and 8 minutes. This test included the following clothing: 2 pairs of boxers (cotton), 4 cotton t-shirts, 1 men’s dress shirt, 3 pairs of men’s khaki dress pants, and 1 pair blue jeans.

Table 10: Psychrometric Data during Test Three

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temp (°F)</th>
<th>DP (°F)</th>
<th>WB (°F)</th>
<th>%RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>98.6</td>
<td>51.8</td>
<td>65.6</td>
<td>21.9</td>
</tr>
<tr>
<td>30</td>
<td>96.6</td>
<td>50.2</td>
<td>67.3</td>
<td>20.8</td>
</tr>
<tr>
<td>45</td>
<td>105.3</td>
<td>55.6</td>
<td>72.1</td>
<td>19.7</td>
</tr>
<tr>
<td>55</td>
<td>100.4</td>
<td>52.7</td>
<td>69.4</td>
<td>20.5</td>
</tr>
<tr>
<td>70</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

7.4.4 Test 4: Winter Condition with “Old Washing Machine”
For this test, we wanted to simulate a winter season dry cycle for clothes that were washed in an older washing machine, one without a high efficiency spin cycle.

To simulate these conditions, the thermostat in the Reyelts’ home turned up so that the furnace was on during the entire drying process. To simulate clothing from an older model washing machine that does not have a spin cycle that removes the majority of the water from the clothes, the high efficiency washing machine used to wash the clothes was set to minimum spin. These clothes were much wetter than clothes in previous tests, with water dripping from them as they were loaded into the prototype. The wet weight of this load was 30 pounds, and when the clothes were taken out of the dryer, they weighed 20 pounds.

All but one garment was dry after 165 minutes. However, this garment was a thick fleece-lined hooded sweatshirt. For time constraint purposes, we chose to finish drying the sweatshirt in a standard tumble dryer because the rest of our clothes were done drying, and it required an additional 90 minutes before it was completely dry. This sweatshirt itself had an additional 5 pounds of water that was removed. The total water weight for the two loads in this test was 15 pounds.

It is also important to note that this test was the first conducted with a circular diffuser, which gave us more even air distribution than our square diffuser (with and without center). Another important note to consider is that because the temperature and humidity were recorded every 5 minutes, the dryer doors needed to be opened to take these measurements. Heat loss from the doors being opened may have impact our dry times negatively. We feel that this is alright, however, because our dry times will not be any worse than what we recorded.
### Table 11: Psychrometric Data for Test 4

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temp (F)</th>
<th>Dew Point (F)</th>
<th>Wet Bulb (F)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>68.7</td>
<td>55.6</td>
<td>56.5</td>
<td>55.0</td>
</tr>
<tr>
<td>10</td>
<td>72.0</td>
<td>59.0</td>
<td>59.8</td>
<td>56.0</td>
</tr>
<tr>
<td>15</td>
<td>77.5</td>
<td>61.1</td>
<td>62.0</td>
<td>49.0</td>
</tr>
<tr>
<td>20</td>
<td>79.7</td>
<td>63.7</td>
<td>64.5</td>
<td>50.5</td>
</tr>
<tr>
<td>25</td>
<td>82.4</td>
<td>61.6</td>
<td>62.7</td>
<td>41.1</td>
</tr>
<tr>
<td>30</td>
<td>85.0</td>
<td>63.4</td>
<td>64.4</td>
<td>40.2</td>
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<tr>
<td>35</td>
<td>88.0</td>
<td>64.6</td>
<td>65.7</td>
<td>37.8</td>
</tr>
<tr>
<td>40</td>
<td>84.6</td>
<td>63.2</td>
<td>64.2</td>
<td>40.5</td>
</tr>
<tr>
<td>45</td>
<td>87.6</td>
<td>64.8</td>
<td>65.8</td>
<td>38.7</td>
</tr>
<tr>
<td>50</td>
<td>90.0</td>
<td>64.6</td>
<td>65.7</td>
<td>35.0</td>
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<tr>
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<td>67.8</td>
<td>33.0</td>
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<td>67.4</td>
<td>38.9</td>
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<td>66.0</td>
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</tr>
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<td>80</td>
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<td>63.9</td>
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<td>27.8</td>
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<td>65.5</td>
<td>67.6</td>
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<td>66.3</td>
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<td>120</td>
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<td>67.9</td>
<td>68.1</td>
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<td>135</td>
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<td>65.7</td>
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<td>67.4</td>
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<tr>
<td>145</td>
<td>111.0</td>
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<td>68.3</td>
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<td>107.8</td>
<td>66.1</td>
<td>67.5</td>
<td>19.8</td>
</tr>
</tbody>
</table>

### 7.4.5 Test 5: Winter Condition with High Efficiency Spin

For this test, we wanted to simulate a best case scenario for drying clothes. We considered drying clothes during the winter (with the furnace on the entire time) and clothes that were washed in a newer model washing machine (with high efficiency spin cycle) to be a best case scenario. This test also used a circular air diffuser for better air distribution, as was the case for Test 4.
The wet weight of these clothes was 16 pounds, and the dry weight was 12 pounds. Thus, the dry cycle for this test removed 4 pounds of water. All of the clothes in this test were dry after 75 minutes.

Table 12: Psychrometric Data for Test 5

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temp (F)</th>
<th>Dew Point (F)</th>
<th>Wet Bulb (F)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>73.9</td>
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<td>66.4</td>
<td>71.1</td>
</tr>
<tr>
<td>10</td>
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<td>70.4</td>
<td>70.6</td>
<td>77.1</td>
</tr>
<tr>
<td>15</td>
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<td>72.0</td>
<td>72.2</td>
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</tr>
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</tr>
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<td>73.9</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>100.9</td>
<td>69.5</td>
<td>70.6</td>
<td>29.2</td>
</tr>
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<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
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<td>97.2</td>
<td>68.9</td>
<td>69.9</td>
<td>32.4</td>
</tr>
<tr>
<td>65</td>
<td>101.8</td>
<td>61.3</td>
<td>69.7</td>
<td>27.4</td>
</tr>
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<td>105.1</td>
<td>62.1</td>
<td>69.3</td>
<td>24.2</td>
</tr>
<tr>
<td>75</td>
<td>112.6</td>
<td>59.5</td>
<td>68.2</td>
<td>18.2</td>
</tr>
</tbody>
</table>

7.4.6 Relative Humidity in Dryer
During test four and five the relative humidity in the dryer was determined using the anemometer. The RH was measured just below where the clothes were hanging so as to get information on the water content of the clothes and the speed at which the clothes were drying. In the figure below it can be see that the dryer humidity at the beginning of test four was much lower than the relative humidity at the beginning of the drying of test four. This could be because test four was completely saturated with water to the point where the clothes were dripping with water. This could mean that the saturated water lowered the humidity at the beginning of the test and took longer to evaporate due to the larger mass of water in the dryer.
Another important result of the above figure is that the RH does not decrease below 15%. This means that the clothes will not over dry as we thought might be a problem. Because the RH in the dryer does not decrease below 15%, this tells us that the clothes that are drying will always have at least 9% of their moisture in them when they are dried. We also know that the clothes will not over dry because during one of the tests the clothes were left in the dryer for several hours after they had dried and they were not stiff nor did they have a bad odor.

7.4.7 Air flow Distribution
To get the best drying results in was necessary for the air distribution to be as even as possible throughout the dryer. The velocity of the air was measured at fifteen different positions within the cabinet. These points were evenly distributed across the dryer directly above where the clothes would be hanging. This point was chosen because we knew that we would not see accurate results of the diffuser if we took measurements below where the clothes were hanging due to disruptions in air flow that the clothes would cause. The first test was done with the square air diffuser. The results are shown in the figure below.
From this data we learned that the diffuser, which we were using in the cabinet, was doing a great job of pushing all air out to the sides. It was doing such a good job that there was little air flow in the middle. We solved this problem by removing the middle part of the diffuser. This put more air flow in the middle but did not solve the problem completely. As seen in the figure below there is still a large area with relatively low air velocity.

We decided to try a third diffuser that was circular. This diffuser did a much better job distributing the air as the velocity at the sides of the dryer were high as well as the air velocity in the middle of the dryer. This can be seen in the figure below.
7.4.8 Odor and Stiffness
Two problems that Jon experienced with the clothes dryer at the military academy in Vilnius Lithuania were that the clothes smelled bad and were stiff. The bad odor was more than likely due to the long dry times. In our tests with both the experimental unit and the prototype we did not experience these problems.

7.5 Theoretical Simulations
7.5.1 Purpose of Theoretical Calculations
There were four main objectives that the theoretical calculations accomplished: functionality during different seasons, fan size, and condensation (duct sweating). Functionality during different seasons, including harsher conditions in Eastern Europe, was key to the design norm of trust; we want our clothes dryer to perform well, even under adverse weather conditions. There are four (4) simulations: a summer case, winter case, a spring/autumn case, and a worst case scenario. 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 in Table 13 as well as later in this section. Figure 33 shows the control volume used for analyzing this system:
The team received a 10” centrifugal duct fan rated at 589 CFM from Marshall & Wells Co, and wanted to know if it would be useable for our design. Iterations were performed using Engineering Equation Solver (EES), first with estimated values for temperatures, humidity, and water weight, and then modified to what was measured from experiments. The results from the estimated values are shown in the table below; these results showed that the donated fan had the capabilities that were needed for ample airflow:

![Control Volume and Statepoints for Dryer](image)

**Figure 33: Control Volume and Statepoints for Dryer**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duct Area [ft^2]</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>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
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<tr>
<td>m_dot_in [lb/s]</td>
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</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>

Table 13: Inputs and Outputs for Estimated Quantities
Another reason for running simulations, both before and after finalization of the design, was to find out if condensation would form on the ducts. Known as duct sweating, this can cause dripping from the ducts, leading to wet spots in the home and ultimately damaging the floors and/or walls if left untreated. Condensation will occur if the dry-bulb temperature of the air falls below the dew point temperature; that is, if the air’s temperature falls below the temperature where the air is saturated, condensation droplets will form on the duct surfaces. In these simulations, none of the seasons had condensation forming on the ducts. The results from the initial calculations are shown below:

Table 14: Inputs and Outputs Regarding Dew Point Temperatures

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duct Area [ft^2]</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>DP_in [F]</td>
<td>97.84</td>
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<td>39</td>
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<td>T drybulb out [F]</td>
<td>106</td>
<td>81</td>
<td>40</td>
</tr>
<tr>
<td>DP_out [F]</td>
<td>102.2</td>
<td>78.18</td>
<td>37.46</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>0.046</td>
<td>0.021</td>
<td>0.005</td>
</tr>
<tr>
<td>m_dot_in [lb/s]</td>
<td>0.4906</td>
<td>0.675</td>
<td>0.8879</td>
</tr>
<tr>
<td>m_dot_out [lb/s]</td>
<td>0.4935</td>
<td>0.6779</td>
<td>0.8908</td>
</tr>
<tr>
<td>Air velocity in [ft/s]</td>
<td>83.32</td>
<td>108.8</td>
<td>131.6</td>
</tr>
</tbody>
</table>

### 7.5.2 Assumptions

Several assumptions were made in order to simplify the calculations. As prototype testing results surfaced, the thermodynamic model was modified in order to account for the discrepancies. This is discussed in section 7.5.7. 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 that 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. As prototype data was collected, it was obvious that pressure drop needed to be accounted for in the model. This is discussed in section 7.5.7.

The third assumption 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.
The final assumption is that 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 L) to find the outgoing dry bulb temperature.

