ABSTRACT

PETTIS, JOSHUA. Develop a New Test Method that Allows Controlled and Dynamic Changes in Temperature and Humidity While Measuring the Pressure Drop Across the Fabric. (Under the direction of Dr. Emiel DenHartog.)

Understanding the air permeability and air resistance in fabrics is important because it provides information on how well the textiles materials allow gasses to move through the material. It is known that certain fabrics and materials are affected by moisture regain caused by damp humid environments. For example, cotton is a fabric that swells when there is high moisture content in the air, and this causes the resistance to permeable gases to increase in the fabric. This is important because fabrics used in personal protection garments can be unutilized and designed for certain environments where the transport of “harmful gases” is important and because ventilation through fabrics may facilitate cooling. It is crucial to understand the importance of humidity changes in fabric because those changes affect the air resistance of the fabric. Therefore, a methodology is designed and validated to test for controlled temperature humidity dependance on wool, cotton, and polyester knitted fabrics. The fabrics are tested at 30 °C at different humidity levels over a 2-hour period. This is to evaluate a humidity dependence on the fabric under controlled conditions. The goal of this paper is to develop and evaluate a test method to measure the air permeability of fabrics while controlling the relative humidity and temperature. This was done by reviewing and evaluating the effect of temperature and humidity dependency on air resistance and air permeability for wool, cotton, and polyester jersey knit fabrics. Air permeability in this paper was derived from the pressure drop at a fixed air flow. The recreated system was able to evaluate air permeability and air resistance of knitted wool, cotton, and polyester fabrics. The system was able to show desired results in showing that

the air resistance of wool and cotton would increase at high humidity levels above 50% relative humidity.

Develop a New Test Method that Allows Controlled and Dynamic Changes in Temperature and Humidity While Measuring the Pressure Drop Across the Fabric

by
Joshua James Pettis

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APPROVED BY:

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Dr. Emiel DenHartog	Dr. Jeffrey Joines
Chair of Advisory Committee	

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Dr. Roger Barker

BIOGRAPHY

My name is Joshua J. Pettis I am from a small town called Kinston, NC and I attended North Carolina State University for undergrade. I received my bachelor's degree in Textiles Technology with a concentration in Technical Textiles and two minors one in Material Science and Engineering and the other in Graphic Communication. During my undergraduate career I had the opportunity to intern at Dystar Inc. as a research and development intern as well as a lab technician for the Johnny Mosley Wastewater Reclamation Center. I also had the opportunity to work as an undergraduate research assistant for the Textile Protection and Comfort Center. I also spent time as a teacher's assistant for foundations of graphic and university studies courses.

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Introduction

Textile materials are used in many applications for which the air permeability through the material is important. This information can be used to assist in the design of fabrics for air filtration or in this time of a global pandemic, for masks. Controlling air permeability is also important because it can affect the comfortability and/or heat loss performance of garments. Moisture in the air influences some natural fibers causing them to swell such as wool and cotton. This swelling of fibers is most of the time referred to as moisture absorption and can cause a change in air resistance and air permeability within the fabric material. Moisture absorption is prevalent in fabrics and since sweating is a part of everyday life for humans, having an understanding of this interaction is important. When there is a lack of evaporation there may be an increase in discomfort and a corresponding decrease in quality of life for the individual. Evaporation is the vaporization of liquids, and this process creates a form of heat loss on the body allowing it to be cooled. Microclimates are formed in areas between the human skin and the garment, and humidity is almost always higher near the skin than away from the body [8]. These microclimates can impact the individual's performance and/or comfortability while conducting their job. The ability to control expected performance and comfortability can best be understood by analyzing and evaluating the air resistance and permeability of the material used. It is also crucial to understand the importance of humidity changes in fabric because those changes affect the vapor resistance of the fabric [3].

Evaporative Resistance

Textiles' vapor resistance can be measured but the methods used do not always produce the same results. This is because the different methods evaluate the fabrics under different temperature and humidity conditions [10]. There are different variants of the vapor transfer apparatuses, Farnworth and Dolhan set up an apparatus to determine the resistance of a textile layer using an air layer between the water surface and the fabrics. Van Beets and Wittgen used a modification of Farnworth and Dolhan method to allow for more accuracy. Each method described by Farnworth and Dolhan and Van Beets and Wittgen respectively is shown in Figure 1. In essence, this method focuses on implementing a two-layered membrane [15],[16]. The two layers of the membrane were permeable to water vapor but impermeable to liquid water and air current [10]. This gave insight into ways a system could be built to use dry and humid air to assess the effects on vapor resistance, but the samples always experience 50% humidity even though the influence of air layers was removed. Successive measurements were taken

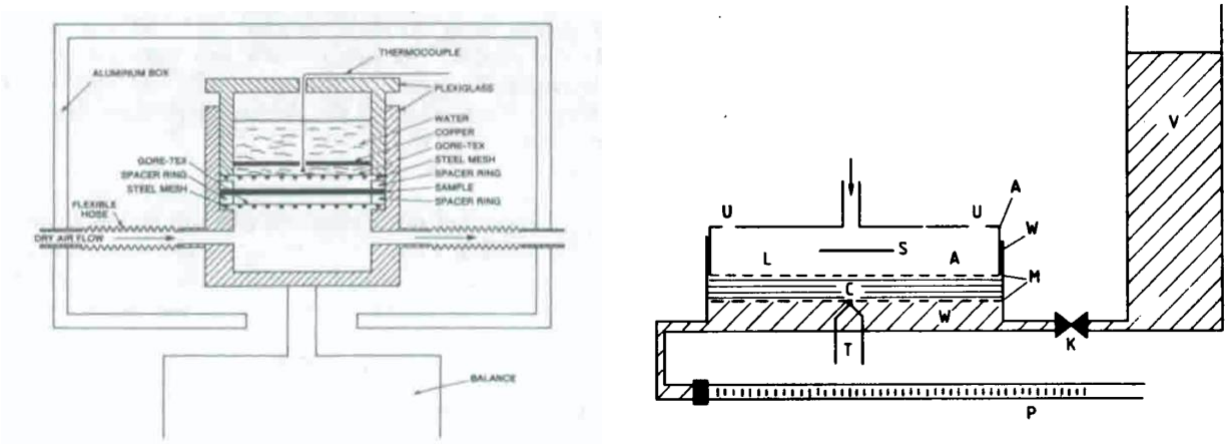


Figure 1: The apparatus on the left is described by Farnworth and Dolhan to measure the water-vapor resistance and the right apparatus described by Van Beets and Wittgen was used to measure the accuracy of vapor resistance. [15,16 (left), 10(right)]

Farnworth and Lotens set up an apparatus similar to Van Beets and Wittgen but with a modification of setting the fabrics at different distances from the wet surface which allowed for variation in relative humidity [10]. In the end, their results showed that the water vapor resistance of hydrophilic films had a strong variation on relative humidity. Though this gave good insight on how humidity was controlled in some apparatuses, this setup proved to be out of scope because it did not allow the user to clearly assess the air resistance of the samples. According to Gibson et. al., it is easy to find fabrics that will double their vapor resistance due to relative humidity [3]. It is known that the fabric structure can influence air resistance. Therefore, looking into those factors may prove useful.

Fabric Structure

Fabric structure and fabric type have a major influence on all material performance and also on the adsorption and transport of vapor and liquids [7]. These two factors seem to create an impact on dynamic water vapor transmission causing a non-steady-state characteristic of moisture transmission in the fabric. Wehner et al. suggest that there are two processes that compete until equilibrium has occurred. These are moisture sorption by the fabric and moisture transmission through the fabric [7],[3]. The non-steady-state condition is influenced by fiber type and moisture sorption capacity. This is because natural fibers such as wool, cotton, and silk have high sorption (regain) capacity, which may cause dimensional changes to occur in the fabric. This can be an issue in clothing because microclimate environments are created between clothing and the skin and air permeability may affect the evaporative resistance. Iqbal et al. discussed how aside from bilayer knitted structures of hydrophobic porous polyester and hydrophilic cellulose fibers compared to plain knit fabrics in terms of higher water vapor absorption. Their

data showed that plain knit architecture had a 105% more cooling performance and attributed that to the woolen knitwear having better water actuation, meaning the fabric is saturated with liquid water [17]. This is different from a humidity dependence that is investigated for this paper but Iqbal et al. data could provide insight on the unique behavior of wool fabrics in moist environments. Humid environments can cause condensation or sweating therefore, understanding saturated wool effects may be useful. Due to the increase in cooling the effect on the human body's thermal management can be beneficial or a hindrance depending on the end-use. This also can affect the microclimates that are formed between the fabric and the body, based on airflow between the layers. Wool was chosen for this study because it is an animal hair, and the water acquisition of animal hair is normally greater than that of natural fibers such as cotton because of the number of water-absorbing functional groups in the chemical structure [17]. The interaction between wool and water caused wool to swell longitudinally by 1.2% and diametral by 16% with increasing humidity, showing shape memory behavior as the changes were reversed when lowering the humidity.

While looking at the chemical reaction of animal hairs with water molecules it has been observed that hairs from sheep, goats, and camels are able to show shrinkage and the ability to return after being deformed. This is due to the presence of alpha-keratin biopolymers allowing the fiber to return to its initial state after being deformed without external force [17]. Descaled knitted wool fibers were analyzed for shape memory performance and were immersed in water at 20 ^{o}C for one hour and then thermal performance was evaluated. The wool fibers needed to be descaled because the presence of fatty acid layers with the scales on the outer surface creates a hydrophobic surface and can prevent maximum liquid water absorption. The prevention of liquid water absorption can also cause high shrinkage of wool in the wetting process because of the

sharp edges pointing to the tip of the fibers because wicking still occurs [17]. Wicking is the transport of liquids via capillary action. Iqbal et al. observed the full interaction of wool and water for water-actuation performance. A single jersey knit structure in the study showed excellent water actuation with an increase in water uptake within the fabric. To understand this behavior, it was important to look at the structure shifting mechanism which was how the fabric structure changed when saturated with water. The double-knit structure had a lower response with recovery behavior when compared to the single-knit fabric [17]. Single wool yarn is constructed via twisting thus assuming it has the ideal packing factor, ignoring the fiber migration along the radial direction. The fibers in a single yarn become straight after wetting, reducing the fiber's curvature, and increasing its length. For plied yarns, this change is seen in length and diameter creating a domino effect that changes the porosity of the wool knitted fabrics. Therefore, Iqbal et al. in their conclusion stated that a wool single jersey knit structure was ideal for better air permeability and cooling when compared to a balanced double-knit fabric [17]. This study illustrated that even under the same environmental conditions other factors might contribute to the air permeability of fabrics. But this study investigated the liquid saturation of wool and not the moisture absorption due to humidity changes. Thus, a more applicable research study was needed to understand more of this interaction.

Structural Aspects

Not only do the environmental conditions affect the air resistance of textiles fabrics but also the structural geometry affects this. The air resistance of textile fabrics is related to the number and size of interstices, but this relationship becomes difficult to define with materials that have high densities because it becomes difficult to determine how many pores are present

[9]. However, it is possible to define the cross-sectional area of an interstice and determine its minimal value. This may lead to an effect of yarn and fabric structure on minimum pore area and may be used to justify the relationships between fabric design and air permeability [9]. Most woven fabrics consist of two or three types of pores, but most natural and synthetic woven fabrics such as cotton and polyester are plain weave which consists of type 1 interstices. Figure 2 shows the four common interstice types for woven fabric. Backer suggests that the interstices with the greatest number of interlacing have the smallest minimum cross-sectional area considering that it is an open fabric which provides a higher air resistance [9].