7.5.3 Summer, Winter, and Spring/Autumn Condition Calculations
The following inputs were used for each case for the final design:

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Area [ft^2]</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>T drybulb in [F]</td>
<td>80</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>DP_in [F]</td>
<td>54</td>
<td>40</td>
<td>29</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>0.30</td>
</tr>
<tr>
<td>Relative humidity out [-]</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Air Velocity [ft/s]</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<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>63</td>
<td>79</td>
<td>39</td>
</tr>
<tr>
<td>T drybulb out [F]</td>
<td>68</td>
<td>84</td>
<td>41</td>
</tr>
<tr>
<td>DP_out [F]</td>
<td>61</td>
<td>49</td>
<td>43</td>
</tr>
<tr>
<td>Time [min]</td>
<td>52</td>
<td>65</td>
<td>58</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. This specification is listed as 80% relative humidity leaving the dryer; this was chosen because the team wished to simulate a situation where an ample amount of water was leaving the control volume without saturating the air.

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 by our design requirement (that is, the clothes must be dried in 1.5 hours).

From these inputs, the wet bulb temperature of the air was determined as a function of the dry bulb temperature, the pressure, and the relative humidity of the air. The absolute humidity of the air was determined 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 Figure 31):

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

Equation 7

Then, the difference of the absolute humidity from the two state points was used in conjunction with Eqn. (8.5.2.1), yielding:

\[ \omega_{\text{out}} - \omega_{\text{in}} = \Delta \omega = m_{\text{air,out}} - m_{\text{air,in}} \]

Equation 8

Once the absolute humidity of the exiting air was determined, the dry bulb temperature was determined at statepoint 2 as a function of the wet bulb temperature, pressure, and absolute humidity. The supporting calculations done in EES can be found in Appendix H.
7.5.4 **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).

7.5.5 **Eastern European Worst Case Simulation**

With Eastern Europe being our primary target market, we had to take into consideration that many homes may not have air conditioning capable of cooling the air during a hot summer day. A simulation of a hot and humid summer day in a part of Eastern Europe was performed. Using data\(^{19}\), the following inputs and outputs were gained from our existing model:

Table 16: Inputs and Results for a Hot Summer Day in Romania

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Romanian Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Area [ft(^2)]</td>
<td>0.2</td>
</tr>
<tr>
<td>T drybulb in [F]</td>
<td>79</td>
</tr>
<tr>
<td>DP in [F]</td>
<td>59</td>
</tr>
<tr>
<td>Pressure [psia]</td>
<td>14.7</td>
</tr>
<tr>
<td>Relative humidity in [-]</td>
<td>0.49</td>
</tr>
<tr>
<td>Relative humidity out [-]</td>
<td>0.80</td>
</tr>
<tr>
<td>Air velocity in [ft/s]</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density [lb/ft(^3)]</td>
<td>0.07</td>
</tr>
<tr>
<td>T wetbulb [F]</td>
<td>66</td>
</tr>
<tr>
<td>T drybulb out [F]</td>
<td>70</td>
</tr>
<tr>
<td>DP out [F]</td>
<td>64</td>
</tr>
<tr>
<td>Time [min]</td>
<td>71</td>
</tr>
</tbody>
</table>

7.5.6 **Duct Condensate Simulations**

Very quickly, we discovered that there was a possibility of condensation forming on duct surfaces (duct sweating), and inside the duct (raining) due to the increased amount of moisture and the decreased dry-bulb temperature in the exiting airstream. Because of the briefly increased amount of moisture in the exiting stream of air for a short amount of time in the beginning of the drying process, we decided to simulate a situation where the exiting relative humidity was 90% and the mass flow rate of water being removed from the clothes was double the amount during the constant drying simulation. This doubled mass flow rate was an amount decided after consulting with Dr. Wayne Wentzheimer about these simulations specifically. The inputs and outputs for each season and the Romanian worst summer case are shown below:

---

\(^{19}\) Source: http://www.romania.climatemps.com/
Correlating Theoretical Results and Prototype Results

After comparing the original results from the theoretical simulations with the results from the prototype, the team realized that the model did not account for any airflow distribution or velocity differences due to pressure drops inside the system. This is because the model for the dryer is a thermodynamic state-point model, and it does not take these things into account due to the nature of the control volume enclosing the clothes inside the dryer. Measurements of velocities with small, medium, and large loads were taken, and the model was adjusted accordingly. The correlation with the prototype results are shown in Figure 34.

Conclusions

According to the results of these simulations, 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 we currently have and/or fans we have deemed as compatible with this apparatus.

The theoretical results and prototype results are strongly correlated, and the largest discrepancy between the two is 10 minutes:

<table>
<thead>
<tr>
<th>Inputs (Duct Sweating)</th>
<th>Winter</th>
<th>Spring/Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Area [ft^2]</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>T drybulb in [F]</td>
<td>80</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>DP_in [F]</td>
<td>54</td>
<td>40</td>
<td>29</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>0.3</td>
</tr>
<tr>
<td>Relative humidity out [-]</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Air Velocity [ft/s]</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs (Duct Sweating)</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>63</td>
<td>52</td>
<td>46</td>
</tr>
<tr>
<td>T drybulb out [F]</td>
<td>65</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>DP_out [F]</td>
<td>62</td>
<td>51</td>
<td>44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Romanian Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct Area [ft^2]</td>
<td>0.2</td>
</tr>
<tr>
<td>T drybulb [F]</td>
<td>79</td>
</tr>
<tr>
<td>DP_in [F]</td>
<td>59</td>
</tr>
<tr>
<td>Pressure [psia]</td>
<td>14.7</td>
</tr>
<tr>
<td>Relative humidity in [-]</td>
<td>0.49</td>
</tr>
<tr>
<td>Relative humidity out [-]</td>
<td>0.80</td>
</tr>
<tr>
<td>Air velocity [ft/s]</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Romanian Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density [lb/ft^3]</td>
<td>0.07</td>
</tr>
<tr>
<td>T wetbulb [F]</td>
<td>66</td>
</tr>
<tr>
<td>T drybulb out [F]</td>
<td>70</td>
</tr>
<tr>
<td>DP_out [F]</td>
<td>64</td>
</tr>
<tr>
<td>Time [min]</td>
<td>71</td>
</tr>
</tbody>
</table>
With this strong correlation, we are confident that our model accurately predicts situations with or without air conditioning during the summer, shown as the “summer” conditions and “Romanian Summer” conditions in Figure 35:

8 Business Plan

8.1 Marketing Strategy

8.1.1 Target Market
We are targeting our market towards European countries with Eastern Europe being our primary target market, because they do not often use tumble dryers due to higher energy costs. We chose
Europe over the Americas because of the more attractive payback time in Europe which can be seen in section 8.5.1 and 8.5.2. Also, we are more likely to be able to sell our product to countries who have HVAC systems in their homes, who have the money to buy our product, and who are already very 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%)\(^\text{20}\), Ireland (87%), Slovenia (79%), and Turkey (100%)\(^\text{21}\). 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, as mentioned earlier in section 6.1.1, 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 our product. 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.

### 8.1.2 Customer’s Motivational Factors

With the energy crisis looming, more of the European population is becoming aware\(^\text{22}\) of the need to conserve energy and to “green” already existing processes. By lowering the amount of energy input for a household, a household saves money on energy consumption. After asking some family members, friends, and environmentally-minded acquaintances, the significant motivational factors are:

#### 8.1.2.1 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.

#### 8.1.2.2 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.

### 8.1.3 Market Size and Trends

#### 8.1.3.1 How large is the market?

Since the awareness of the energy crisis is spreading, 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 other “green” appliance or those who are thinking of owning a “green” appliance.

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\(^{22}\) [http://www.energyawareness.eu/beaware/](http://www.energyawareness.eu/beaware/)
8.1.3.2 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. Energy Star qualification is a principle which is common in America, but it is also well known in Europe. 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 in Europe are already familiar with “green” technology, the demand for the HVAC clothes dryer is most likely to increase; hence, the targeted market is growing.

8.1.4 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.

8.1.4.1 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).

8.1.4.2 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.

8.1.4.3 Offline Promotion
Brochures: The brochures would mainly be advertisement for the HVAC clothes dryer. An updated brochure would be distributed annually to appliance stores via mail, noting any changes and improvements with the clothes dryer including: design changes, functionality, and cost.

8.1.4.4 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).

8.2 Business Strategy
8.2.1 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.

8.2.2 Company Goals and Objectives
8.2.2.1 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

23 http://www.eu-energystar.org/
are no secondary shipment in between raw materials coming in and a final product going out to the consumer.

8.2.2.2 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.

8.3 Competitor Analysis
8.3.1 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.

8.3.1.1 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.

8.3.1.2 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.

8.3.2 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.

8.4 Cost Estimates
A cost analysis was done on our design in order to find an approximate market price for which our product could be sold. In order to find an appropriate cost, aspects such as production location, material cost, and labor costs had to be taken into account.

8.4.1 Location of Production
In order to choose the right location for production three different criteria had to be met. First the country in which production occurred had to be a member of the European Union (EU) Next, the country had to have inexpensive labor costs as well as inexpensive building space in order to help keep our production costs down. A space of 200 ft$^2$ was assumed for the building space that
would be needed. This is enough space to fit two dryers being assembled simultaneously with room for a large metal bender, sheet metal cutter, a sheet metal punching machine, as well as a station for riveting. Tables of both labor costs and building space costs can be seen below.

Table 19: Cost of Labor in EU Nations

<table>
<thead>
<tr>
<th>Country</th>
<th>Labor Costs (€/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>€ 38.44</td>
</tr>
<tr>
<td>Belgium</td>
<td>€ 37.70</td>
</tr>
<tr>
<td>Sweden</td>
<td>€ 35.99</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>€ 3.70</td>
</tr>
<tr>
<td>Romania</td>
<td>€ 4.20</td>
</tr>
</tbody>
</table>

Table 20: Cost of Renting Building Space in EU Nations

<table>
<thead>
<tr>
<th>Country</th>
<th>Building Space Costs (€/ft²)</th>
<th>Total Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>€ 221</td>
<td>€ 44,275</td>
</tr>
<tr>
<td>Belgium</td>
<td>€ 59</td>
<td>€ 11,756</td>
</tr>
<tr>
<td>Sweden</td>
<td>€ 110</td>
<td>€ 21,985</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>€ 53</td>
<td>€ 10,534</td>
</tr>
<tr>
<td>Romania</td>
<td>€ 44</td>
<td>€ 8,702</td>
</tr>
</tbody>
</table>

Because Bulgaria has inexpensive building space as well as inexpensive labor, we chose Bulgaria as a good place for production of our product.

8.4.2 Market Price

Once an appropriate location for production had been chosen, a price for the product was calculated including raw materials, labor costs, installation costs, and building space costs. When researching to find an appropriate markup for our product, our team consulted with Professor Medema who stated that an appropriate market price for European appliances was approximately 150% of the cost of manufacturing. A list of the materials and the costs involved in the production, as well as the market price can be seen in a table below.

---


### Table 21: Cost of Materials and Market Price

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost (€)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Fan</td>
<td>200</td>
<td>260</td>
</tr>
<tr>
<td>Cost of Sheet Metal</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Cost of Duct Work</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Total Manufacturing Costs</td>
<td>450</td>
<td>590</td>
</tr>
<tr>
<td>Market Price</td>
<td>675</td>
<td>885</td>
</tr>
</tbody>
</table>

Using the current conversion rate of the American dollar to euros, which is 1.31 $/€, our market price came to be just under €700. The cost of manufacturing also includes the cost of labor in Bulgaria. The assumption of 20 hours was made from the hours that our team spent building the prototype for our design. In Bulgaria the cost of labor is €3.70 which means the cost of labor per unit is €56.49. If the labor cost is added to the material cost this means our manufacturing cost is €450.

### 8.5 Payback Period

#### 8.5.1 Europe

The goal of our design is for the dryer to be an energy and cost efficient product. In order for this to succeed, when our product is bought, it must pay the customer back in savings in a reasonable time before the life of the product ends. In order to calculate the payback period for the European market, energy performance data for gas and electric tumble dryers, drying cabinets, and our own HVAC dryer was gathered and can be seen in the table below.