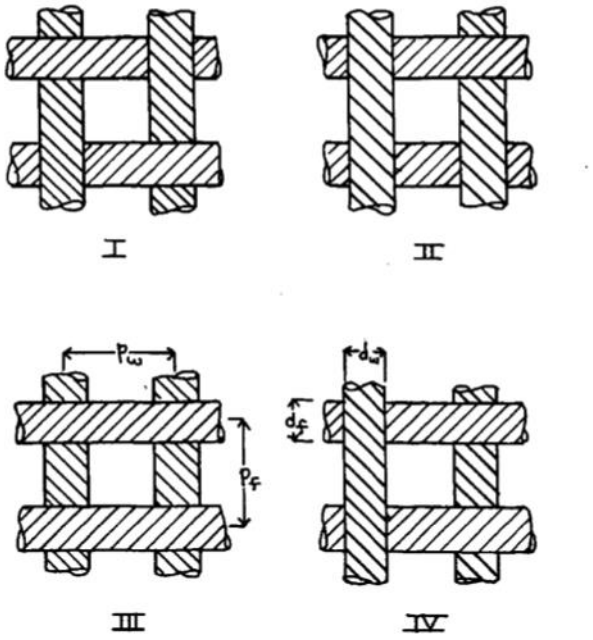


Figure 2: The four interstice types. Type 1 is where all four yarns of the unit cell alternate from the top to the bottom surface of the cloth and vice versa. Type 2 is where one warp and filling yarn alternately. Type 3 is where no alteration of the yarn takes place. Type 4 is where either two-warp yarn or filling yarns alternate from top to bottom surface or vice versa. [9]

It is still uncertain to what extent the weave patterns' theoretical geometry may be applied to the pore sizes of actual fabrics. Backer [9] studied a variety of weave patterns to determine the pore type distribution for the structures. But some of the observed fabrics were

more open than apparel materials showing a higher number of scatter points for the air permeability versus the average minimum pore area than expected [9]. This posed the problem of using a single parameter of average pore areas computed by the fabrics' geometric structure to predict air permeability. The use of crimp studied by Schiefer [18] gave insight into how the use of closely woven fabrics with more interlacing had a lower air permeability than a fabric of the same weight but was relatively loosely woven. Thus, this helped predicting air permeability for balanced fabrics with equal textures but is not helpful for unbalanced fabrics. Backer illustrated other factors that could affect air permeability such as twist direction, finishing techniques, and stress on the fabric. All these characteristics are used to affect air permeability in different ways but all of them relate to the minimum pore areas expressed in the fabric [9]. Backer concluded that even though there were some benefits to understanding minimum pore area and its effect on flow characteristics, but it was not always a clear correlation, and the calculation assumptions were often violated [9]. Backer provided a helpful analysis of the effect fabric structure could have on air permeability, but due to the nature of the evaluated woven fabrics and the scope of this research Backer's evaluation proved to be out of the scope of this project. The fabrics used for my project are knitted compared to the woven analysis of Backer's, in addition to the uncertainty of his findings in his paper. But Backer's findings suggested that fabric structure is an important factor that plays into air resistance and should not be completely overlooked. The importance of humidity in air resistance is also not addressed in Backer's research and is crucial to the proposed thesis therefore a more in-depth analysis is required.

Humidity Dependence

Wehner et al. [7] utilized the cotton swelling anisotropy graph from Collins to demonstrate the response to humidity. This showed how the fibers tended to swell due to humidity changes. For example, as the humidity increases, there is a high degree of anisotropy swelling which will affect the fabric structure. Air permeability is an important property of many performance fabrics, such as filters, and is used as a quality control method. Though air permeability is dependent on relative humidity there are not a lot of investigations on their effect according to Wehner et al. The goal of Wehner et al. was to analyze the effect of moisture sorption via relative humidity on air permeability. Pore size and thickness had an important role in the influence on air resistance. It can be assumed that moisture sorption is a factor to be considered for air resistance because moisture sorption has an effect on pore size and thickness. Moisture sorption affects the diameter as it may cause swelling of natural fibers, thus increasing or decreasing pore size depending on the fiber. Wehner et al. explored this by relating the permeability of a porous medium to the porosity of that medium. The porosity changes were assumed to be caused by fiber swelling due to moisture absorption and thus creating the importance of the dependency of air permeability on relative humidity [7]. The current ASTM D737-75 method of measuring air permeability states the importance of humidity but only test at 65% and 21 ^{o}C. However, this does not give information on how different humidity levels affect the air permeability of fabrics.

Wehner et al. learned through Gates and Jennings that the micronaire method of determining cotton fiber diameters was similar to the method of measuring air permeability. This was due to the fact that at a known pressure drop an airflow was forced across a fabric. But the difference was in the fact that moisture sorption increased the mass which skewed the micronaire

readings [7]. What Wehner et al. wanted to show in their research was an experimental approach to measure airflow across a variety of fabrics under specific pressure drops and at a range of relative humidity. Wehner et. al. used a model that relates to the flow of fluid through a porous medium under one of the two idealized extremes. The idealized extremes were that at a high porosity the medium can be treated as flow around a submerged object and at a low porosity the medium is treated as flow through a bundle of tubes. Most fabrics have a porosity in the range of 0.5 and 0.9 and Wehner et al. considered the range to be relatively small therefore they could utilize a model that treats airflow as flow through a bundle of small tubes. Under this condition, the pressure drop is made up of two terms inertial forces and viscous forces. Which uses this equation:

$$\frac{\Delta P}{L} = a\mu V + b\rho V^2$$

where μ is the fluid viscosity (s/m), ρ is the fluid density (m/v), L is the thickness (m) of the porous medium, and a and b depend on the structure of the porous medium [7].

The proposed experiment by Wehner et al. was set up in a way that the pressure drops, and relative humidity across the fabric samples was varied. The air supply was guided through a drying agent, distilled water, or a saturated solution of an inorganic salt to obtain the desired humidity levels [7]. The controlled humidified air flowed through the fabric in the test cell. A pressure drop was measured across the fabric using an inclined U-tube manometer. The permeability cell consisted of two 0.125-inch diameter tubes located between the flanges where the pressure gauges are located up and downstream from the specimen [7]. The air speed through the system was up to 0.10 m/s and the pressure drop through the tubes alone was of the order of 10^{-5} Pa and was thus neglected. The relative humidity and airflow rate were measured as the air exit the permeability cell; The apparatus is shown in Figure 3 [7].

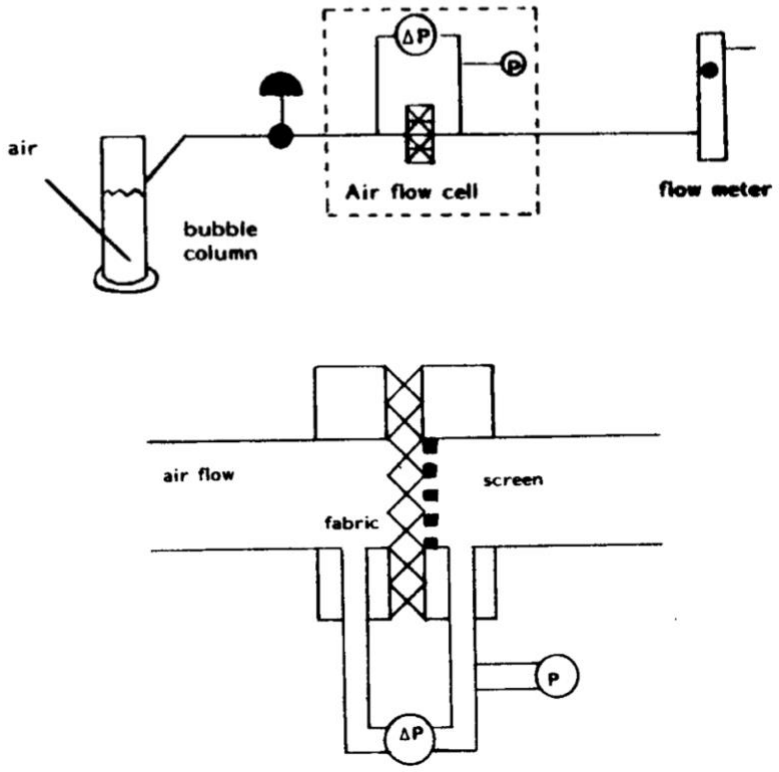
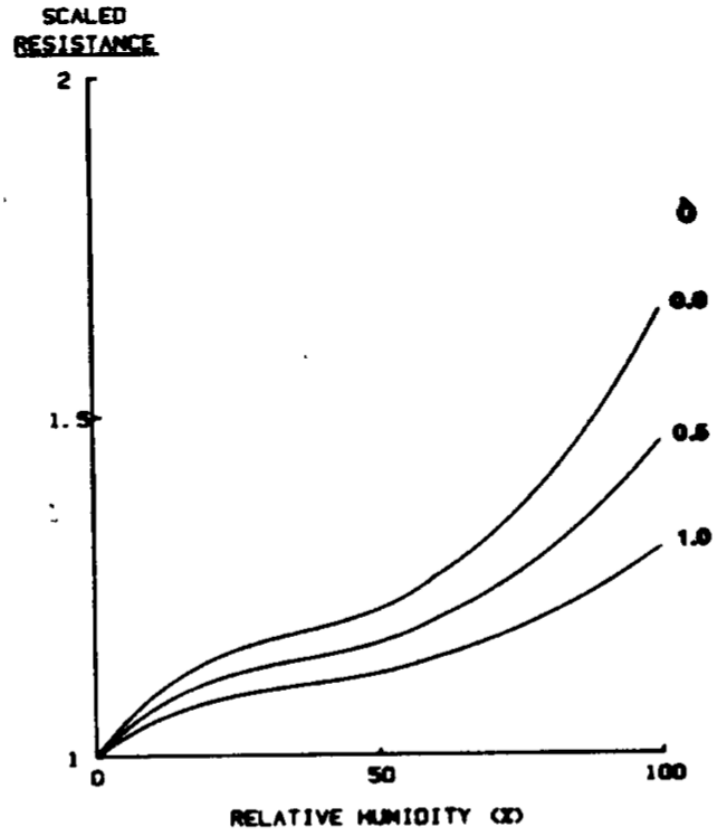


Figure 3: Schematic diagram of Wehner et. al. airflow resistance apparatus [7].

The experiments showed that the air permeability was sensitive to changes in relative humidity. The data was collected at 0%, 40.5%, 68%, and 94% relative humidity and it was determined that the important factor for the pressure drop across the fabric was the humidity and not the given air velocity [7]. Wehner et al. claimed that the relatively small difference in data acquired at 40.5% and 68% relative humidity were significant. The second goal was to show the structural alterations that resulted from moisture absorption. Based on their findings, Wehner et al. suggested that swelling of the fibers leads to changes in fabric thickness and porosity. It is called hygral expansion, meaning that there was radial swelling and a concurrent increase in the radius of the yarns when moisture absorption increased the fabric dimensions [7]. This phenomenon varies differently depending on fabric type and structure of fabrics but for woven

wool, it is about 5%. This is helpful to understand the effects on air permeability because as the yarn dimensions increase so does the resistance of the airflow in the porous medium. The porosity of the fabric is equal to one minus the fiber volume fraction, but the fabric thickness is very difficult to quantify. This is difficult because most synthetic fibers have a very limited moisture absorption capacity which was making it difficult to collect data to show if the thickness changed or not. There is a variability between fabric thickness and since absorption is low it was difficult to compare initial and final thickness results because they were so close. Therefore, Wehner et al. used an indirect method of relating dimensional swelling to moisture sorption by expressing it in a quantity of $\delta = (\Delta L/L_0)/(\Delta D/D_0)$ where L was the fabric thickness and D was the diameter of the fiber. The changes were defined this way so that δ would be positive but it would vary fabric to fabric, due to the varying effects of hygral expansion in different fabrics. The varying effects of hygral expansion make it difficult to set external constraints or justify comparable dimension changes because they are not always clear. But this indirect method allowed Wehner et al. to show that the most hygroscopic fabrics with internal constraints changed their structure resulting in a change in thickness. This supported the suggestion that there is a relation between structural changes caused by moisture absorption and the dependence of air permeability on relative humidity [7].

Based on the model developed by Wehner et al. the airflow resistance curve of intrinsic resistance versus relative humidity can be made and it corresponds to different δ values. But due to the fact that these fabrics were free to expand with no external constraints and there were no other available methods to quantify the structure, which made it near impossible to determine if the different δ values led to significant differences in air permeability based on the result in Figure 4 [7].



Fabric	δ
Wool	0.88
Cotton I	0.92
Cotton II	0.75
Rayon nonwoven	0.80

Figure 4: Effect of the moisture absorption on airflow resistance for varying levels of fabric constraint and δ values for the fabric [7].

To confirm the hypothesis about the dependence of δ on intra-fiber constraint Wehner et. al. constructed thermally bonded nonwoven rayon fabrics. The fabrics were constructed with a varied amount of vinyon binder fiber from 4.8 to 30% with the nonwoven rayon. The reason for adding and adjusting the number of vinyon fibers to the rayon fibers was to create more bonding points, allowing the fabric to be more constrained. The results (which are shown in Figure 5) seemed to be in line with the previously proposed hypothesis that the added vinyon increased the

intra-fabric constraint. The vinyon moisture uptake was relatively small, while the rayon had a high moisture absorption and the absorption increased with bonding points. This allowed Wehner et al. to evaluate the effect the blend has on moisture sorptive capacity due to the vinyon on the intra-fabric constraint [7]. This data continued to show the correlation between the fabric structure and moisture absorption being relevant factors contributing to air resistance and air permeability. Studying the effects of fabric structure was out of scope for this project, but it provided good insight into the expected or unexpected behavior of fabrics when challenged at different humidity levels and the importance of a reliable method to assess air permeability at different humidity levels.

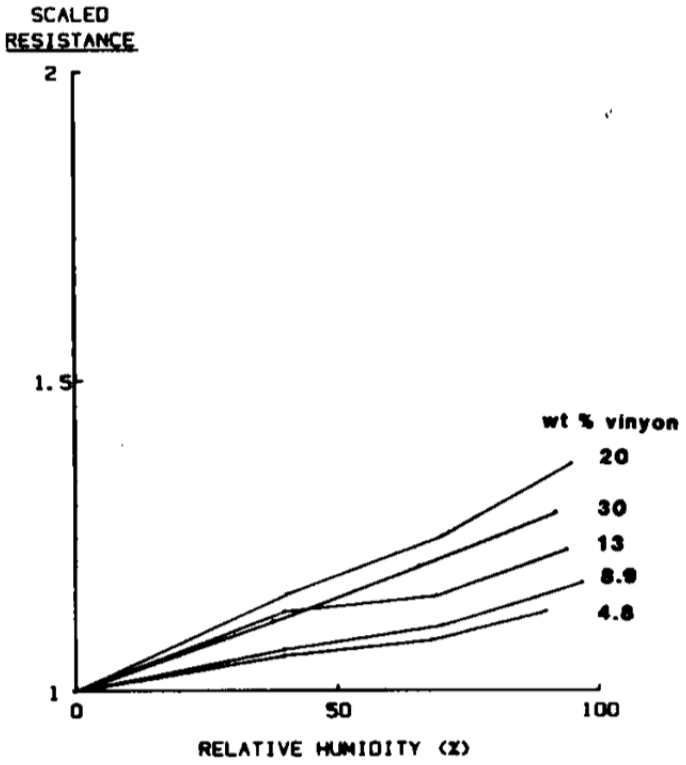


Figure 5: Shows the measured values of airflow resistance of the blended rayon nonwoven fabrics with varying amounts of vinyon as a function of humidity [7].

As there are different factors that affect air resistance as a function of relative humidity it is important to understand how they interact. Wehner et. al. tackled these various factors by looking at the flow resistance. A deeper dive into air permeability and its driving factors are assessed to provide a better understanding of humidity effects and whether the constructed system provides enough accurate data to evaluate air permeability.

Fabric Sorption

Fabric sorption is a difficult process. Therefore, Barnes and Holcombe investigate this behavior with the theory of ideal sportive fabrics. In practical terms, the hygroscopic fabric will absorb and desorb small amounts of moisture while maintaining constant humidity in the air. This also means that for an ideal non-sorption fabric absolutely no vapor is absorbed, and the fabric constraints and resistance remain unchanged [8]. There are other components that play into how vapor pressure is expressed through clothing such as through the complex movement of the garments. To capture a piece of this complexity, one idealized mode of movement was used by Barnes and Holcombe. Due to assumptions such as the fabric laying perfectly parallel to the skin and that the ambient atmosphere is constant [8]. Creates a simple model of movement for the fabric between the environment and the skin which allowed Barnes and Holcombe to solely evaluate vapor resistance. An ideal nonsorptive fabric based on this model is assumed to have no moisture capacity therefore there is no effect on the diffusion between the skin and atmosphere. In other literature Crank [19] defined diffusion across a region without moisture capacity as equal to the concentration difference divided by vapor resistance. An experiment was run for four complete cycles and a ratio for an ideal sorptive fabric of moisture transport with movement

and without movement was derived. This result showed that ideal sorptive fabrics remove significantly more moisture than non-sorptive which was expected.

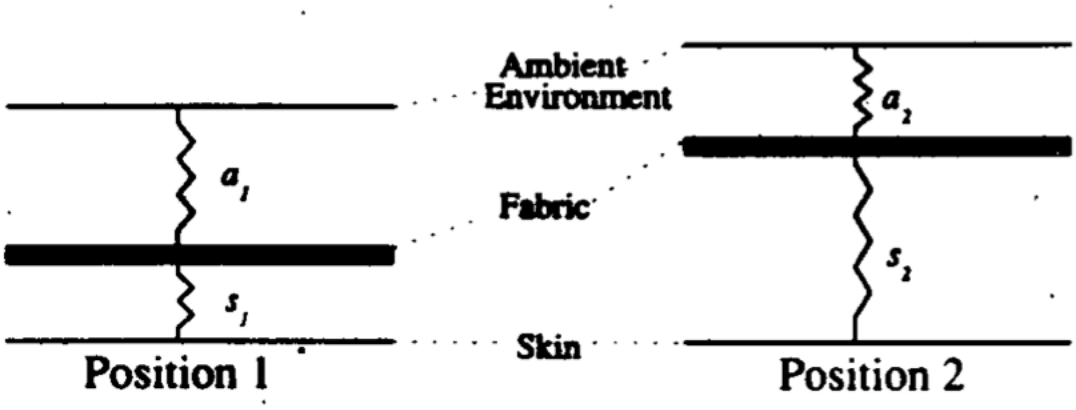


Figure 6: Model created to show vapor resistance between the skin and the fabric, where the fabric is assumed to move repeatedly between the two positions. The a and s values represent the different resistance in those areas [8].

In real-world applications, the fabric-ambient vapor resistance is often constant, while skin-fabric vapor resistance varies with skin-fabric separation. Barnes and Holcombe used the data collected from the model in Figure 6 to create a theoretical ratio equation of ideal and nonideal sorptive fabrics for moisture transport from the skin. Because the theoretical ratio did not account for real-world application Barnes and Holcombe changed the ratio equation from the theoretical $Ratio = \frac{R^2}{4s_1(R-s_1)}$ to $\frac{2(\frac{1}{s_1}+\frac{1}{s_2})}{a(\frac{1}{s_1+a}+\frac{1}{s_2+a})(\frac{1}{s_1}+\frac{1}{s_2}+\frac{2}{a})}$ where there is constant vapor resistance between the fabric and the ambient environment [8]. Barnes and Holcombe designed an experimental apparatus to demonstrate and verify the process of how fabric sorption increases moisture transport from sweating skin below moving fabrics. The apparatus (Figure 7) consisted of several components with test tubes partially filled with water and an oscillating fabric sample. The fabric samples being tested were a range of woven wool, polyester, and blend fabrics with varying structures. The concept of the system was that, as the water evaporated up the tubes into

the ambient atmosphere, the hygroscopic fabric specimen would absorb the water vapor near the bottom and would release it near the top. The transport would be measured by weighing the tube/water/fabric assembly [8].

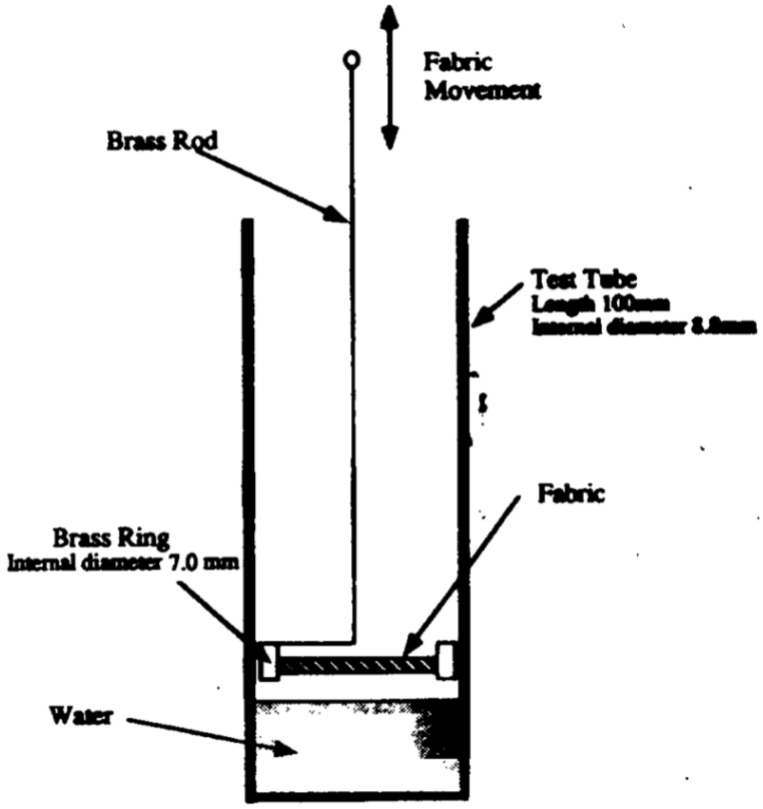


Figure 7: Simple movement experimental system. The parameters are water depth 30mm, water-fabric separation oscillating between 5 and 65 mm, and water-ambient separation of 70mm. Operation lab temperature is 20°C and 65% RH [8].