### Table 22: Energy Performance Data for Different Laundry Dryers in Europe

<table>
<thead>
<tr>
<th>Dryer Type</th>
<th>Power (W)</th>
<th>Daily Energy (kWh)</th>
<th>Cost of Use per Year (€)</th>
<th>Cost Drying Unit (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tumble Dryers (elect)</td>
<td>4350</td>
<td>4.35</td>
<td>277</td>
<td>700</td>
</tr>
<tr>
<td>Tumble Dryer (gas)</td>
<td>6450</td>
<td>6.45</td>
<td>65</td>
<td>700</td>
</tr>
<tr>
<td>Drying Cabinets</td>
<td>2070</td>
<td>2.07</td>
<td>132</td>
<td>1,100</td>
</tr>
<tr>
<td>HVAC Dryer</td>
<td>196</td>
<td>0.196</td>
<td>12</td>
<td>587</td>
</tr>
</tbody>
</table>

An important part of the above table is the significant difference in the daily energy used between the HVAC dryer and the rest of the dryers. This was calculated based on the assumption that the average household uses their laundry dryer for one hour every day.

The cost of electricity that was used in these calculations was €0.17, which is an average of the electricity price in several different European countries can be seen in the table below.
Table 23: Electricity Cost in Europe

<table>
<thead>
<tr>
<th>Country</th>
<th>Cost (€/kWh)</th>
<th>Country</th>
<th>Cost (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>€ 0.20</td>
<td>Latvia</td>
<td>€ 0.13</td>
</tr>
<tr>
<td>Belgium</td>
<td>€ 0.23</td>
<td>Lithuania</td>
<td>€ 0.13</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>€ 0.08</td>
<td>Luxembourg</td>
<td>€ 0.17</td>
</tr>
<tr>
<td>Cyprus</td>
<td>€ 0.23</td>
<td>Malta</td>
<td>€ 0.17</td>
</tr>
<tr>
<td>Czech Rep.</td>
<td>€ 0.15</td>
<td>Netherlands</td>
<td>€ 0.21</td>
</tr>
<tr>
<td>Denmark</td>
<td>€ 0.30</td>
<td>Poland</td>
<td>€ 0.14</td>
</tr>
<tr>
<td>Estonia</td>
<td>€ 0.11</td>
<td>Portugal</td>
<td>€ 0.19</td>
</tr>
<tr>
<td>Finland</td>
<td>€ 0.16</td>
<td>Romania</td>
<td>€ 0.11</td>
</tr>
<tr>
<td>France</td>
<td>€ 0.14</td>
<td>Slovakia</td>
<td>€ 0.17</td>
</tr>
<tr>
<td>Germany</td>
<td>€ 0.26</td>
<td>Slovenia</td>
<td>€ 0.15</td>
</tr>
<tr>
<td>Greece</td>
<td>€ 0.13</td>
<td>Spain</td>
<td>€ 0.19</td>
</tr>
<tr>
<td>Hungary</td>
<td>€ 0.16</td>
<td>Sweden</td>
<td>€ 0.20</td>
</tr>
<tr>
<td>Ireland</td>
<td>€ 0.21</td>
<td>United Kingdom</td>
<td>€ 0.15</td>
</tr>
<tr>
<td>Italy</td>
<td>€ 0.22</td>
<td>Average</td>
<td>€ 0.17</td>
</tr>
</tbody>
</table>

Assuming that a user would already have a tumble dryer on hand and that the HVAC dryer would be completely replacing tumble dryer, the HVAC dryer would save the user about €264.35 per use of the dryer. Due to these savings the payback for the HVAC dryer can be seen in the figure below.

Figure 36: Payback for the HVAC Dryer with Electric Tumble Dryer

26 http://www.energy.eu/#domestic
This graph shows that the payback time for the HVAC dryer replacing an electric tumble dryer would be approximately 2.5 years. In the next graph, a payback time can be seen for the HVAC dryer if the buyer previously owns a gas tumble dryer.

![Figure 37: Payback for the HVAC Dryer with Gas Tumble Dryer](image)

This graph shows a payback time of approximately 12.8 years. In the next graph, a payback time can be seen for a drying cabinet.

![Figure 38: Payback for a Drying Cabinet with Electric Tumble Dryer](image)

The calculations for the drying cabinet were done with the same frequency of usage as the tumble dryer and HVAC dryer. However, the drying cabinet is designed to be used in combination with a tumble dryer so half of the energy consumed in a drying load from a tumble
dryer was added to the energy to dry the clothes in the drying cabinet. Because the continued use of the tumble dryer only causes the drying cabinet to save the user €6.68 per year and due to the high cost of the drying cabinet the payback period does not seem to occur after 30 years which is much longer than the life expectancy of a tumble dryer or a drying cabinet. Because the life expectancy of tumble dryers and drying cabinets is 15 years, the user would have to buy new units before the payback period occurred. Due to this extra expense at 15 years this causes users to not get any energy savings from purchasing a drying cabinet.

To get exact values of a payback period the numerical values for a payback were calculated can be seen below.

Table 24: Payback Periods for Each of the Drying Units

<table>
<thead>
<tr>
<th>Replacement</th>
<th>Previous Dryer</th>
<th>HVAC</th>
<th>Drying Cabinet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Tumble Dryer</td>
<td>2.5</td>
<td></td>
<td>Never</td>
</tr>
<tr>
<td>Gas Tumble Dryer</td>
<td>12.8</td>
<td></td>
<td>Never</td>
</tr>
</tbody>
</table>

As seen in this table and the previous figures, the payback period for the HVAC dryer in replacement of an electric or gas dryer is 2.5 and 12.8 years respectively. An important note about this table is if a drying cabinet is bought and used in conjunction with a gas or electric tumble dryer there is no payback because the payback does not occur before the user would have to replace both the drying cabinet and the dryer.

### 8.5.2 America

To further show why Europe was chosen as a target market payback periods were calculated for an American market. The same method as the European market was followed however different results were received. The table below shows the energy performance data used for the calculations.

Table 25: Energy Performance Data for Laundry Dryers in America

<table>
<thead>
<tr>
<th></th>
<th>Power (W)</th>
<th>Daily Energy (kWh)</th>
<th>Cost of Use per Year ($)</th>
<th>Cost Drying Unit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tumble Dryers (elect)</td>
<td>4350</td>
<td>4.35</td>
<td>191</td>
<td>917</td>
</tr>
<tr>
<td>Tumble Dryer (gas)</td>
<td>6450</td>
<td>6.45</td>
<td>32</td>
<td>917</td>
</tr>
<tr>
<td>Drying Cabinets</td>
<td>2070</td>
<td>2.07</td>
<td>91</td>
<td>1441</td>
</tr>
<tr>
<td>HVAC Dryer</td>
<td>196</td>
<td>0.20</td>
<td>9</td>
<td>881</td>
</tr>
</tbody>
</table>
For the costs per year the same assumption of an hour of use per day was used. The average electricity cost in America is $0.12/kWh\[^{27}\] which was used to calculate the cost of use per year. When assuming that the user would be replacing an electric tumble dryer the payback period is just over 4 years as seen in the figure below.

![Figure 39: Payback for HVAC Dryer with Electric Tumble Dryer](image)

While this payback time is still acceptable, it is not as good as the payback time if the HVAC dryer replaces the electric tumble dryer in Europe. A graph of the payback time for the HVAC dryer replacing the gas tumble dryer can be seen in the figure below. The payback period is about 15 years due to the fact that our system has a much longer life expectancy than a tumble dryer and a tumble dryer would need to be replaced after 15 years of use.

![Figure 40: Payback for HVAC Dryer with Electric Tumble Dryer](image)

\[^{27}\] http://www.eia.gov/electricity/data.cfm#sales
This payback period is again not as good as the payback time as the European payback period for the replacement of the gas dryer. Below is the payback time for a drying cabinet in combination with an electric tumble dryer.

![Figure 41: Payback for Drying Cabinet with Electric Tumble Dryer](image)

This graph is very similar to the payback period of the drying cabinet in Europe. Because the drying cabinet is designed to be used in combination with a tumble dryer so half of the energy consumed in a drying load from a tumble dryer was added to the energy to dry the clothes in the drying cabinet. Because the continued use of the tumble dryer causes the drying cabinet to only save the user $4.60 per year and due to the high cost of the drying cabinet, the payback period does not seem to occur after 30 years which is much longer than the life expectancy of a tumble dryer or a drying cabinet. Similar to the European case, due to life expectancy the drying cabinet does not allow the user to accumulate any energy savings.

A table of all of the payback periods for America can be seen in the table below.

<table>
<thead>
<tr>
<th>Table 26: Energy performance data for different laundry dryers in America</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous Dryer</td>
</tr>
<tr>
<td>Electric Tumble Dryer</td>
</tr>
<tr>
<td>Gas Tumble Dryer</td>
</tr>
</tbody>
</table>

Again, it can be seen that the payback for the gas tumble dryer in combination with the drying cabinet is negative which means that the payback does not occur. Another important factor about this table is that all of the payback times for the HVAC dryer are greater than the respective
payback times in Europe. This is one of the main reasons why our team chose Europe as our target market.

9 Conclusion

After performing theoretical simulations, conducting research, and running tests on our experimental unit and prototype, we determined that the design does dry clothes in a timely manner in all seasons. During the winter with hot air coming into the dryer, which is our best case scenario, our dryer was able to dry the clothes in 37 minutes per load. In a worst case scenario, which is during the spring and fall when ambient air is running through the dryer, the dryer was able to dry the clothes in 74 minutes per load. This worst case scenario is slower than a tumble dryer but by an amount that is acceptable because our best case scenario is much faster than a tumble dryer. These drying times meet our design goal of drying clothes in an average of one hour per load.

This drying process also saves on energy costs for a household by decreasing the energy consumption. In our target market of Europe, our product saves the user approximately €265 per year if the dryer is used for one hour every day and is replacing an electric dryer. When a gas dryer is being replaced our dryer saves the user €53. The decrease in savings is due to the low cost of gas compared to electricity. The pay back times for replacing an electric or gas tumble dryer are 2.5 and 12.8 years respectively. With a low cost of €675 for a market price to customers in our target market, our unit would be especially ideal for those replacing a tumble dryer or purchasing a new home where this design could be installed.

Through this project, we hoped 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. Because our design is both energy and cost efficient we feel that we have been successful in meeting our design criteria.
10 Acknowledgements

Dr. Wayne Wentzheimer
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 our team 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.
**Robert Medema**

Professor Medema was very instrumental in our project when it came to considering the economics and business aspect of our dryer. He assisted with approximating our market price for our design and also gave us guidance in choosing a target market.

**Rich DeJong**

Professor DeJong was very helpful with the theoretical aspect of our project. When our team was considering modeling our dryer in a CFD program he gave us advice on how to go about modeling our dryer and what we could expect from the results.

**Koops Inc**

Koops was very helpful when they donated their time to our project. This company was very helpful in modeling our system in a CFD program. They helped us acquire and interpret the results of the analysis.
11 Appendices

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Industrial Consultant Brief for 10/25/12
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
Project Description

Our project is a clothes drying apparatus that uses air from a home’s central air system. Our design is intended to replace a home’s traditional tumble dryer, and deliver significant energy savings. Our design is both economically and environmentally friendly, as well as effective in dry time and the quality of the clothes once the clothes are dry.

Our design taps into the main supply duct of a home’s HVAC system, drawing air through the chamber across the clothing, and is exhausted back into the return duct of the home’s system.

We have two conditions to consider and target our design towards. The first is when the home’s HVAC system is in heating mode (spring, fall, and winter seasons). In this case air is hot and dry, and effectively removes moisture from the clothing. This is the easier of the two conditions to design for. The second, and more difficult condition, is in cooling mode (summer season). During this time, the home’s HVAC system is supply cold, dry air. Although the air is dry, the cold temperature will be less effective at removing moisture from the clothing. We expect longer dry times during this condition.