The system was simplified by minimizing the number of variations in temperature and humidity of the skin and ambient atmosphere. This is different from real skin behavior because there are temperature and humidity fluctuations within the microenvironments. The system used a saturated water layer to simulate sweating and the presence of salts in water [8]. The lab temperature was also held at a constant temperature to assist with the testing conditions of the ambient air. Due to the fact that wicking could occur on the fabric if it came in contact with the water layer and that could cause issues with hygroscopic effects and reproducibility, the fabric

was not allowed to touch the water layer. It should be noted that the movement of clothing would create complex air movements, but the experimental system was built to lower the number of uncertainties in moisture transport such as turbulence [8]. To measure the moisture, transport the entire assembly was measured after several hours of running. This was done because the results showed that long durations made the effect of any net change in fabric moisture content during one cycle negligible compared with total moisture transport over time.

The experiment ran without fabric movement and with fabric movement to evaluate moisture transport. The moisture transport without movement aligns with the hypothesized theoretical predictions for various water ambient separations. It was observed that there was no difference experimentally between the moisture flux with stationary wool and stationary polyester fabrics, shown in Figure 8 [8].

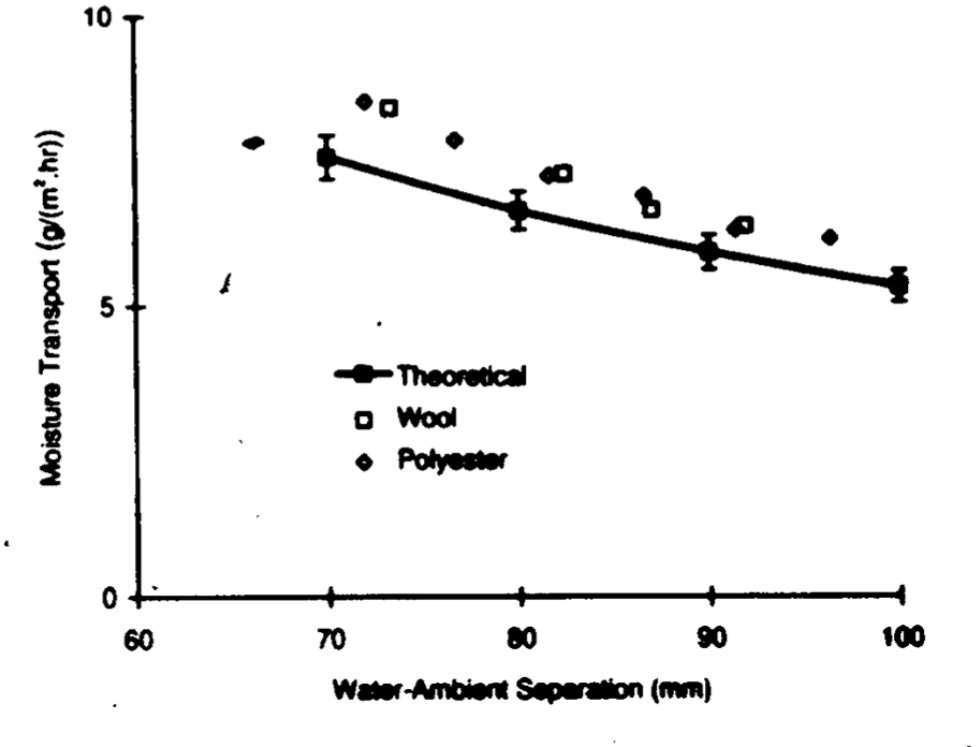


Figure 8: Shows the results of the moisture transport with stationary fabrics and the theoretical predictions. The calculated uncertainties from the theoretical come from the ambient temperature and humidity and the uncertainties from the measured results come from the tube cross-sectional area [8].

The moisture transport for the fabric movement test increased with the fabric movement speed and for the ideal sorptive fabric, the transport was 3.8 times bigger, while for the non-sorptive there was no effect. Figure 9 shows that the wool fabric has exhibited a significantly higher increase in moisture transport than with a stationary fabric and then has decreased with slower movement. Polyester fabric showed a similar increase with fabric movement but to a much lesser extent than the wool [8]. Barnes and Holcombe defined the sorptive uptake as the quantity of moisture that, during each movement cycle, was absorbed by a fabric in one position and desorbed in the other position. The water vapor is absorbed near the water layer and ambient atmosphere and not at the plane.

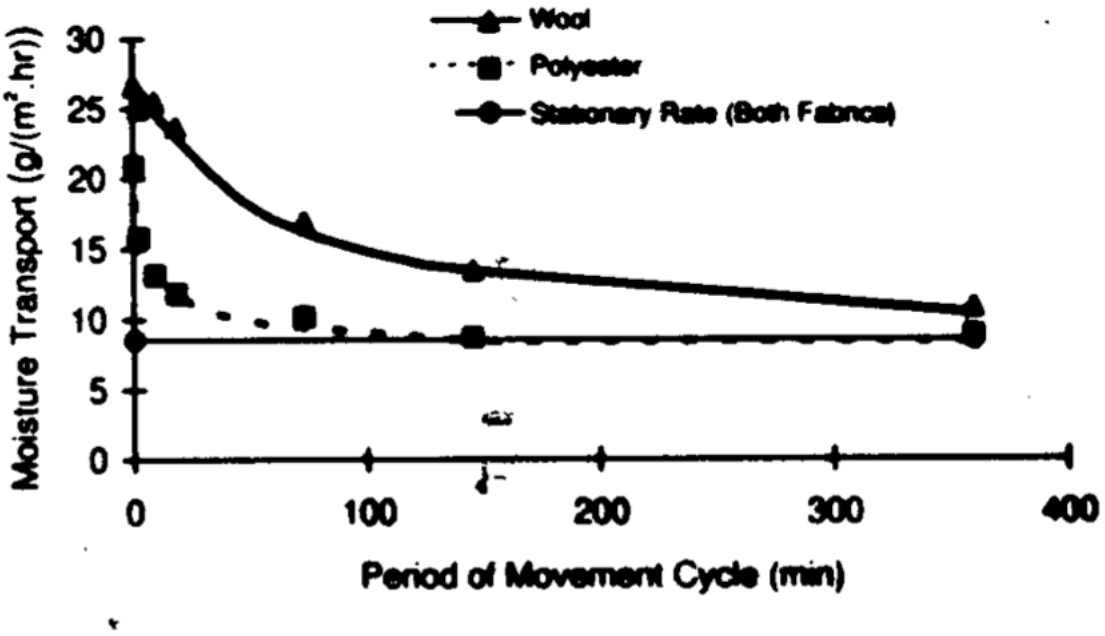


Figure 9: Moisture transport results of wool, polyester, and their stationary values [8].

This means that the vapor concentration decreased near the skin and increased near the ambient atmosphere, therefore reducing the diffusion between the two points. Meaning that the active (convective) transport dominated and resulted in a more effective transport of water vapor. It was

difficult to get a direct measurement in fabric moisture content because the change in weight was very small around 1 mg for long cycles, especially for wool fabric.

Air Permeability

As seen in other works of literature such as Wehner et al., Farnworth et al., and Gibson et al. there is a strong theme of relative humidity being a significant factor in air resistance. Depending on test conditions and humidity levels there can be significant changes in convective gas flow transport, especially in woven and nonwoven materials because of fiber swelling due to moisture sorption [1]. Gibson et al. created an apparatus of automatic flow that characterized this as humidity-dependent permeability. The main focus of most gas and liquid flow through porous material systems is on a correlation of structural properties with pressure drop – flow rate data. According to Gibson et al. [1], There are various ways in which air permeability is defined, the most common is Darcy's Law:

$$v = \frac{-k_D}{\mu}\frac{\Delta p}{\Delta x}$$

Where:

ν = apparent gas flow velocity (m/s)

K_D = permeability constant (m^2)

μ = gas viscosity (1.785×10^{-5} Pa-s for N_2)

Δp = pressure drop across the sample (Pa)

Δx = thickness (m)

Due to the low flow rates, the plot of air permeability versus velocity should not deviate from linearity. This is because the apparent Reynolds number is less than 10 and the inertial effects become unimportant and gave a constant value for the permeability constant k_D. The Reynolds

number is based on nominal particle diameter or pore size which can be related to the flow transmission of porous materials [1]. Similarly, to the transport of a fluid through a porous system, part of the energy of a gas is used to overcome friction against the fibers within the porous fabric structure. The dependence of this friction can be described by the Blasius equation, which is expressed as $\lambda = ARe^{-n}$, which uses the Reynolds number Re, the porosity of the material A and the flow regime, where n is between 0 and 1 [12]. Depending on the value of the Reynolds number will determine if the fluids flow is laminar or turbulent. When the Reynolds number becomes greater than 1, the coefficient n becomes independent of the Reynolds number and becomes a laminar flow instead of a turbulent flow. This is beneficial because it keeps the plots from deviating from linearity and the inertial effects won't compete with the viscous flow effects [1]. This was further defined by Kulichenk and Langenhove [12] as the transport of fluid through a porous system, where part of the energy of the fluid is used to overcome the friction of liquid on the fabric. Based on experimental data the relationships of Re for monofilament nets, fabrics, and cylindrical metal tubes become independent of the Reynolds numbers but when the Re value is less than 1 and for steel tubes greater than 40 the flow becomes turbulent. The main cause for the difference in the steel tube and fabrics is surface roughness because it affects the character of liquid flow through the pore system. A system with parallel tubes, like porous materials, can be presented as laminar flow because they are usually based on the Poiseuille formula for one capillary [12]. The Poiseuille equation can be represented as:

$$Q = K\left(\frac{\Delta P}{L}\right)d^4$$

Where:

Q = flow rate of liquid through pore

ΔP = pressure drop (Pa)

L = pore length

d = diameter of the pore

K = proportionality coefficient, related to liquid viscosity, η, by Stokes' formula: $K = \Pi/128\eta$

When porous systems are examined by open-porosity calculations only a small section of the pore cross-section will be considered referring to the distance (d) between pores. Thus, causing the square cross-section at the pore input and output to be larger [12]. This is why the values obtained experimentally for the laminar flow regime give higher values for net structures than the theoretical methods. The addition of Darcy's Law with Poiseuille's formula made it possible to predict the permeability of woven fabric, but it is necessary to implement a correction coefficient that correlates with the hairiness of yarns because the equation is for net-type pore systems with smooth surfaces [12].

Gibson's Air Permeability Method

Gibson et al. [1] used seven different types of fabrics that varied in construction, physical properties, and water sorption properties, which were wool, cotton, silk, wool/polyester blend, nylon/cotton blend, nylon, and polyester. The test method was developed similarly to ASTM F778-88, Standard Methods for Gas Flow Resistance of Filtration Media. Essentially, Gibson et al. created an automated gas permeability test for fabrics.

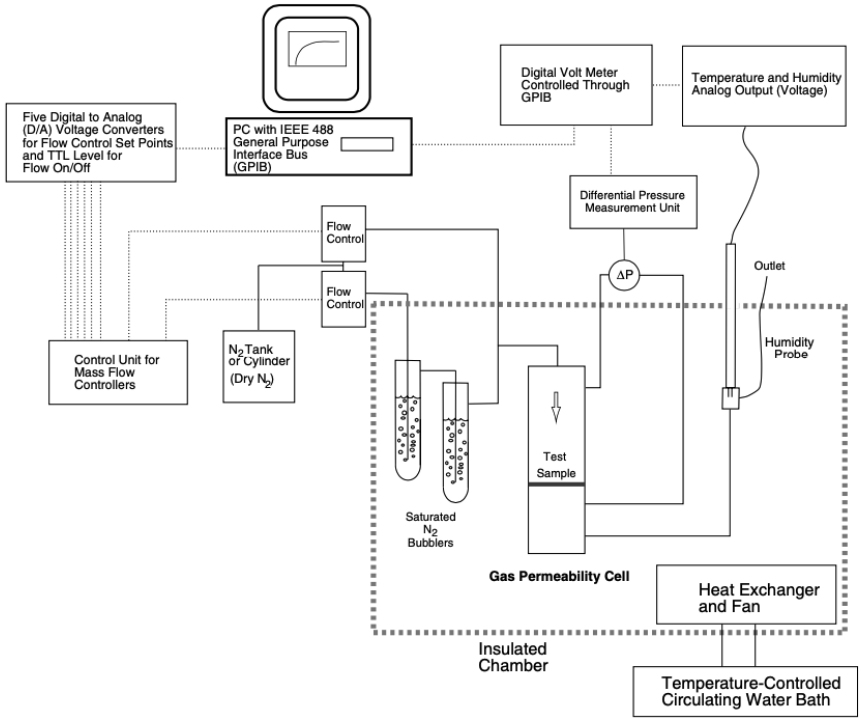


Figure 10: Apparatus for Gibson et al. gas permeability test [1].