Requirements Summary

- Effectively dry clothes in the same amount of time as a tumble dry with same quality of dry
  - If our drying apparatus can hold two loads of laundry, we want the dry time to be equal to or less than it would take a tumble dryer to dry two loads.
  - The quality of the dry is important; if the clothes are over-dried, they will be stiff and uncomfortable to wear, and have the potential for wrinkles. If the clothes are under-dried, they will be damp and unacceptable to be worn.
- Significant energy savings for user
  - We have calculated the cost to run a tumble dryer and the cost it takes to run our exhaust fan. When on full power for the same amount of time, our fan uses just 1% of the energy that a high-efficiency tumble dryer uses. So, if a family spends $500 a year on energy to dry their clothes, that can save $450 a year using our design.

Design Decisions

- Exhaust fan: blow versus draw air through drying apparatus
- Dimensions of final prototype
- Desiccant

Significant Issues

- We had an anemometer that gave us a reading of 99% humidity out of a furnace
• Found that bunched clothes do not dry well, so final design needs to allow for clothes to hang freely
• Desiccant
  o Potential for skin and lung irritation
  o Decrease flow rate
  o Air flow to fast for it to be effective
  o Would need to be regenerated by the user
• Would this sell in the U.S.? What out in Europe?
• Is it possible to over dry the clothes? How can we prevent this?
• Will this system work/ be feasible in the summer? Spring? Fall?

**Current Status**
• The defective anemometer was replaced and we are now ready to collect real psychrometric data and perform analysis
• Ordered and are waiting on sheet metal to begin building prototype
• Looking into the potential market in Europe, specifically eastern Europe
• Doing FEA analysis on air flow
• Looking into a way to incorporate desiccant
Appendix C: 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.
Appendix D: 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.

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. Notes were taken by Jon Wilgus in order that what was discussed in our weekly meetings could be remembered and checked off a list when they were completed. Every week the tasks that had been accomplished and the tasks that needed to be done were discussed in detail.

Team Communication

Due to the fact that each team member had different individual parts of the project, weekly team meetings and emails were 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.

Schedule

We created two Work Breakdown Schedules (WBS) in the form of gantt charts at the beginning of each 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. The gantt chart was also helpful in managing all of the individual tasks that needed to be completed. The gantt chart ensured that our team was kept on schedule but also allowed us to be flexible with the schedule and task management.

Tasks

As mentioned above in section 4.2 the tasks were divided up into smaller tasks that were manageable. Amanda Doyle was in charge of a large portion of the theoretical side of the project. These theoretical calculations that were performed allowed us to know the fan speed required to dry clothes as well as know what kind of drying time to expect for each season of the year. Amanda was also in charge of researching for our target market and making sure that our product was something that a customer would consider purchasing.

Stephen Kraft was in charge of the desiccant bed feasibility when this design option was being considered. This option did not end up being a part of the final design but calculations including pressure drop, exposure time, and regeneration frequency and costs were all considered when making this decision. Stephen was also in charge of the economics for this project. This includes calculating the market price for our product as well as the payback periods for the HVAC dryer.
Drew Reyelts was responsible for the design and building of the experimental unit and prototype throughout the year. This being the case Drew spent most of his time in the metal shop building. Drew, with his experience in the HVAC industry, also made sure that both of the designs had the best possible air distribution.

Jon Wilgus assisted Drew with all of the design and building that occurred throughout the year by being a second hand whenever it was needed but was also responsible for drawing and updating the design in a CAD program. This ensured that all of the metal cuts that were made were the correct dimensions in order to have a working prototype at the end of the year.

**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.
Appendix E: Experimental Unit Calculations

"(1) With No Filter"
\[ V = 11.7 \times \text{convert}(\text{m/s, ft/min}) \]
\[ D = 4.5 \text{ [in]} \]
\[ A = \pi D^2 / 4 \times \text{convert}(\text{in}^2, \text{ft}^2) \]
\[ \text{CFM} = V \times A \]
\[ V_{\text{cone}} = 1794.709 \times \text{convert}(\text{in}^2, \text{ft}^2) \]
\[ V_{\text{box}} = 22.5[\text{in}] 	imes 18.5[\text{in}] \times 16.375[\text{in}] \times \text{convert}(\text{in}^3, \text{ft}^3) \]
\[ V_{\text{total}} = V_{\text{cone}} + V_{\text{box}} \]
\[ \text{AirChange}_{\text{hour}} = \left( \frac{\text{CFM}}{V_{\text{total}}} \right) \times \text{convert}(\text{1/min, 1/hr}) \]

"The velocity of the air"  
"The diameter of the duct"  
"The cross sectional area of the duct"  
"The flow rate in cubic feet per minute (CFM)"  
"Volume of the hood"  
"Volume of the Box"  
"The total volume"  
"The number of times the air is completely changed in one hour"

"(2) Smaller diameter duct, with a filter"
\[ V_2 = 11.7 \times \text{convert}(\text{m/s, ft/min}) \]
\[ D_2 = 3 \text{ [in]} \]
\[ A_2 = \pi D_2^2 / 4 \times \text{convert}(\text{in}^2, \text{ft}^2) \]
\[ \text{CFM}_2 = V_2 \times A_2 \]
\[ \text{AirChange}_{\text{hour,2}} = \left( \frac{\text{CFM}_2}{V_{\text{total}}} \right) \times \text{convert}(\text{1/min, 1/hr}) \]

"The velocity of the air"  
"The diameter of the duct"  
"The area of the duct"  
"The flow rate in CFM"  
"The number of air changes"

"Same diameter duct, as #2, with a filter, with a layer of desiccant"
\[ V_3 = 3.3 \times \text{convert}(\text{m/s, ft/min}) \]
\[ \text{CFM}_3 = V_3 \times A_2 \]
\[ \text{AirChange}_{\text{hour,3}} = \left( \frac{\text{CFM}_3}{V_{\text{total}}} \right) \times \text{convert}(\text{1/min, 1/hr}) \]

"The Velocity of the air"  
"The number of times the air is completely changed in one hour"

"Furnace Out - Air In"
\[ V_{\text{furnace, on}} = 6 \times \text{convert}(\text{m/s, ft/s}) \]
\[ \text{CFM}_{\text{furnace, on}} = \frac{A \times V_{\text{furnace, on}}}{\text{convert}(\text{ft}^3/\text{s, ft}^3/\text{min})} \]

"The speed of the air coming out of the furnace"  
"The flow rate without the aid of a fan"

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

"The velocity of the air"  
"Area of the outlet"  
"Flow rate of the air coming out"  
"The air changes that are coming out"

Unit Settings: SI C kPa kJ mass deg

\begin{align*}
A &= 0.1104 \text{ [m]}^2 \\
A_{\text{out}} &= 0.08507 \text{ [m]}^2 \\
\text{CFM}_3 &= 31.89 \text{ [ft}^3/\text{min}] \\
D &= 4.5 \text{ [in]} \\
V_2 &= 2303 \text{ [ft/min]} \\
V_{\text{cone}} &= 1.039 \text{ [ft}^3] \\
V_{\text{total}} &= 5.196 \text{ [ft}^3] \\
A_{\text{out}} &= 0.08507 \text{ [m]}^2 \\
\text{CFM}_3 &= 31.89 \text{ [ft}^3/\text{min}] \\
\text{CFM}_{\text{furnace, on}} &= 130.4 \text{ [ft}^3/\text{min}] \\
D_2 &= 3 \text{ [in]} \\
V_2 &= 2303 \text{ [ft/min]} \\
V_{\text{out}} &= 4150 \text{ [ft}^3] \\
V_{\text{out}} &= 1555 \text{ [ft}^3/\text{min}] \\
\text{AirChange}_{\text{hour,2}} &= 1305 \text{ [1/hr]} \\
\text{AirChange}_{\text{hour,3}} &= 368.2 \text{ [1/hr]} \\
\text{AirChange}_{\text{out}} &= 2937 \text{ [1/hr]} \\
\text{CFM}_2 &= 113.1 \text{ [ft}^3/\text{min}] \\
\text{CFM}_{\text{out}} &= 264.6 \text{ [ft}^3/\text{min}] \\
V &= 2303 \text{ [ft/min]} \\
V_{\text{furnace, on}} &= 19.63 \text{ [ft/s]} \\
\end{align*}

No unit problems were detected.
Appendix F: Experimental Unit Theoretical Calculations

Winter Conditions

Assume SS for all calculations

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

\[
\rho_{\text{airwinter}} = \rho \left[ \text{"Air"} , \ T = T_{\text{in,winter}} , \ P = P_1 \right]
\]

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

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

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

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

\[
\rho_{\text{in,winter}} = \rho \left[ \text{"AirH}_2\text{O}" , \ T = T_{\text{in,winter}} , \ B = T_{\text{wet,in,winter}} , \ P = P_1 \right]
\]

\[
P_2 = P_1
\]

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

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

\[
\rho_{\text{out,winter}} = \rho \left[ \text{"AirH}_2\text{O}" , \ T = T_{\text{out,winter}} , \ B = T_{\text{wet,out,winter}} , \ P = P_2 \right]
\]

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

\[
\dot{m}_{\text{water,winter}} = \frac{\delta \ [\text{lb}] }{\text{time}}
\]

\[
\dot{m}_{\text{in,winter}} + \dot{m}_{\text{water,winter}} = \dot{m}_{\text{out,winter}}
\]

\[
\omega_{\text{out,winter}} = \omega_{\text{in,winter}} = \frac{\dot{m}_{\text{water,winter}}}{\dot{m}_{\text{in,winter}}}
\]

Psychrometric chart

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

Summer Conditions

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

\[
T_{\text{in,summer}} = 55 \ [\text{F}]
\]
\[ T_{\text{wet,summer}} = \text{WB} \left[ '\text{AirH2O}', T = T_{\text{in,summer}}, R = r_{\text{in,summer}}, P = P_1 \right] \]

\[ r_{\text{in,summer}} = 0.15 \]

\[ \omega_{\text{in,summer}} = \omega \left[ '\text{AirH2O}', T = T_{\text{in,summer}}, B = B_{\text{wet,in,summer}}, P = P_1 \right] \]

\[ T_{\text{wet,summer}} = T_{\text{wet,in,summer}} \]

\[ r_{\text{out,summer}} = 0.8 \]

\[ \omega_{\text{out,summer}} = \omega \left[ '\text{AirH2O}', T = T_{\text{out,summer}}, B = B_{\text{wet,summer}}, P = P_2 \right] \]

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

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

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

\[ \omega_{\text{out,summer}} = \omega_{\text{in,summer}} \frac{\dot{m}_{\text{water,summer}}}{\dot{m}_{\text{in,summer}}} \]

*Psychrometric chart*

\[ T_{\text{out,summer}} = T \left[ '\text{AirH2O}', R = r_{\text{out,summer}}, B = B_{\text{wet,summer}}, P = P_2 \right] \]

*Spring/Fall Conditions*

\[ f_{\text{air, sf}} = \rho \left[ '\text{Air}', T = T_{\text{in, sf}}, P = P_1 \right] \]

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

\[ T_{\text{wet,in, sf}} = \text{WB} \left[ '\text{AirH2O}', T = T_{\text{in, sf}}, R = r_{\text{in, sf}}, P = P_1 \right] \]

\[ r_{\text{in, sf}} = 0.4 \]

\[ \omega_{\text{in, sf}} = \omega \left[ '\text{AirH2O}', T = T_{\text{in, sf}}, B = B_{\text{wet,in, sf}}, P = P_1 \right] \]

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

\[ r_{\text{out, sf}} = 0.8 \]

\[ \omega_{\text{out, sf}} = \omega \left[ '\text{AirH2O}', T = T_{\text{out, sf}}, B = B_{\text{wet,out, sf}}, P = P_2 \right] \]
About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer

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

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

\[ \dot{\omega}_{\text{out, sf}} - \dot{\omega}_{\text{in, sf}} = \frac{m_{\text{water, sf}}}{m_{\text{in, sf}}} \]

**Psychrometric chart**

\[ T_{\text{out, sf}} = T \left[ \text{Air+H2O}, R = m_{\text{out, sf}}, B = T_{\text{wet, out, sf}}, P = P_1 \right] \]