The apparatus was composed of two nitrogen streams where one was dry, and the other was water-saturated and these both flowed into the gas permeability cell. A mass flow controller was being used to control the volumetric flow rates, but Gibson et al. noted that the flow rates will be varied with temperature. The standard conditions of the flow meter are 0^0C and the atmospheric pressure was 1.01325 x 10^5 Pa. The temperature and relative humidity were measured after the test sample with a capacitance-type probe and Type HMP 35 sensors [1].

The test ran at a certain humidity level and set flow rates which were controlled by the flow meters. The relative humilities were 20%, 40%, 60%, 80%, and 100% while the flow rates were 2000, 1500, 1000, 750, 500 cm^3/min going through the samples. A permeability constant was derived by plotting a pressure drop versus mass flow rate and volumetric flow rate or apparent flow velocity (Gibson et.al., 1997).

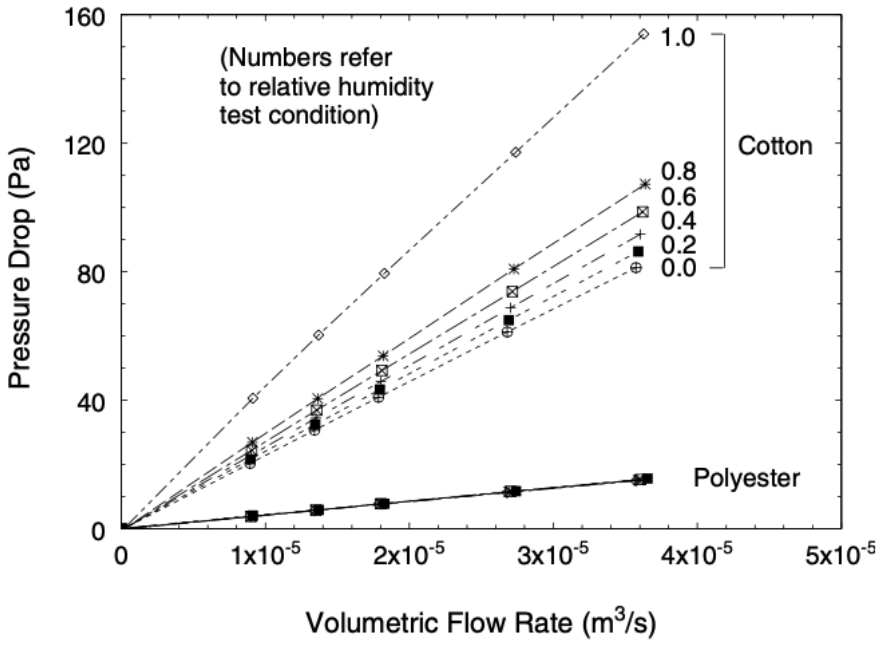


Figure 11: Shows the pressure drop versus volumetric flow rate for two fabrics as a function of relative humidity [1].

The above plot shows the variability of cotton with relative humidity but with polyester, there didn't seem to be any. This allowed Gibson et al. [1] to calculate air permeability from Darcy's law at each of the relative humidity conditions. The flow resistance defined by Darcy's Law is rather beneficial because it allows for the measurement of individual material flow rates to be added together to give the total flow rates. The volumetric flow rate was used for the permeability constant and the equation is expressed as:

$$k_D = \frac{\mu Q}{A}\frac{\Delta x}{\Delta p}$$

Where:

μ = gas viscosity (17.84×10^{-6} kg/m-s for N_2 at 20°C)

Q = total volumetric flow rate (m^3/s)

A = apparent sample flow area (9.678×10^{-4} m^2 for present sample holder)

Δx = Thickness (m)

Δp = Pressure drop across the sample (N/m^2 or Pa)

In Textiles the thickness of the fabric can cause errors if incorporated into the measurements of Darcy permeability, therefore it is presented as an apparent flow resistance shown as:

$$R_D = \frac{A\Delta p}{\mu Q}$$

R_D = Darcy apparent flow resistance (m^{-1})

Thus, the Darcy air permeability can be found as:

$$k_D = \frac{\Delta x}{R_D}$$

From the results in Figure 12, it was shown that polyester was not affected by humidity-dependent porosity changes, and this supported that the additive approach works for measuring the total flow resistance. This was valid for low flow rates but not for flow rates when inertial effects are important [1].

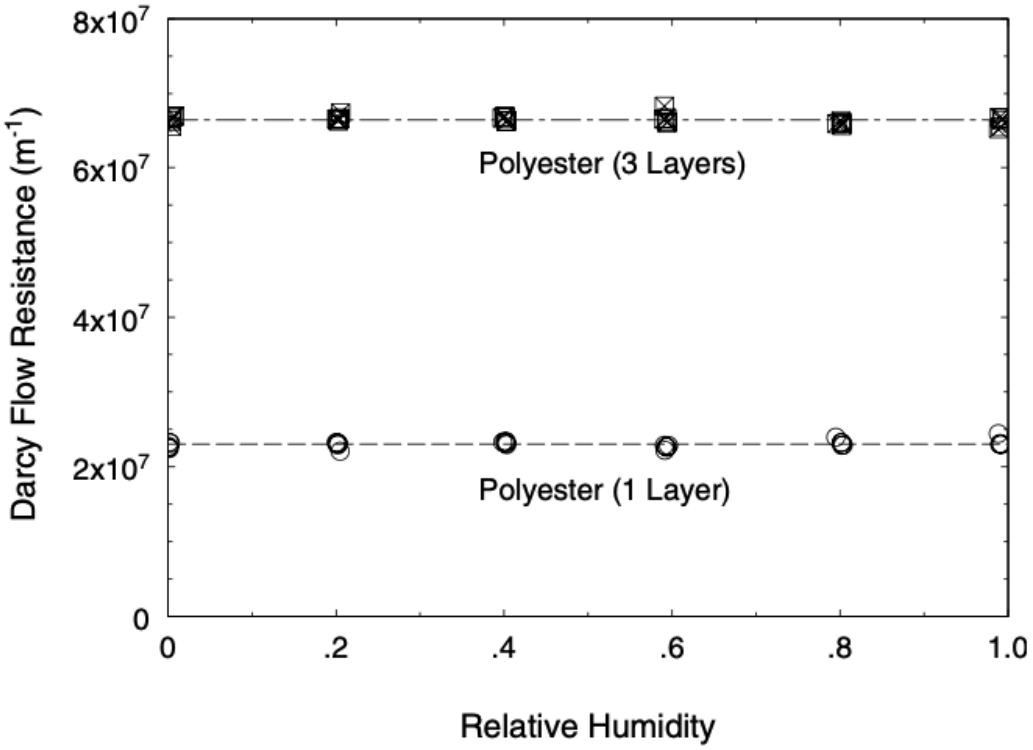


Figure 12: Polyester humidity-dependent results single and multi-layered [1].

Based on the results shown in Figure 13 by Gibson et al. cotton, wool, and silk had a large increase in air resistance at higher humidities, whereas fibers such as polyester and nylon show less variation with relative humidity.

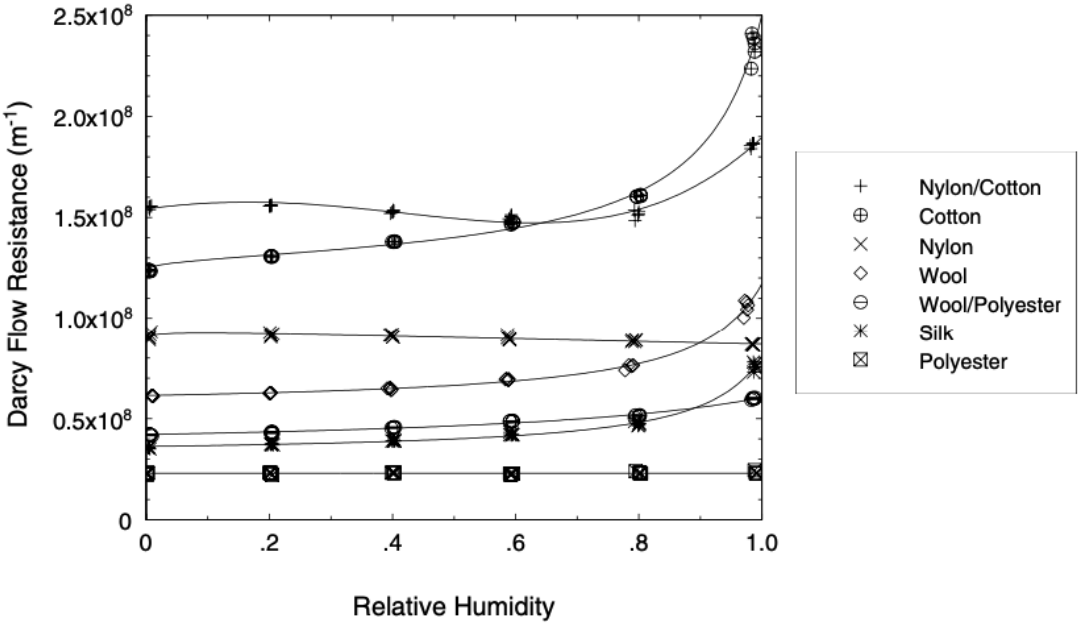


Figure 13: Different Fabric humidity dependence on flow resistance [1].

Based on Gibson et al.'s findings confirmed that there are clear changes in fabric air resistance with changing humidities. The hygroscopic fabrics show a large change in resistance to convection flow at the higher humidities due to fiber swelling and a decrease in free air volume in the fabric. While polyester and nylon which are less hygroscopic show less variation with relative humidity [1]. There are several examples of fabric that are known to change their relative air permeability based on relative humidity and Gibson et al.'s focus were on cotton and nylon/cotton fabric. Unlike cotton which showed a significant increase in air resistance nylon has a tendency to slightly decrease in air resistance. In Figure 14, the nylon/cotton fiber shows a slight decrease before increasing, unlike the cotton fabric that has a steady increase in air resistance.