**Time that clothes must be dried in**

\[ \text{time} = 1.5 \left( \frac{3600}{\text{hour}} \right) \]

\[ \Delta \dot{\omega}_{\text{winter}} = \dot{\omega}_{\text{out, winter}} - \dot{\omega}_{\text{in, winter}} \]

\[ \Delta \dot{\omega}_{\text{summer}} = \dot{\omega}_{\text{out, summer}} - \dot{\omega}_{\text{in, summer}} \]

\[ \Delta \dot{\omega}_{\text{sf}} = \dot{\omega}_{\text{out, sf}} - \dot{\omega}_{\text{in, sf}} \]

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

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

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

Unit Settings: Eng F psia mass deg

\[ A_{\text{duct}} = 0.0875 \text{ [ft}^2] \]
\[ \Delta \text{ summer} = 0.00335 \]
\[ m_{\text{in, sf}} = 0.3954 \text{ [lb/s]} \]
\[ m_{\text{in, winter}} = 0.2861 \text{ [lb/s]} \]
\[ m_{\text{out, summer}} = 0.4896 \text{ [lb/s]} \]
\[ m_{\text{water, sf}} = 0.001481 \text{ [lb/s]} \]
\[ m_{\text{water, winter}} = 0.001481 \text{ [lb/s]} \]
\[ \omega_{\text{in, summer}} = 0.001362 \]
\[ \omega_{\text{out, sf}} = 0.02026 \]
\[ \omega_{\text{out, winter}} = 0.04527 \]
\[ \rho_{\text{air, summer}} = 0.0771 \text{ [lb/ft}^3] \]
\[ \rho_{\text{air, winter}} = 0.4 \]
\[ \rho_{\text{in}} = 2 \]
\[ \rho_{\text{out, summer}} = 0.8 \]
\[ \text{time} = 5400 \text{ [s]} \]
\[ T_{\text{in, summer}} = 55 \text{ [F]} \]
\[ T_{\text{out, sf}} = 84.1 \text{ [F]} \]
\[ T_{\text{out, winter}} = 105.2 \text{ [F]} \]
\[ T_{\text{wat, in, summer}} = 38.92 \text{ [F]} \]
\[ T_{\text{wat, out, sf}} = 78.98 \text{ [F]} \]
\[ T_{\text{wat, out, winter}} = 102.7 \text{ [F]} \]
\[ v_{\text{in, summer}} = 72.36 \text{ [ft/s]} \]
\[ v_{\text{in, winter}} = 48.6 \text{ [ft/s]} \]

No unit problems were detected.

Arrays Table: Main

<table>
<thead>
<tr>
<th>( P_i )</th>
<th>[psia]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.7</td>
</tr>
<tr>
<td>2</td>
<td>14.7</td>
</tr>
</tbody>
</table>
"Summer Condition Calculations—Without Air-Conditioning"

"Using Romaine as 'test' country"

"Statepoint 1"
T_drybulb[1]=79 [F]
P=14.7 [psia]
DP[1]=(63 [F]+54 [F])/2
T_wetbulb[1]=WetBulb(AirH2O,T=T_drybulb[1],D=DP[1],P=P)
omega[1]=HumRat(AirH2O,T=T_drybulb[1],D=DP[1],P=P)
rh[1]=RelHum(AirH2O,T=T_drybulb[1],D=DP[1],P=P)

Area_duct=12.6*convert(in^2,ft^2)
rho_air=Density(air,T=T_drybulb[1],P=P)

"Statepoint 2"
rh[2]=0.8

"About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer"
time=5400 [s]
m_dot_water=8[lb_f]/time
m_dot[1]-m_dot_water=m_dot[2]
omega[2]-omega[1]=(m_dot_water/m_dot[1])

"Velocity needed in order to work."
m_dot[1]=vel_in*rho_air*Area_duct

\[ \text{Unit Settings: } \text{Eng F psi mass deg} \]
\[
\begin{align*}
\text{Area_duct} &= 0.0875 \text{ [ft}^2\text{]} & \dot{m}_{\text{water}} &= 0.001481 \text{ [lb/s]} & P &= 14.7 \text{ [psia]} \\
\rho_{\text{air}} &= 0.07356 \text{ [lb_f/ft}^3\text{]} & \text{time} &= 5400 \text{ [s]} & \text{vel_in} &= 110.1 \text{ [ft/s]} \\
\end{align*}
\]

Click on this line to see the array variables in the Arrays Table window

No unit problems were detected.

Calculation time = .0 sec.
"Winter Conditions" 

"Assume SS for all calculations"

Area_duct=12.3*convert(m^2,ft^2)  
rho_air_winter=Density_air,T=T_in_winter,P=P[1]  
T_in_winter=130 [F]  
T_wet_in_winter=WebBulb(Air=H2O,T=T_in_winter,rh_in_winter,P=P[1])  
(T_wet_in_winter=60 [F]; rh_in_winter=0.4)  
P[1]=14.7 [psia]  
omega_in_winter=HumRel(Air=H2O,T=T_in_winter,B=T_wet_in_winter,P=P[1])  
DP_in_winter=DewPoint(Air=H2O,T=T_in_winter,omega=omega_in_winter,P=P[1])

T_wet_out_winter=T_wet_in_winter  
rh_out_winter=0.9  
omega_out_winter=HumRel(Air=H2O,T=T_out_winter,B=DP_out_winter,P=P[2])  
DP_out_winter=DewPoint(Air=H2O,T=T_out_winter,omega=omega_out_winter,P=P[2])

"About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer"  
m_dot_water_winter=(0.5*Sigal/time)*2  
m_dot_in_winter=m_dot_water_winter-m_dot_out_winter  
omega_in_winter=omega_out_winter/m_dot_water_winter/m_dot_in_winter

"Psychrometric chart"  
T_out_winter=Temperature(Air=H2O,rh=rh_out_winter,B=T_wet_out_winter,P=P[1])

"Summer Conditions"  
rho_air_summer=Density_air,T=T_in_summer,P=P[1]  
T_in_summer=55 [F]  
T_wet_in_summer=WebBulb(Air=H2O,T=T_in_summer,rh_in_summer,P=P[1])  
(T_wet_in_summer=50 [F]; rh_in_summer=0.15)  
omega_in_summer=HumRel(Air=H2O,T=T_in_summer,B=T_wet_in_summer,P=P[1])  
DP_in_summer=DewPoint(Air=H2O,T=T_in_summer,omega=omega_in_summer,P=P[1])

T_wet_out_summer=T_wet_in_summer  
rh_out_summer=0.9  
omega_out_summer=HumRel(Air=H2O,T=T_out_summer,B=DP_out_summer,P=P[2])  
DP_out_summer=DewPoint(Air=H2O,T=T_out_summer,omega=omega_out_summer,P=P[2])

"About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer"  
m_dot_water_summer=(0.5*Sigal/time)*2  
m_dot_in_summer=m_dot_water_summer-m_dot_out_summer  
omega_in_summer=omega_out_summer/m_dot_water_summer/m_dot_in_summer

"Psychrometric chart"  
T_out_summer=Temperature(Air=H2O,rh=rh_out_summer,B=T_wet_out_summer,P=P[1])
"Spring/Fall Conditions"

\[\text{rho}_{\text{air sf}} = \text{Density(air, T= T_{in sf}, P=P[1])}\]

\[T_{in sf} = 70 \, \text{[F]}\]

\[T_{\text{wet in sf}} = \text{WetBulb(AirH}_{2}O, T= T_{in sf}, r= r_{in sf}, P=P[1])}\]

\[r_{in sf} = 0.4\]

\[\text{omega}_{\text{in sf}} = \text{HumRel(AirH}_{2}O, T= T_{in sf}, B= T_{\text{wet in sf}}, P=P[1])}\]

\[DP_{in sf} = \text{DewPoint(AirH}_{2}O, T= T_{in sf}, w= \text{omega}_{\text{in sf}}, P=P[1])}\]

\[T_{\text{wet out sf}} = T_{\text{wet in sf}}\]

\[r_{\text{out sf}} = 0.9\]

\[\text{omega}_{\text{out sf}} = \text{HumRel(AirH}_{2}O, T= T_{\text{out sf}}, B= T_{\text{wet out sf}}, P=P[2])}\]

\[DP_{\text{out sf}} = \text{DewPoint(AirH}_{2}O, T= T_{\text{out sf}}, w= \text{omega}_{\text{out sf}}, P=P[2])}\]

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

\[m_{\text{dot water sf}} = (8\, \text{[lb]} \cdot \text{[flh]}/\text{[time]]) \cdot 2\]

\[m_{\text{dot in sf}} = m_{\text{dot water sf}} \cdot \text{m}_{\text{dot out sf}}\]

\[\text{omega}_{\text{out sf}} = \text{omega}_{\text{in sf}} \cdot \text{m}_{\text{dot water sf}} \cdot \text{m}_{\text{dot in sf}}\]

"Psychrometric chart"

\[T_{\text{out sf}} = \text{Temperature(AirH}_{2}O, r= r_{\text{out sf}}, B= T_{\text{wet out sf}}, P=P[1])}\]

"Time that clothes must be dried in"

\[\text{time} = 1.5 \times \text{convert(hour, s)}\]

\[\text{DELTA}_{\text{omega winter}} = \text{omega}_{\text{out winter}} - \text{omega}_{\text{in winter}}\]

\[\text{DELTA}_{\text{omega summer}} = \text{omega}_{\text{out summer}} - \text{omega}_{\text{in summer}}\]

\[\text{DELTA}_{\text{sf}} = \text{omega}_{\text{out sf}} - \text{omega}_{\text{in sf}}\]

\[m_{\text{dot in winter}} = \text{vel}_{\text{in winter}} \times \text{rho}_{\text{air winter}} \times \text{Area duct}\]

\[m_{\text{dot in summer}} = \text{vel}_{\text{in summer}} \times \text{rho}_{\text{air summer}} \times \text{Area duct}\]

\[m_{\text{dot in sf}} = \text{vel}_{\text{in sf}} \times \text{rho}_{\text{air sf}} \times \text{Area duct}\]

---

**Unit Settings:** Eng F psia mass deg

- \(\text{Air in} = 0.0075\, [\text{F}]\)
- \(\text{DP}_{\text{summer}} = 18.7\, [\text{F}]\)
- \(\text{n}_{\text{dot out}} = 0.675\, [\text{hph}]\)
- \(\text{n}_{\text{dot water}} = 0.4905\, [\text{hph}]\)
- \(\text{n}_{\text{dot water}} = 0.003963\, [\text{hph}]\)
- \(\text{P}_{\text{water}} = 0.0401\, [\text{hph}]\)
- \(\text{P}_{\text{water}} = 0.00771\, [\text{hph}]\)
- \(\text{P}_{\text{water}} = 0.8\, [\text{hph}]\)
- \(\text{T}_{\text{out SF}} = 100\, [\text{F}]\)
- \(\text{T}_{\text{water}} = 105.5\, [\text{F}]\)
- \(\text{T}_{\text{water out}} = 39.92\, [\text{F}]\)

\[\Delta \text{H}_{\text{total}} = 0.00337\]

\[\text{DP}_{\text{out summer}} = 78.18\, [\text{F}]\]

\[\text{m}_{\text{dot in}} = 0.4906\, [\text{hph}]\]

\[\text{m}_{\text{dot water}} = 0.002963\, [\text{hph}]\]

\[\text{P}_{\text{water}} = 0.003\, [\text{hph}]\]

\[\text{P}_{\text{water}} = 0.00771\, [\text{hph}]\]

\[\text{T}_{\text{out SF}} = 100\, [\text{F}]\]

\[\text{T}_{\text{water out}} = 39.92\, [\text{F}]\]

\[\text{vel}_{\text{in}} = 100\, [\text{F}]\]

\[\text{vel}_{\text{in}} = 0.00604\]

\[\text{DP}_{\text{out summer}} = 37.48\, [\text{F}]\]

\[\text{m}_{\text{dot in}} = 0.6779\, [\text{hph}]\]

\[\text{m}_{\text{dot water}} = 0.02963\, [\text{hph}]\]

\[\text{P}_{\text{water}} = 0.004693\]

\[\text{P}_{\text{water}} = 0.8\, [\text{hph}]\]

\[\text{T}_{\text{out SF}} = 91.4\, [\text{F}]\]

\[\text{T}_{\text{water out}} = 102.7\, [\text{F}]\]

\[\text{vel}_{\text{in}} = 121.6\, [\text{F}]\]

\[\text{DP}_{\text{out SF}} = 71.33\, [\text{F}]\]

\[\text{m}_{\text{dot in}} = 102.2\, [\text{F}]\]

\[\text{m}_{\text{dot water}} = 0.0008\, [\text{hph}]\]

\[\text{P}_{\text{water}} = 0.01631\]

\[\text{P}_{\text{water}} = 0.01614\]

\[\text{P}_{\text{water}} = 0.15\]

\[\text{time} = 5480\, [\text{s}]\]

\[\text{T}_{\text{out SF}} = 40.16\, [\text{F}]\]

\[\text{T}_{\text{water out}} = 10.98\, [\text{F}]\]

\[\text{vel}_{\text{in}} = 0.032\, [\text{F}]\]

---

Click on this line to see the array variables in the Analyzer Table window.

No unit problems were detected.

Calculation time = 3 sec.
"Summer Condition Calculations--Without Air-Conditioning"

"Statepoint 1"
T_drybulb[1]=79 [°F]
P=14.7 [psia]
DP[1]=(63 [°F]+54 [°F])/2

T_wetbulb[1]=WetBulb(AirH₂O,T=T_drybulb[1],D=DP[1],P=P)
omega[1]=HumRat(AirH₂O,T=T_drybulb[1],D=DP[1],P=P)
rh[1]=RelHum(AirH₂O,T=T_drybulb[1],D=DP[1],P=P)

Area_duct=12.6*convert(in^2*ft^2)
rho_air=Density(air,T=T_drybulb[1],P=P)

"Statepoint 2"
rh[2]=0.9

omega[2]=HumRat(AirH₂O,B=T_wetbulb[2],r=rh[2],P=P)


"About 1/2 of weight of clothes out of a washer is the water to be removed by the dryer"
time=5400 [s]
m_dot_water=water(6[lb_f]/time)*2

m_dot[1]=m_dot_water=m_dot[2]


"Velocity needed in order to work"
m_dot[1]=vel_in*rho_air*Area_duct

"Dewpoint of outside air"

DP_outside_duct=DewPoint(AirH₂O,T=75 [°F],P=P,r=.5)

---

**Unit Settings: Eng F psia mass deg**

Area_duct = 0.0875 [ft²]

DP_outside_duct = 55.12 [°F]

m_water = 0.002963 [lb/s]

time = 5400 [s]

---

Click on this line to see the array variables in the Arrays Table window

No unit problems were detected.
<table>
<thead>
<tr>
<th></th>
<th>DP_i [F]</th>
<th>m_i [lb/s]</th>
<th>α_i</th>
<th>rh_i</th>
<th>T_{drybulb,i} [F]</th>
<th>T_{wetbulb,i} [F]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.01045</td>
<td>0.4948</td>
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<tr>
<td>[2]</td>
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<td>1.137</td>
<td>0.01307</td>
<td>0.9</td>
<td>67.73</td>
<td>65.69</td>
</tr>
</tbody>
</table>
Appendix G: Desiccant Equations with Ergun Equation

{Pressure Difference - Ergun Equation}

\[ \Delta P = \frac{150 \mu (1 - \epsilon)^2 \mu_o}{\epsilon^3 D_{desiccant}} + \frac{1.75 (1 - \epsilon) \rho_{air} \mu_o^2}{\epsilon^3 D_{desiccant}} \]

{Desiccant absorption}

\[ \rho_{desiccant} = 0.8 \text{ convert(g/mL kg/m}^3) \]
\[ \text{Percent absorption} = 0.15 \]
\[ \rho_{water} = \text{density(water, x = 0, T = 54)} \]
\[ D_{cylinder} = 4 \text{ in} \times \text{convert(in, m)} \]
\[ V_{cylinder} = \frac{\pi (D_{cylinder}/2)^2 L}{\text{Volume of desiccant cylinder}} \]
\[ V_{desiccant} = \frac{\pi}{4} D_{desiccant}^3 \]
\[ N_{beads} = V_{cylinder}/\epsilon \]
\[ V_{total desiccant} = N_{beads} V_{desiccant} \]
\[ V_{water absorbed} = \text{Mass water absorbed}/\rho_{water} \]

{Desiccant Exposure Time}

\[ \text{Mass desiccant} = V_{total desiccant} \rho_{desiccant} \]
\[ \text{Mass water absorbed} = \text{Percent absorption} \times \text{Mass desiccant} \]
\( \text{Time}_{\text{exp}} = \frac{L}{\eta_{\mu c}} \)  
\( \text{Regeneration Frequency} \)

\( R_{\text{absorb}} = 0.03 \text{ [kg/m}^3\text{h]} \)  
\( \text{Desiccant absorption rate} \)

\( A_{\text{desiccant}} = \pi \frac{\text{D}_{\text{desiccant}}^2}{4} \)  
\( \text{Desiccant surface area} \)

\( T_{\text{full desiccant}} = \frac{\text{Mass}_{\text{water}} \cdot \text{absorbed}}{R_{\text{absorb}} \cdot A_{\text{desiccant}}} \)  
\( \text{Time for desiccant to absorb full capacity} \)

\( T_{\text{desiccant used}} = 0.75 \text{ [h]} \)  
\( \text{Drying Time or time desiccant is used per load} \)

\( N_{\text{dry}} = T_{\text{full desiccant}} \cdot T_{\text{desiccant used}} \)  
\( \text{Number of uses before desiccant needs to be regenerated} \)

\( N_{\text{use}} = 365 \text{ [1/yr]} \)  
\( \text{Number of uses of dryer per year, assume one use per day} \)

\( N_{\text{regenerate year}} = N_{\text{use}} / N_{\text{dry}} \)  
\( \text{Number of regenerations per year} \)

\( \text{Cost of Regeneration} \)

\( T_{\text{room}} = 25 \text{ [C]} \)  
\( \text{Room Temperature} \)

\( T_{\text{boil}} = 100 \text{ [C]} \)  
\( \text{Water Boiling Temperature} \)

\( s_{\text{water}} = 4.184 \text{ [kJ/kg}^0\text{C]} \)  
\( \text{Specific Heat of Water} \)

\( \text{DELTA}H_{\text{vap}} = 40.79 \text{ [kJ/mol]} \)  
\( \text{Enthalpy of Vaporization of Water} \)

\( Y_{\text{water}} = 0.018 \text{ [kg/mol]} \)  
\( \text{Water moles} \)

\( N_{\text{moles}_{\text{water}}} = \frac{\text{Mass}_{\text{water}} \cdot \text{absorbed}}{Y_{\text{water}}} \)  
\( \text{Number of moles} \)

\( q_{\text{boil}} = \frac{\text{Mass}_{\text{water}} \cdot \text{absorbed} \cdot s_{\text{water}} \cdot (T_{\text{boil}} - T_{\text{room}})}{Y_{\text{water}}} \)  
\( \text{Energy to heat} \)

\( q_{\text{vap}} = N_{\text{moles}_{\text{water}}} \cdot \text{DELTA}H_{\text{vap}} \)  
\( \text{Energy to Evaporate} \)

\( q_{\text{tot}} = q_{\text{boil}} + q_{\text{vap}} \)  
\( \text{Total Energy Needed} \)

\( Q_{\text{dot supply}} = 2 \text{ [kW/h]} \cdot \text{convert(kW/h to kJ/s)} \)  
\( \text{Energy supplied by oven} \)

\( T_{\text{regenerate}} = \frac{q_{\text{tot}}}{Q_{\text{dot supply}}} \cdot \text{convert(s to h)} \)  
\( \text{Time to regenerate} \)

\( \text{Cost}_{\text{Oven}} = 0.32 \text{ [$/h]} \)  
\( \text{Cost to run oven} \)

\( \text{Cost}_{\text{Regenerate}} = \text{Cost}_{\text{Oven}} \cdot T_{\text{regenerate}} \)  
\( \text{Cost of single regeneration} \)

\( \text{Cost}_{\text{Regenerate year}} = N_{\text{regenerate year}} \cdot \text{Cost}_{\text{Regenerate}} \)  
\( \text{Cost of regeneration per year} \)

**Unit Settings**: SI C kPa kJ mass deg

\( A_{\text{desiccant}} = 0.05745 \text{ [m}^2\text{]} \)

\( \text{Cost}_{\text{Regenerate year}} = 0.0541 \text{ [$/yr]} \)

\( \Delta P = 701.1 \text{ [Pa]} \)

\( \text{D}_{\text{desiccant}} = 0.00635 \text{ [m]} \)

\( \text{Mass}_{\text{desiccant}} = 2.9913 \text{ [kg]} \)

\( \mu = 6.036 \text{ [m/s]} \)

\( N_{\text{moles}_{\text{water}}} = 2.432 \text{ [mol]} \)

\( \text{Percent absorption} = 0.15 \)

\( \text{Cost}_{\text{Regenerate}} = 0.08502 \text{ [$]} \)

\( \Delta P = 701.1 \text{ [Pa]} \)

\( \text{D}_{\text{desiccant}} = 0.00635 \text{ [m]} \)

\( \text{Mass}_{\text{desiccant}} = 2.9913 \text{ [kg]} \)

\( \mu = 6.036 \text{ [m/s]} \)

\( N_{\text{moles}_{\text{water}}} = 2.432 \text{ [mol]} \)

\( \text{Percent absorption} = 0.15 \)

\( \text{Cost}_{\text{Regenerate}} = 0.08502 \text{ [$]} \)
Appendix H: Prototype Theory Calculations

Winter Conditions
Assume SS for all calculations

\[ \text{Area}_{\text{duct}} = 28.27 \times 0.006944444 \times \frac{\text{ft}^2}{\text{in}^2} \]

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

\[ T_{\text{in, winter}} = 80 \quad \text{[F]} \]

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

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

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

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

\[ D\text{P}_{\text{in, winter}} = D\text{P} \left( \text{AirH}_2\text{O}^\circ, T = T_{\text{in, winter}}, w = \omega_{\text{in, winter}}, P = P_1 \right) \]

\[ P_2 = P_1 \]

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

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

\[ \text{rh}_{\text{out, winter2}} = 0.5 \]

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

\[ \omega_{\text{out, winter2}} = \omega \left( \text{AirH}_2\text{O}^\circ, T = T_{\text{out, winter}}, P = P_2, R = \text{rh}_{\text{out, winter2}} \right) \]

\[ D\text{P}_{\text{out, winter}} = D\text{P} \left( \text{AirH}_2\text{O}^\circ, T = T_{\text{out, winter}}, w = \omega_{\text{out, winter}}, P = P_2 \right) \]

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

\[ \dot{m}_{\text{water, winter}} = \frac{10}{\text{time}} \quad \text{[lb.]} \]

\[ \dot{m}_{\text{in, winter}} + \dot{m}_{\text{water, winter}} = \dot{m}_{\text{out, winter}} \]

\[ \omega_{\text{out, winter}} - \omega_{\text{in, winter}} = \frac{\dot{m}_{\text{water, winter}}}{\dot{m}_{\text{o},\text{winter}}} \]

Psychrometric chart

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

\[ P_{\text{air,summer}} = \rho \left( `\text{Air}', \ T = T_{\text{in,summer}}, \ P = P_1 \right) \]

\[ T_{\text{in,summer}} = 60 \quad [\text{F}] \]

\[ T_{\text{wet,summer}} = \text{WD} \left( `\text{AirH2O}', \ T = T_{\text{in,summer}}, \ R = \text{rh}_{\text{in,summer}}, \ P = P_1 \right) \]

\[ \text{rh}_{\text{in,summer}} = 0.3 \]

\[ \omega_{\text{in,summer}} = \omega \left( `\text{AirH2O}', \ T = T_{\text{in,summer}}, \ B = T_{\text{wet,summer}}, \ P = P_1 \right) \]

\[ \text{DP}_{\text{in,summer}} = \text{DP} \left( `\text{AirH2O}', \ T = T_{\text{in,summer}}, \ W = \omega_{\text{in,summer}}, \ P = P_1 \right) \]

\[ T_{\text{wet,summer}} = T_{\text{wet,summer}} \]