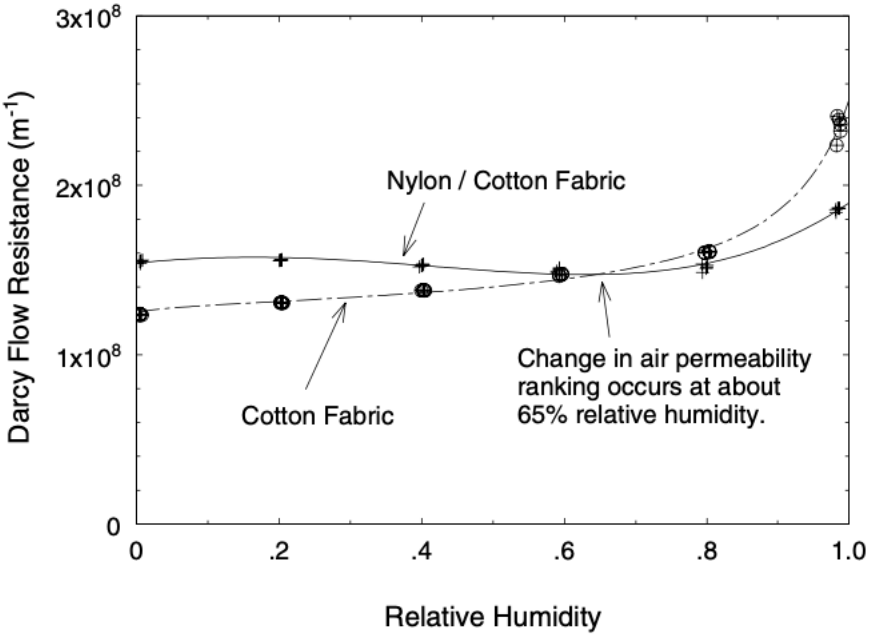


Figure 14: Shows the reversal of air permeability ranking due to the relative humidity test for cotton and Nylon/Cotton fabric [1].

This just further shows that with nylon fibers moisture sorption has a tendency to swell axially instead of radially like other hygroscopic fibers. When testing just nylon fabric there is a tendency to decrease in air resistance at high humidity levels [1]. Gibson et al. took time to show a hysteresis of sorption to better illustrate how the Darcy flow resistance versus humidity curve was similar to that of the sorption isotherm of cotton. The comparison in Figure 15 is given to show clear evidence of fiber swelling at high humidities had an effect on air resistance. In the graph, the same cotton fabric was used, and the sorption isotherm was plotted in terms of fabric regain R, which is defined as R = (mass of absorbed water) / (initial mass of dry sample). Both samples were tested at 20°C [1].

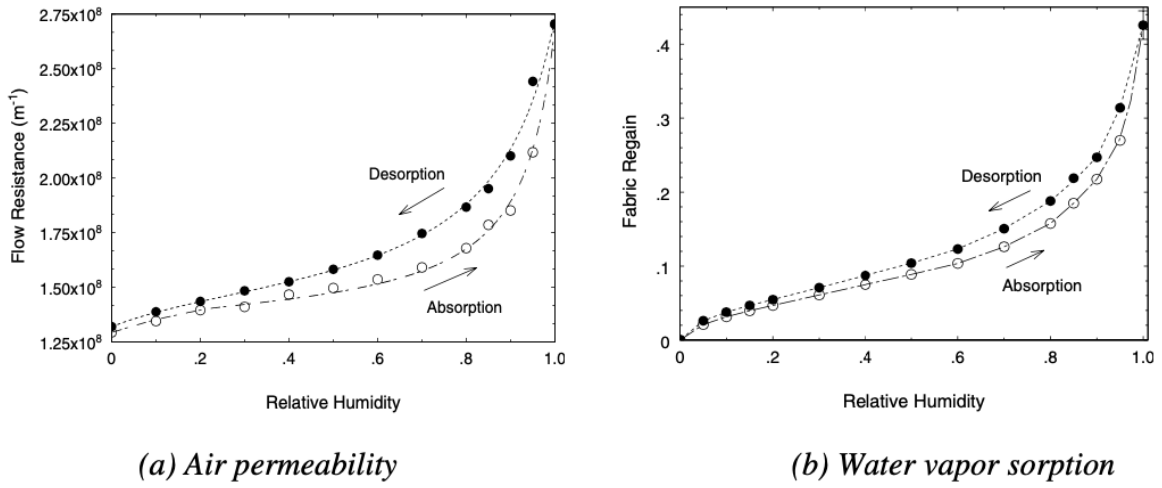


Figure 15: (a) shows the sorption hysteresis in an inverse flow resistance curve for a cotton fabric at 20°C, and (b) is a water vapor sorption isotherm and hysteresis for a cotton fabric at the same condition [1].

The variability in results may have been caused by sorption hysteresis, flow rate, and relative humidity test conditions plus material variations can play a role as well. Due to the automated nature of the system acquisition, it was possible to obtain transient data following the change in relative humidity of gas flowing into the permeability cell. There was a time-related aspect to fiber sorption because, for certain fibers, such as wool, it took a long time to swell and show a difference in air resistance. The Gibson et al. apparatus allowed for automated data acquisition in exploring and characterizing the way in which fabric structural changes, caused by moisture sorption at high humidities, can change the air permeability of porous textile materials [1].

Objective

The objective of this thesis was to re-create the test methodology that Gibson et al. developed and studied whether it might be used as a standardized test to evaluate air permeability of the fabrics at different humidities [11],[1],[3]. Furthermore, the uncertain effects

of fabric thickness to assess the Darcy's permeability and flow resistance were studied. The focus of this thesis was method development but a variety of fabrics with different hygroscopic properties were used, such as wool, cotton, and polyester with relative humidity.

Chapter 2 Methodology and Materials

Materials

The goal of this system is to measure a pressure drop across a fabric at a fixed flow rate that allows measurement at different relative humidities. The listed materials were used to display this ability to measure the pressure drop across the fabric. The materials for the test system were an air supply system, 2 mass flow controllers from AALBORG, a bubbler, a dissident container, a heated oven from Frigidaire, a closed test cell, an Elitech measuring device that recorded temperature and humidity, and a series 477AV digital manometer. The different components were connected via Tygon tubing assisted by polycarbonate connectors. This set up was a modification of Gibson et al. [7] setup for their response on humidity-dependent textile materials. The description of each component is listed below with pictures.

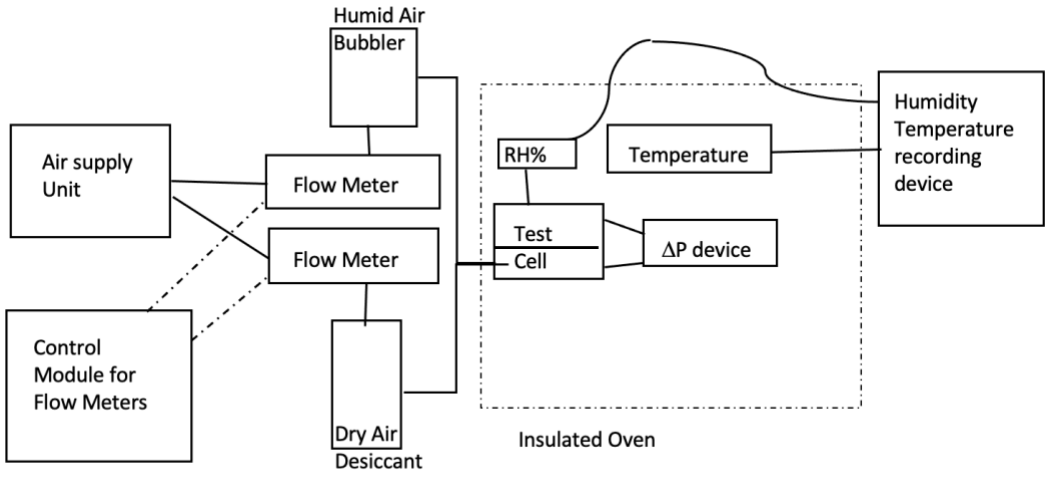


Figure 16: This shows an illustration of the test setup.

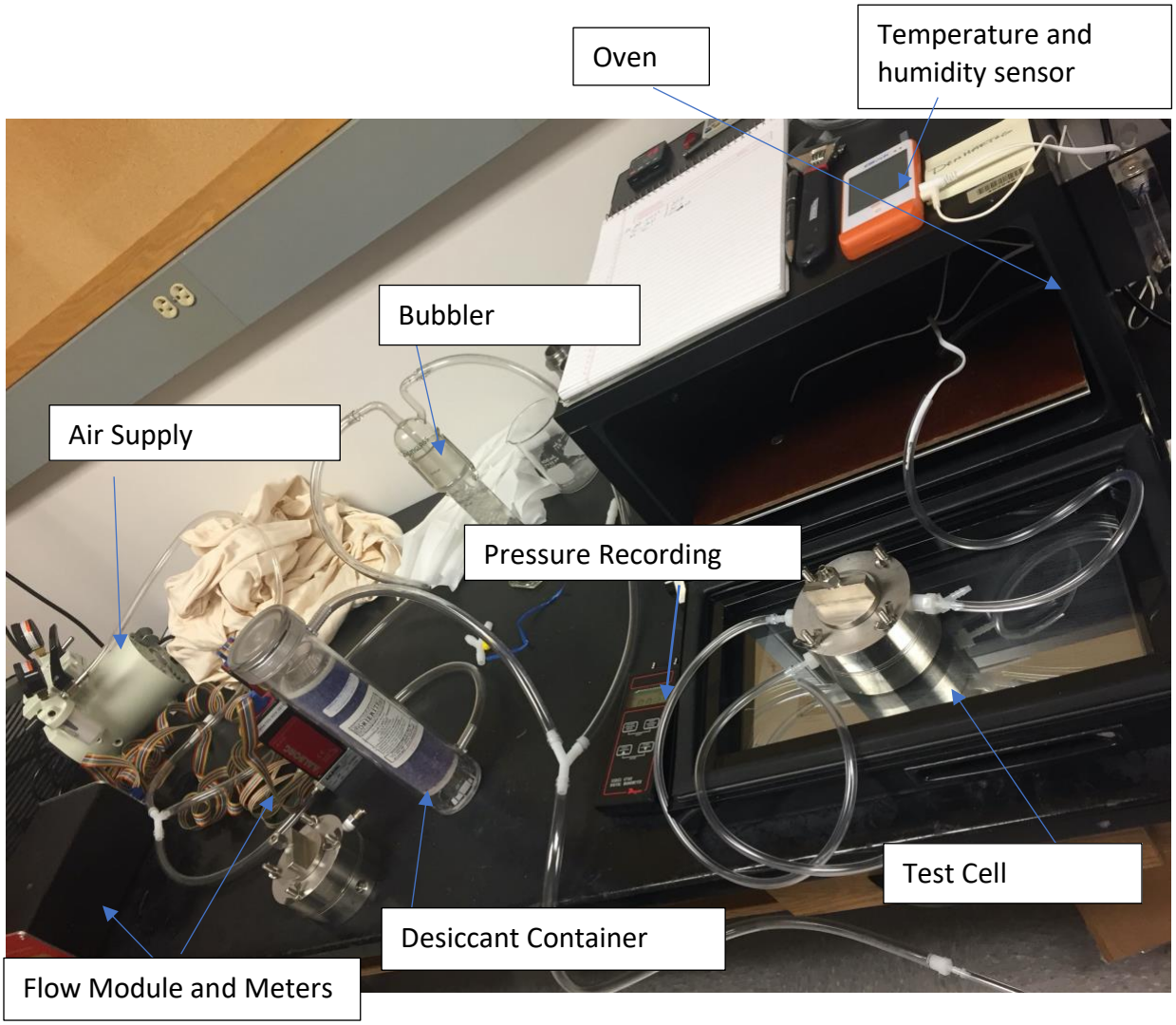


Figure 17: Complete System Set up

The Air supply component shown in Figure 18 was to provide the air for the entire system by pulling the environmental air through a vacuum and pushing it out through the tygon tubes.