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

\[ \omega_{\text{out,summer}} = \omega \left( `\text{AirH2O}', \ T = T_{\text{out,summer}}, \ B = T_{\text{wet,summer}}, \ P = P_2 \right) \]

\[ \omega_{\text{out,summer2}} = \omega \left( `\text{AirH2O}', \ T = T_{\text{out,summer}}, \ R = \text{rh}_{\text{out,summer}}, \ P = P_2 \right) \]

\[ \text{DP}_{\text{out,summer}} = \text{DP} \left( `\text{AirH2O}', \ T = T_{\text{out,summer}}, \ W = \omega_{\text{out,summer}}, \ P = P_2 \right) \]

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

\[ \dot{m}_{\text{water,summer}} = \frac{10 \ [\text{lb}] \ \text{time}} \]

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

\[ \omega_{\text{out,summer}} = \omega_{\text{in,summer}} = \frac{\dot{m}_{\text{water,summer}}}{\dot{m}_{\text{in,summer}}} \]

Psychrometric chart

\[ T_{\text{out,summer}} = T \left( `\text{AirH2O}', \ R = \text{rh}_{\text{out,summer}}, \ B = T_{\text{wet,summer}}, \ P = P_1 \right) \]
Spring/Fall Conditions

\[ \rho_{\text{air, sf}} = \rho (\text{'Air'}, T = T_{\text{in, sf}}, P = P_1) \]

\[ T_{\text{in, sf}} = 65 \ [\text{F}] \quad \text{This is temp of furnace} \]

\[ T_{\text{wet, in, sf}} = \text{WB} (\text{'AirH2O'}, T = T_{\text{in, sf}}, R = rh_{\text{in, sf}}, P = P_1) \]

\[ rh_{\text{in, sf}} = 0.4 \]

\[ \omega_{\text{in, sf}} = \omega (\text{'AirH2O'}, T = T_{\text{in, sf}}, B = T_{\text{wet, in, sf}}, P = P_1) \]

\[ \text{DP}_{\text{in, sf}} = \text{DP} (\text{'AirH2O'}, T = T_{\text{in, sf}}, W = \omega_{\text{in, sf}}, P = P_1) \]

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

\[ rh_{\text{out, sf}} = 0.8 \]

\[ \omega_{\text{out, sf}} = \omega (\text{'AirH2O'}, T = T_{\text{out, sf}}, B = T_{\text{wet, out, sf}}, P = P_2) \]

\[ \omega_{\text{out,2}} = \omega (\text{'AirH2O'}, T = T_{\text{out, sf}}, B = rh_{\text{out, sf}}, P = P_2) \]

\[ \text{DP}_{\text{out, sf}} = \text{DP} (\text{'AirH2O'}, T = T_{\text{out, sf}}, W = \omega_{\text{out, sf}}, P = P_2) \]

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

\[ m_{\text{water, sf}} = \frac{10 \ [\text{lb}]}{\text{time}} \]

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

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

Psychrometric chart

\[ T_{\text{out, sf}} = T (\text{'AirH2O'}, R = rh_{\text{out, sf}}, B = T_{\text{wet, out, sf}}, P = P_1) \]

Time that clothes must be dried in

\[ \text{time} = 3120 \cdot \left( \frac{3600 \cdot \frac{\text{s}}{\text{hour}}}{\text{hour}} \right) \]

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

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

\[ \Delta \omega_{\text{f1}} = \omega_{\text{out, sf}} - \omega_{\text{in, sf}} \]

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

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

\[ m_{\text{w, sf}} = \text{vel}_{\text{in, sf}} \cdot \rho_{\text{air, sf}} \cdot \text{Area}_{\text{duct}} \]
Unit Settings: Eng °F psia mass deg

\begin{align*}
\text{Area}_{\text{duct}} &= 0.1963 \ [\text{ft}^2] \\
\text{DP}_{\text{in, sf}} &= 40.12 \ [\text{F}] \\
\text{DP}_{\text{out, summer}} &= 42.83 \ [\text{F}] \\
\no_{\text{in, winter}} &= 0.0003125 \ [\text{lb}/\text{s}] \\
\no_{\text{water, summer}} &= 8.903E-07 \ [\text{lb}/\text{s}] \\
\no_{\text{in, summer}} &= 0.003271 \\
\no_{\text{out, summer}} &= 0.005812 \\
\no_{\text{al, summer}} &= 0.07563 \ [\text{lb}_{\text{in}}/\text{ft}^3] \\
\no_{\text{in, summer}} &= 0.3 \\
\no_{\text{out, winter}} &= 0.8 \\
T_{\text{in, summer}} &= 60 \ [\text{F}] \\
T_{\text{out, winter}} &= 67.65 \ [\text{F}] \\
T_{\text{wet, out, sf}} &= 51.93 \ [\text{F}] \\
\no_{\text{out, summer}} &= 0.02337 \ [\text{lb}/\text{s}] \\
\Delta \theta_{\text{in, summer}} &= 0.002203 \\
\Delta \theta_{\text{in, winter}} &= 28.91 \ [\text{F}] \\
\Delta \theta_{\text{out, winter}} &= 61.25 \ [\text{F}] \\
\no_{\text{out, summer}} &= 0.0004049 \ [\text{lb}/\text{s}] \\
\no_{\text{water, summer}} &= 8.903E-07 \ [\text{lb}/\text{s}] \\
\no_{\text{in, winter}} &= 0.008707 \\
\no_{\text{out, winter}} &= 0.005812 \\
\no_{\text{al, winter}} &= 0.07635 \ [\text{lb}_{\text{in}}/\text{ft}^3] \\
\no_{\text{in, winter}} &= 0.4 \\
\no_{\text{out, winter}} &= 0.6 \\
T_{\text{in, winter}} &= 60 \ [\text{F}] \\
T_{\text{wet, in, sf}} &= 51.93 \ [\text{F}] \\
T_{\text{wet, out, winter}} &= 45.77 \ [\text{F}] \\
\no_{\text{in, winter}} &= 0.02166 \ [\text{lb}/\text{s}] \\
\Delta \theta_{\text{winter}} &= 0.002848 \\
\Delta \theta_{\text{out, sf}} &= 49.27 \ [\text{F}] \\
\no_{\text{in, summer}} &= 0.0003594 \ [\text{lb}/\text{s}] \\
\no_{\text{out, winter}} &= 0.0003135 \ [\text{lb}/\text{s}] \\
\no_{\text{in, sf}} &= 0.005216 \\
\no_{\text{out, winter}} &= 0.007421 \\
\no_{\text{out, winter}} &= 0.008625 \\
\no_{\text{al, winter}} &= 0.4 \\
\no_{\text{out, summer}} &= 0.8 \\
T_{\text{wet, out, in}} &= 65 \ [\text{F}] \\
T_{\text{out, winter}} &= 48.77 \ [\text{F}] \\
T_{\text{wet, in, winter}} &= 63.48 \ [\text{F}] \\
\no_{\text{in, sf}} &= 0.02721 \ [\text{lb}/\text{s}]
\end{align*}
Appendix I: Duct Sweating/ Raining

Winter Conditions

Assume SS for all calculations

\[ \text{Area}_{\text{duct}} = 23.27 \cdot \left| \frac{\text{ft}^2}{\text{in}^2} \right| \]

\[ \rho_{\text{air, winter}} = \rho \left( '\text{Air}', T = T_{\text{in, winter}}, P = P_1 \right) \]

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

\[ T_{\text{wet, in, winter}} = \text{WB} \left( '\text{AirH}_2\text{O}', T = T_{\text{in, winter}}, R = \text{rh}_{\text{in, winter}}, P = P_1 \right) \]

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

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

\[ \omega_{\text{in, winter}} = \omega \left( '\text{AirH}_2\text{O}', T = T_{\text{in, winter}}, B = T_{\text{wet, in, winter}}, P = P_1 \right) \]

\[ \text{DP}_{\text{in, winter}} = \text{DP} \left( '\text{AirH}_2\text{O}', T = T_{\text{in, winter}}, W = \omega_{\text{in, winter}}, P = P_1 \right) \]

\[ P_2 = P_1 \]

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

\[ m_{\text{out, winter}} = 0.9 \]

\[ \omega_{\text{out, winter}} = \omega \left( '\text{AirH}_2\text{O}', T = T_{\text{out, winter}}, B = T_{\text{wet, out, winter}}, P = P_2 \right) \]

\[ \text{DP}_{\text{out, winter}} = \text{DP} \left( '\text{AirH}_2\text{O}', T = T_{\text{out, winter}}, W = \omega_{\text{out, winter}}, P = P_2 \right) \]

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

\[ \dot{m}_{\text{water, winter}} = \frac{8 \cdot [\text{lb}] \cdot \text{time}}{2} \]

\[ \dot{m}_{\text{in, winter}} + \dot{m}_{\text{water, winter}} = \dot{m}_{\text{out, winter}} \]

\[ \omega_{\text{out, winter}} = \frac{\dot{m}_{\text{water, winter}}}{\dot{m}_{\text{in, winter}}} \]

Psychrometric chart

\[ T_{\text{out, winter}} = T \left( '\text{AirH}_2\text{O}', R = \text{rh}_{\text{out, winter}}, B = T_{\text{wet, out, winter}}, P = P_1 \right) \]
Appendix I: Duct Sweating/ Raining

Winter Conditions

Assume SS for all calculations

\[ \text{Area}_{\text{duct}} = 28.27 \cdot \left| 0.000944444 \cdot \frac{r^2}{\text{in}^2} \right| \]

\[ P_{\text{air, winter}} = \rho \left( \text{Air}, T = T_{\text{in, winter}}, P = P_1 \right) \]

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

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

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

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

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

\[ D\text{P}_{\text{in, winter}} = D\text{P} \left( \text{AirH}_2\text{O}, T = T_{\text{in, winter}}, W = \omega_{\text{in, winter}}, P = P_1 \right) \]

\[ P_2 = P_1 \]

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

\[ \text{rh}_{\text{out, winter}} = 0.9 \]

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

\[ D\text{P}_{\text{out, winter}} = D\text{P} \left( \text{AirH}_2\text{O}, T = T_{\text{out, winter}}, W = \omega_{\text{out, winter}}, P = P_2 \right) \]

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

\[ \dot{m}_{\text{water, winter}} = \frac{8 \text{ [lb]} \cdot 2}{\text{time}} \]

\[ \dot{m}_r, \text{winter} + \dot{m}_{\text{water, winter}} = \dot{m}_{\text{cut, winter}} \]

\[ \omega_{\text{out, winter}} - \omega_{\text{in, winter}} = \frac{\dot{m}_{\text{water, winter}}}{\dot{m}_r, \text{winter}} \]

Psychrometric chart

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

\[ p_{\text{air, summer}} = \rho \left( \text{Air}, T = T_{\text{in, summer}}, P = P_1 \right) \]

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

\[ T_{\text{wet, in, summer}} = W B \left( \text{AirH}_2\text{O}, T = T_{\text{in, summer}}, R = r_{\text{h, in, summer}}, P = P_1 \right) \]

\[ r_{\text{h, in, summer}} = 0.15 \]

\[ \omega_{\text{in, summer}} = \omega \left( \text{AirH}_2\text{O}, T = T_{\text{in, summer}}, B = T_{\text{wet, in, summer}}, P = P_1 \right) \]

\[ D P_{\text{in, summer}} = D P \left( \text{AirH}_2\text{O}, T = T_{\text{in, summer}}, W = \omega_{\text{in, summer}}, P = P_1 \right) \]

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

\[ r_{\text{h, out, summer}} = 0.9 \]

\[ \omega_{\text{out, summer}} = \omega \left( \text{AirH}_2\text{O}, T = T_{\text{out, summer}}, B = T_{\text{wet, out, summer}}, P = P_2 \right) \]

\[ D P_{\text{out, summer}} = D P \left( \text{AirH}_2\text{O}, T = T_{\text{out, summer}}, W = \omega_{\text{out, summer}}, P = P_2 \right) \]

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

\[ \dot{m}_{\text{water, summer}} = \frac{8 \text{ [lb]} \text{ [t]}}{\text{time}} \cdot 2 \]

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

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

Psychrometric chart

\[ T_{\text{out, summer}} = T \left( \text{AirH}_2\text{O}, R = r_{\text{h, out, summer}}, B = T_{\text{wet, out, summer}}, P = P_1 \right) \]
Spring/Fall Conditions

\[ \rho_{\text{air, sf}} = \rho \left( \text{Air}^{\prime}, T = T_{\text{in, sf}}, P = P_1 \right) \]

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

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

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

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

\[ \text{DP}_{\text{in, sf}} = \text{DP} \left( \text{AirH2O}^{\prime}, T = T_{\text{in, sf}}, W = \omega_{\text{in, sf}}, P = P_1 \right) \]

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

\[ \text{rh}_{\text{out, sf}} = 0.9 \]

\[ \omega_{\text{out, sf}} = \omega \left( \text{AirH2O}^{\prime}, T = T_{\text{out, sf}}, B = T_{\text{wet, out, sf}}, P = P_2 \right) \]

\[ \text{DP}_{\text{out, sf}} = \text{DP} \left( \text{AirH2O}^{\prime}, T = T_{\text{out, sf}}, W = \omega_{\text{out, sf}}, P = P_2 \right) \]

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

\[ \dot{m}_{\text{water, sf}} = \frac{8 \ \text{[lb]} \cdot 2}{\text{time}} \]

\[ \dot{m}_{\text{n, sf}} + \dot{m}_{\text{water, sf}} = \dot{m}_{\text{out, sf}} \]

\[ \omega_{\text{out, sf}} - \omega_{\text{in, sf}} = \frac{\dot{m}_{\text{water, sf}}}{\dot{m}_{\text{n, sf}}} \]

Psychrometric chart

\[ T_{\text{out, sf}} = T \left( \text{AirH2O}^{\prime}, R = \text{rh}_{\text{out, sf}}, B = T_{\text{wet, out, sf}}, P = P_1 \right) \]

Time that clothes must be dried in

\[ \text{time} = 1.5 \cdot 3600 \cdot \left[ \frac{s}{\text{hour}} \right] \]

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

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

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

\[ \dot{m}_{\text{n, winter}} = \text{vel}_{\text{n, winter}} \cdot \rho_{\text{air, winter}} \cdot \text{Area}_{\text{duct}} \]

\[ \dot{m}_{\text{n, summer}} = \text{vel}_{\text{n, summer}} \cdot \rho_{\text{air, summer}} \cdot \text{Area}_{\text{duct}} \]
Unit Settings: Eng F psia mass deg

\( A_{\text{exit}} = 0.1963 \text{ [ft}^2\text{]} \)
\( \Delta P_{\text{in, sf}} = 71.33 \text{ [F]} \)
\( \Delta P_{\text{out, summer}} = 37.46 \text{ [F]} \)
\( m_{\text{in, winter}} = 0.4906 \text{ [lb/s]} \)
\( \dot{m}_{\text{water, sf}} = 0.002963 \text{ [lb/s]} \)
\( \omega_{\text{in, summer}} = 0.001362 \)
\( \omega_{\text{out, winter}} = 0.04614 \)
\( \rho_{\text{in, sf}} = 0.4 \)
\( \rho_{\text{in, winter}} = 0.9 \)
\( T_{\text{in, summer}} = 55 \text{ [F]} \)
\( T_{\text{out, winter}} = 105.8 \text{ [F]} \)
\( T_{\text{wet, out, sf}} = 78.98 \text{ [F]} \)
\( v_{\text{in, summer}} = 58.66 \text{ [ft/s]} \)
\( \Delta \rho_{\text{summer}} = 0.003337 \)
\( \Delta \rho_{\text{winter}} = 0.003337 \)
\( \dot{m}_{\text{in, sf}} = 0.675 \text{ [lb/s]} \)
\( \dot{m}_{\text{in, winter}} = 0.8903 \text{ [lb/s]} \)
\( \dot{m}_{\text{water, winter}} = 0.002963 \text{ [lb/s]} \)
\( \omega_{\text{out, sf}} = 0.0209 \)
\( \rho_{\text{air, summer}} = 0.0771 \text{ [lb/ft}^3\text{]} \)
\( \rho_{\text{air, winter}} = 0.4 \)
\( \text{time} = 5400 \text{ [s]} \)
\( T_{\text{out, sf}} = 81.4 \text{ [F]} \)
\( T_{\text{wet, in, summer}} = 38.92 \text{ [F]} \)
\( T_{\text{wet, out, winter}} = 102.7 \text{ [F]} \)
\( \Delta \rho_{\text{in, summer}} = 0.00439 \)
\( \Delta \rho_{\text{in, winter}} = 10.77 \text{ [F]} \)
\( \dot{m}_{\text{out, sf}} = 0.6779 \text{ [lb/s]} \)
\( \dot{m}_{\text{water, summer}} = 0.002963 \text{ [lb/s]} \)
\( \omega_{\text{in, winter}} = 0.0401 \)
\( \rho_{\text{air, sf}} = 0.0771 \text{ [lb/ft}^3\text{]} \)
\( \rho_{\text{in, summer}} = 0.15 \)
\( \rho_{\text{out, winter}} = 0.9 \)
\( T_{\text{in, winter}} = 130 \text{ [F]} \)
\( T_{\text{wet, in, sf}} = 73.98 \text{ [F]} \)
\( T_{\text{wet, out, summer}} = 38.92 \text{ [F]} \)
\( v_{\text{in, winter}} = 37.14 \text{ [ft/s]} \)
\( \Delta \rho_{\text{winter}} = 0.00504 \)
\( \Delta \rho_{\text{out, sf}} = 76.13 \text{ [F]} \)
\( \dot{m}_{\text{water, summer}} = 0.8879 \text{ [lb/s]} \)
\( \dot{m}_{\text{water, winter}} = 0.4935 \text{ [lb/s]} \)
\( \omega_{\text{sf}} = 0.01651 \)
\( \omega_{\text{out, summer}} = 0.004639 \)
\( \rho_{\text{air, winter}} = 0.06725 \text{ [lb/ft}^3\text{]} \)
\( \rho_{\text{out, sf}} = 0.9 \)
\( T_{\text{in, sf}} = 100 \text{ [F]} \)
\( T_{\text{out, summer}} = 40.16 \text{ [F]} \)
\( T_{\text{wet, in, winter}} = 102.7 \text{ [F]} \)
\( v_{\text{in, sf}} = 46.49 \text{ [ft/s]} \)
Summer Condition Calculations—Without Air-Conditioning

Using Romania as test country

Statepoint 1

\[ T_{\text{dry bulb},1} = 79 \text{ [F]} \]

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

\[ DP_1 = \frac{63 \text{ [F]} + 54 \text{ [F]}}{2} \]

\[ T_{\text{wet bulb},1} = \text{WB ('AirH2O', T=T_{\text{dry bulb},1}, D=DP_1, P=P)} \]

\[ \omega_1 = \omega ('AirH2O', T=T_{\text{dry bulb},1}, D=DP_1, P=P) \]

\[ rh_1 = \text{RH ('AirH2O', T=T_{\text{dry bulb},1}, D=DP_1, P=P)} \]

\[ \text{Area}_{\text{duct}} = 28.27 \cdot 0.006944444 \cdot \frac{r^2}{\ln^2} \]

\[ p_{\text{air}} = p ('Air', T=T_{\text{dry bulb},1}, P=P) \]

Statepoint 2

\[ T_{\text{wet bulb},2} = T_{\text{wet bulb},1} \]

\[ rh_2 = 0.9 \]

\[ \omega_2 = \omega ('AirH2O', B=T_{\text{wet bulb},2}, R=rh_2, P=P) \]

\[ T_{\text{dry bulb},2} = T ('AirH2O', R=rh_2, B=T_{\text{wet bulb},2}, P=P) \]

\[ DP_2 = \text{DP ('AirH2O', T=T_{\text{dry bulb},2}, R=rh_2, P=P)} \]

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

\[ \text{time} = 3370 \text{ [s]} \]

\[ \dot{m}_{\text{water}} = \frac{4}{\text{time}} \text{ [lb/d]} \]

\[ \dot{m}_1 + \dot{m}_{\text{water}} = \dot{m}_2 \]

\[ \omega_2 - \omega_1 = \frac{\dot{m}_{\text{water}}}{m_1} \]

Velocity needed in order to work

\[ \dot{m}_1 = \text{vel} \cdot \rho_{\text{air}} \cdot \text{Area}_{\text{duct}} \]

Dewpoint of outside air

\[ DP_{\text{outside duct}} = \text{DP ('AirH2O', T = 75 \text{ [F]}, P = P, R = 0.5)} \]
**Unit Settings:** Eng F psia mass deg

\[ \text{Area}_{\text{duct}} = 0.1963 \text{ ft}^2 \]

\[ \text{DP}_{\text{outside duct}} = 55.12 \text{ [F]} \]

\[ \rho_{\text{air}} = 0.07366 \text{ [lb/ft}^3\text{]} \]

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

\[ m_{\text{water}} = 0.001187 \text{ [lb/s]} \]

\[ \rho_{\text{air}} = 0.07366 \text{ [lb/ft}^3\text{]} \]

\[ \text{time} = 3370 \text{ [s]} \]

\[ \text{vel}_{\text{in}} = 31.41 \text{ [ft/s]} \]

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<th>( m_i ) [lb/s]</th>
<th>( \omega_i )</th>
<th>( \rho_i )</th>
<th>( T_{\text{dry bulb},i} ) [F]</th>
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<td>67.73</td>
<td>65.69</td>
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Appendix J: Reynolds Number Calculations

"Air Properties"
T = 50 [°F]
P = 100*convert(kPa, PSI)
rho = Density(Air_ha, T=T, P=P)
v = 80*convert(ft/min, ft/hr)
mu = Viscosity(Air_ha, T=T, P=P)

"Temperature"
"Pressure, atmospheric"
"Density"
"Velocity 80 min, 300 max"
"Dynamic Viscosity"

"Box"
Depth = 30*convert(in,ft)
Width = 4 [ft]

"Depth of the Box"
"Width of the Box"

"Hydraulic Diameter"
A = Depth * Width
Pr = 2*depth + 2*Width
D_H = (4*A) / Pr

"Area of the Box"
"Wetted Perimeter"
"Hydraulic Diameter"

"Reynolds Number"
Re = (rho * v * D_H) / mu

"Reynolds Number"

Unit Settings: Eng F psi mass deg
A = 10 [ft²]
μ = 0.0428 [lbm/(ft•hr)]
Pa = 93290 [daN]
v = 18000 [ft/hr]
Depth = 25 [ft]
P = 14.5 [psi]
p = 0.07663 [lbm/(ft³)]
Width = 4 [ft]
D_H = 3.077 [ft]
Pr = 13 [ft]
T = 50 [°F]
Appendix K: Performance Graph for Experimental Unit Fan

Figure 42: Fan curve for experimental unit
Appendix L: Psychometric Chart

Figure 43: Psychrometric Chart
Appendix M: Parametric Tables

Air Velocity vs. Dry Time-Winter

Figure 44: Velocity vs Dry Time for Winter

Air Velocity vs. Dry Time-Spring/Fall

Figure 45: Velocity vs Dry time for Spring and Fall
Appendix N: Gantt Chart
<table>
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<tr>
<th>ID</th>
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<th>Task Name</th>
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Project: Gantt Chart for whole year
Date: Wed 5/8/13

Page 4
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