Figure 18: Shows the environmental air supply unit.

The Mass flow controllers in Figure 19 were from AALBORG (0-10 L/min) and their primary goal is to split up the flow rates of the humid and dry air and control humidity.

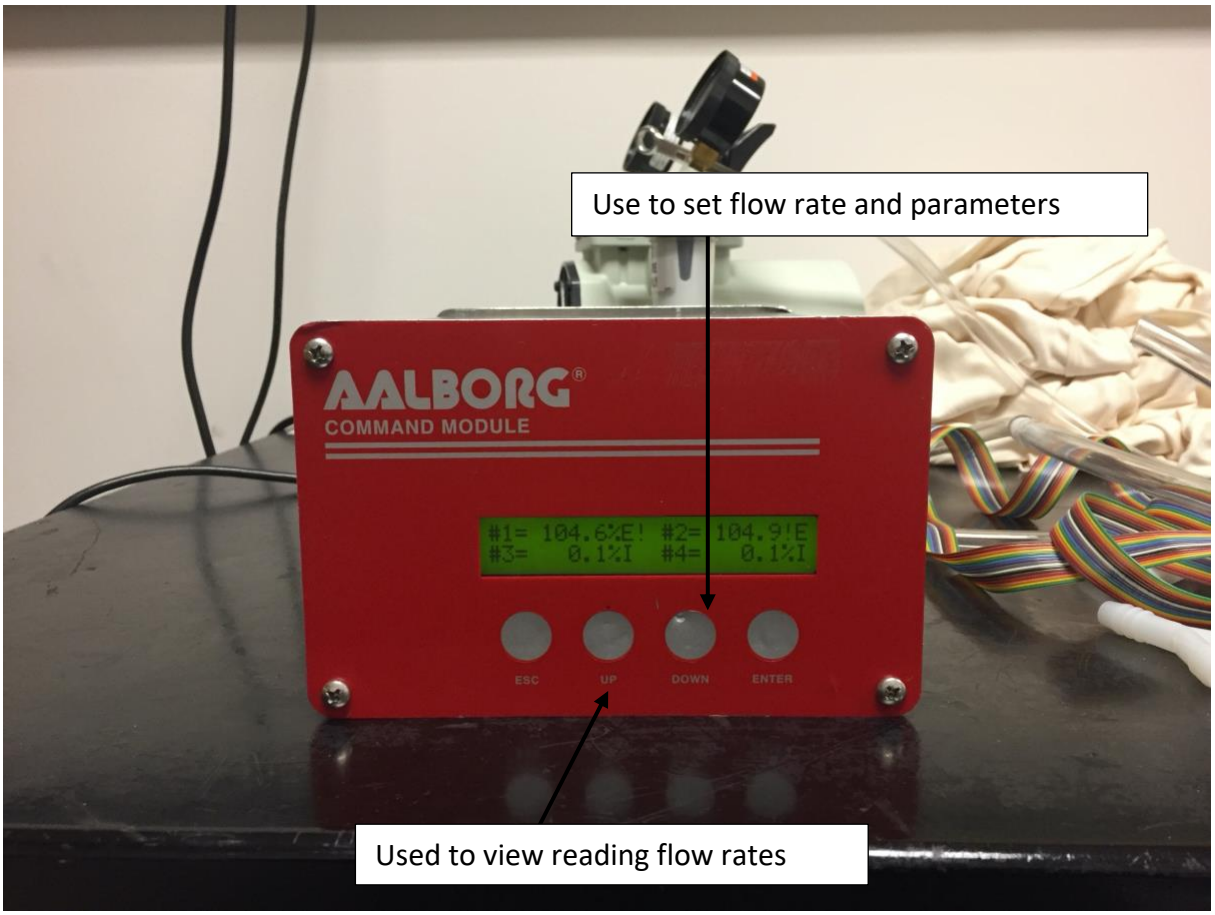


Figure 19: AALBORG command module

Next is the bubbler (left image below) shown in Figure 20 which provides humid air to the system. To increase the humidity of the air is to add heated water but note that too high temp water will cause condensation to build up the tubes. The parameters set for the gas were the density and desired flow rate in terms of standard liters per minute. The density of oxygen can be found in the AFC Mass Flow Controllers manual [13].

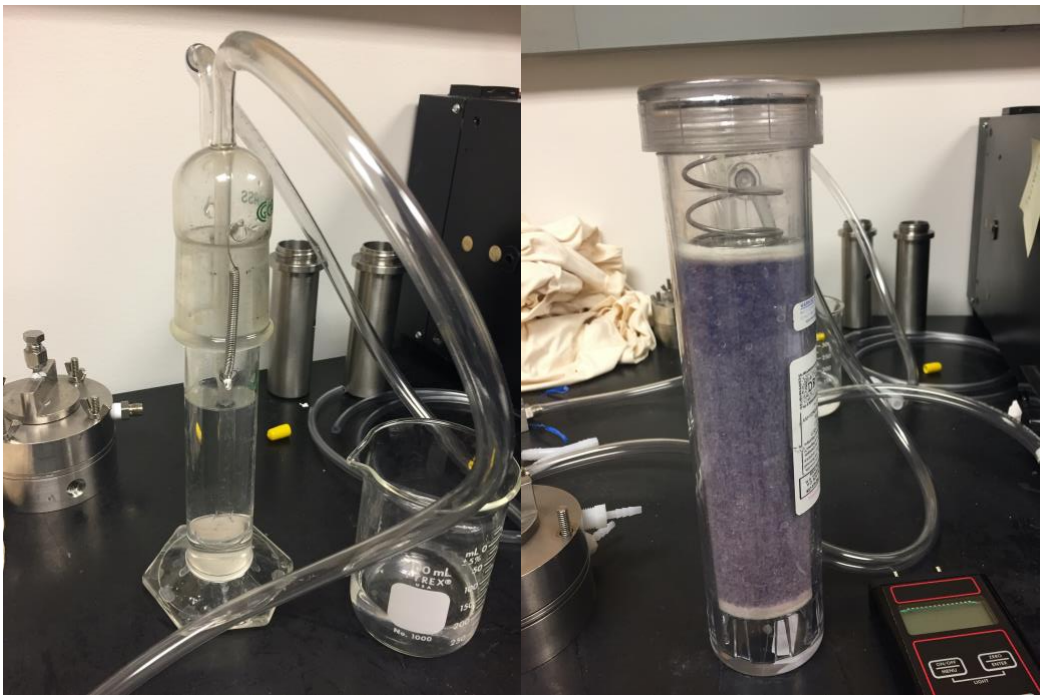


Figure 20: Bubbler (on the right) and Desiccant Cylinder (on the left).

The dry (above right image) air is created with silicon desiccant gels in a cylinder container to dry out the environmental air that is being supplied by the air vacuum system.

The tubes then lead into the Frigidaire, which is the control climatic oven where the temperature is set for testing. Figure 21 shows how the temperature is controlled. The temperature is set by using the arrow keys and submitted by pressing the red set button. The temperature is accurate to ±0.3 according to the measured temperature.

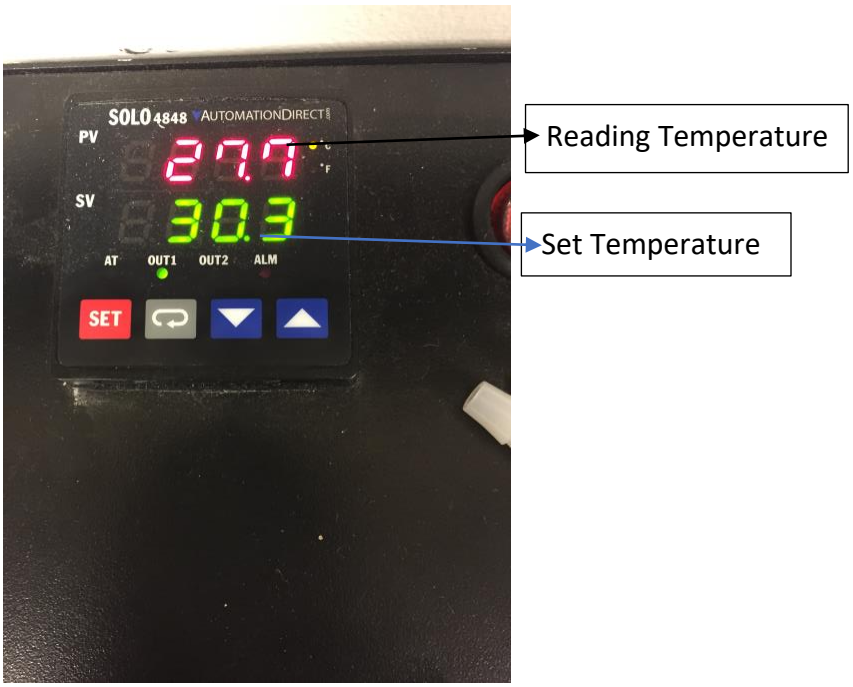


Figure 21: Control panel for the oven.

The test cell is similar to a permeation test cell works the same way. Figure 22 below represents the Test cell closed, open, and with sample respectively. The samples are folded in a 4 layered method which based on Gibson et. al. findings do not affect the analysis process of air permeability because it is an additive process.

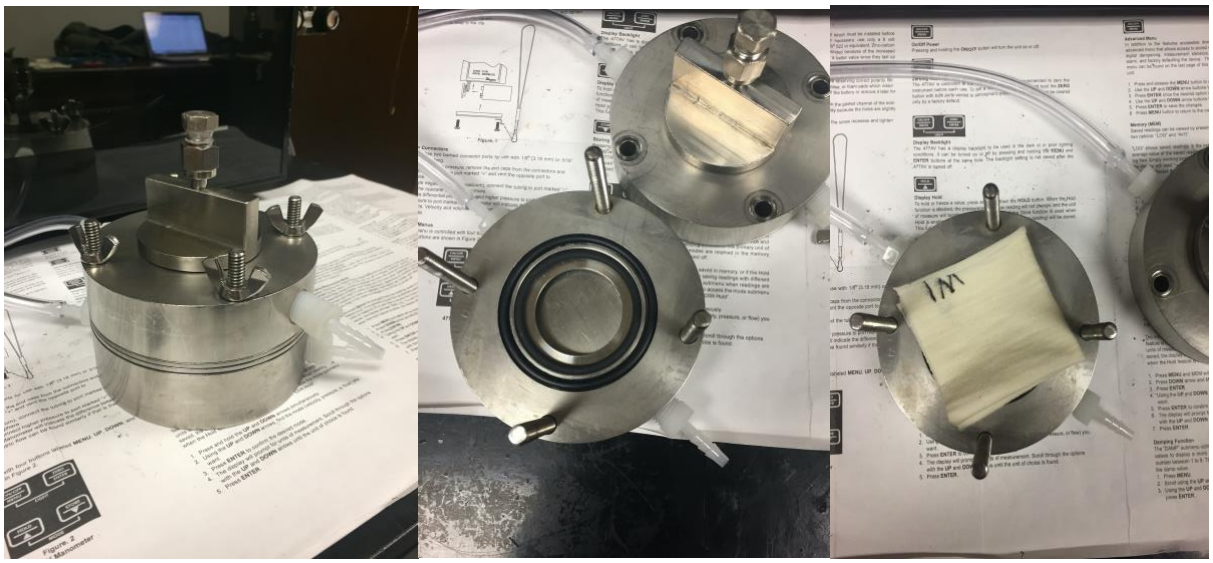


Figure 22: Test cell and sample placement.

The measuring tool that was used was the 477AV manometer which measured the pressure drop and the Elitech GSP-6 which measures humidity and temperature. When using the measuring tools make sure to tare/zero the 477AV due to the readings drifting from accurate readings. The accuracy of the 477AV is ± 0.5% and the Elitech GSP-6 temperature accuracy is ±0.5 and the humidity sensor accuracy is ±5%.

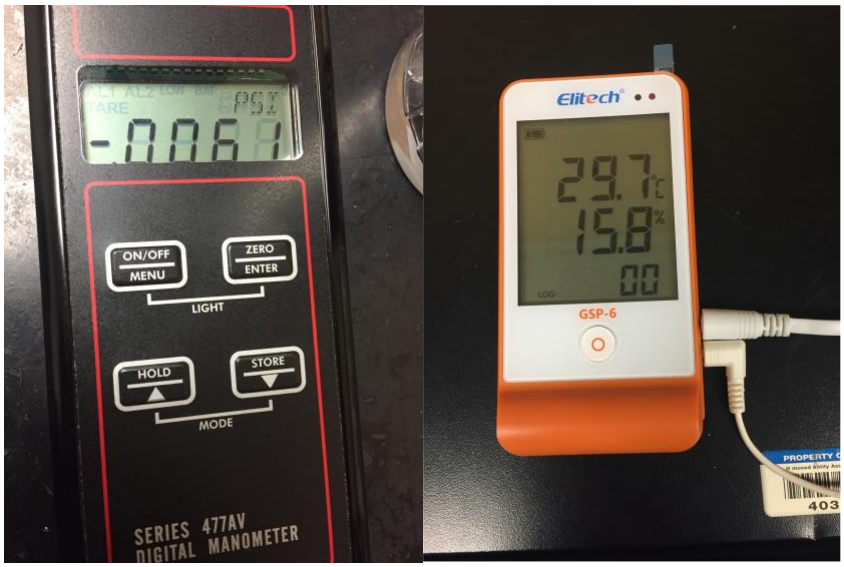


Figure 23: 477AV differential measuring device (on the right) and The Elitech GSP-6 Humidity/Temperature measuring device (on the left).

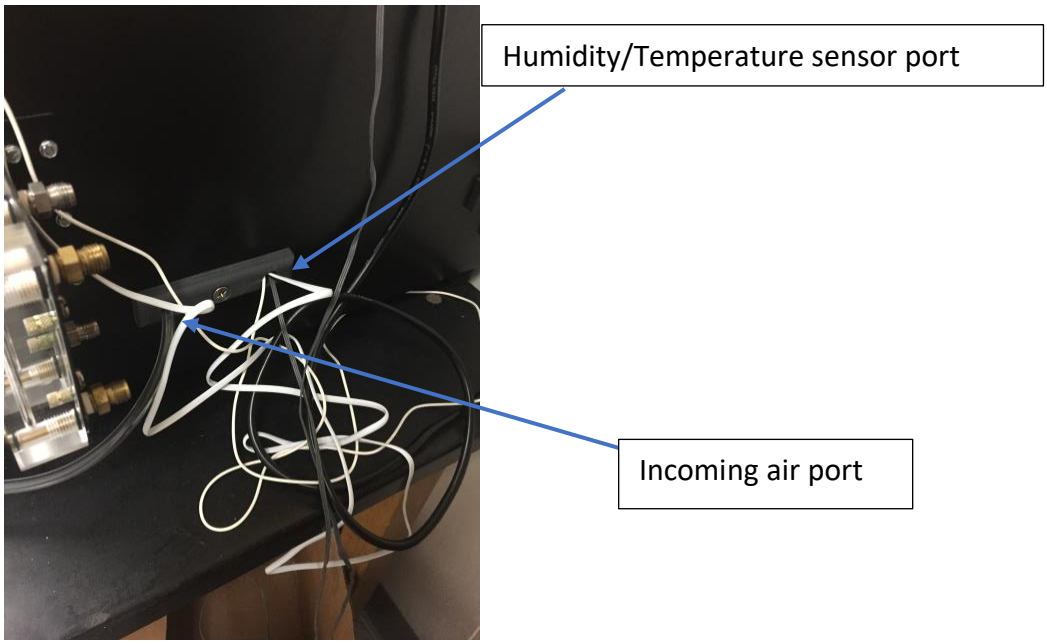


Figure 24: Shows the side of the oven to show placement of incoming airline and humidity/temperature sensor cords.

Method

The experiment was conducted with six jersey knit wool, polyester, and cotton fabrics. Referring to ASTM D22 Committee Methods for Gas Flow Resistance Testing of Filtration Media an evaluation process was derived for the following test practices [6]. A critical or choke flow was assessed for the test cell, which is when a gas velocity reaches sonic conditions when the absolute pressure ratio is .528. But the air velocity and pressure ratio did not meet the required measurements, and this was dismissed as an issue [2].

Initial Experiments

During the 1st couple of experiments, it was shown that the humidity of the incoming air was significantly higher than the outgoing air. The difference could present skewed data and not fully represent air resistant changes in the fabric. The error showed that there may be a humidity leak in the system or there was condensation build up in the test cell. After checking the test cell and lines for condensation there was none observed. The room temperature and humidity were measured and then it was advised to check the temperature of the ingoing and outgoing lines. This showed that the temperature of the incoming and outgoing air was different and due to the difference in the room temperature and the oven temperature there was a humidity difference. This was causing an error with recording accurate data therefore this had to be corrected. To fix this problem the incoming air tygon tube was extended longer into the oven to allow time for the air to acclimate to the oven temperature. This was a trial-and-error process because it was not known how much of the tube needed to be in the oven to make sure that the humidity would be at equilibrium, therefore the majority of the tube was placed in the oven and the result was as followed. This allowed the humidity levels to reach a 2% to 6% difference in reading which is

small enough to be null in effecting air permeability. Therefore, make sure the humidity sensor reads the desired humidity level for both incoming and outgoing air.

To being testing open the oven and place the test cell inside and place the incoming air tube on the bottom port. Place the humidity sensor probe in the top port tube so that the humidity will be monitored constantly. The humidity and temperature sensor will go in the second hole on the side of the oven next to the hole for the incoming air tube (see figure 24). The temperature sensor will just sit inside the oven to measure its temperature continuously. The air supply unit will be connected to a Y- polycarbonate connector splitting the air into the two flow meters. The flow meters will be connected to the module in channel 1 and channel 2 ports. Channel 1 port will be connected to the humid air caused by the bubbler and channel 2 will be connected to the desiccant cylinder. Once the air passes through the flow meters and humid and dry air systems, it will converge at another Y-connector into a single tube running into the oven and eventually to the test cell.

The initial experiments were challenged under the condition that the oven was set to 30 degrees Celsius, and it took about 15-30 minutes to reach the desired temperature after setting. The 30 degrees was chosen to simulate microclimates near the skin when interacting with clothing. The initial run for the test method was 15 minutes and then moved to 30 minutes but after looking at the results of wool and cotton there were little to no changes in humidity. There were some variations with the results as well showing some samples decreasing in air resistance. There was expected to be a change in the cotton samples because of the suspected regain rate. After reviewing Barnes and Holcombe's article it was noted that there is a significant time length for fabrics to absorb enough moisture to have a change in air permeability [8]. Thus, the run was moved to an hour, and measurements were recorded at 15-minute intervals, but this still proved

to not give enough to see notable changes in the wool samples. The final run time that was selected was 2 hours with measurements recorded at 15-minutes intervals. This provided notable data points to show the effects of humidity on the air permeability of fabrics. An overview of the final procedure is provided in the Appendix A.

Chapter 3 Test Challenges

Challenges

In conducting this test there arose a few obstacles in the design and methodology of the experiment. The start of the set up was to control the humidity of the incoming air by using the flow meter, bubbler, and desiccant container. The issue was that the flow meters were reading different flow rates but there was no to minimal change in humidity. This is to be assumed that the flow meter was not able to make drastic flow changes or that the airflow was too low to show a different humidity when splitting the flow rates. After conducting a test just using the environmental air without flow meters, it shows that the flow meters were not allowing a major change in flow rates due to similar humidity levels compared to when the flow meters were in use. There is some control of airflow created by the flow meters because when a single line is running straight from the air supply unit to the bubbler or desiccant cylinder without the flow meter the measured air permeability and humidity increased significantly. For example, Cotton sample 6 measured a pressure drop of 0.0126 psi with flow meters but without flow meters Cotton sample 6 measured a pressure drop of 0.0199 psi. To achieve the highest and lowest humidity levels it is best to have the air just run through either the desiccant or the bubbler with the flow meters and this proved to have changed the reading of the humidity by a large margin. This was done due to the lack of flow control adjustment with the AABLORG module. The flow rate was not changing significantly enough to show humidity changes. Hot water can be added to the bubbler to reach humidity levels above 60% but if water is too hot it can cause condensation to build up in the line skewing the data collection. Condensation is the accumulation of water molecules on a surface that is cooler than that of the humid air surrounding it. This will cause the

humidity to increase without any control over it before it enters the test cell. The addition of hot water was explored and initially provided a higher humidity up to 75%. But after a few minutes' condensations began to build changing the humidity and causing the line to be removed and replaced with a dry line. In addition, fabric temperature is measured during the 2-hour period, and it was seen that the fabric temperature was lower than the oven temperature but over the course of the run the fabric temperature reached that of the oven temperature. This could be used to assess the effect of fabric temperature but that is beyond the scope of this paper.

A mechanical hand properties test was conducted on the wool, cotton, and polyester with the Kawabata Evaluation system to make objective measurements on the samples' thickness compressional properties. The samples were conditioned, and measurements were made using the specimen size of 10 cm x 15 cm in three replications. The compressional properties of a 2 cm^2 area were measured with the KES-FB3 Compression Tester at 0 to 50 gf/cm^2 for all the samples. The thickness was a 2 cm^2 area measured 0.5 gf/cm^2 and reported in millimeters. The compressional energy and resilience (RC), linearity of compression, thickness, and compressibility (EMC) were all measured. This data could later be used to assess the relation of further air resistance effects on fabric properties. ASTM D737 test method was conducted on the fabrics for air permeability. Each sample was tested on the Frazier Air Permeability Tester at 125 Pa with a 2.75-inch test area diameter. Cotton was tested with an 8-mm orifice and Wool and Polyester was tested with a 11-mm orifice to obtain permeability readings. This test data was used as a reference for the proposed method.

Fabric Samples

The fabrics used in this study were 100% jersey knitted wool, cotton, polyester. The fabrics were folded twice to create a four-layered test sample. There were 6 samples for each fabric material, and they were all conditioned in the same non-testing environment. The samples were labeled 1-6 to identify each sample for testing.

Table 1: Shows the details of the fabric used in this study for testing.

Fabric Material	Number of Samples	Illustration
Wool	6 samples of 100% jersey knit wool	
Cotton	6 samples of 100% jersey knit cotton	
Polyester	6 samples of 100% jersey knit polyester. Note: there is a possible defect on fabric with the hole located at top of fabric.	

Chapter 4: Results

Results Introduction

In this section, the data collected from the above method of this experiment is shown and described. The wool, cotton, and polyester samples were tested under various humidity levels, with constant airflow of about 9-10 (L/min) while a pressure drop was measured and evaluated for the validity of the constructed system. The figures below show the results of the pressure drop (in psi) with time for polyester, wool, and cotton samples separately. The air resistance and air permeability were derived using the Darcy equations used by Gibson et al.

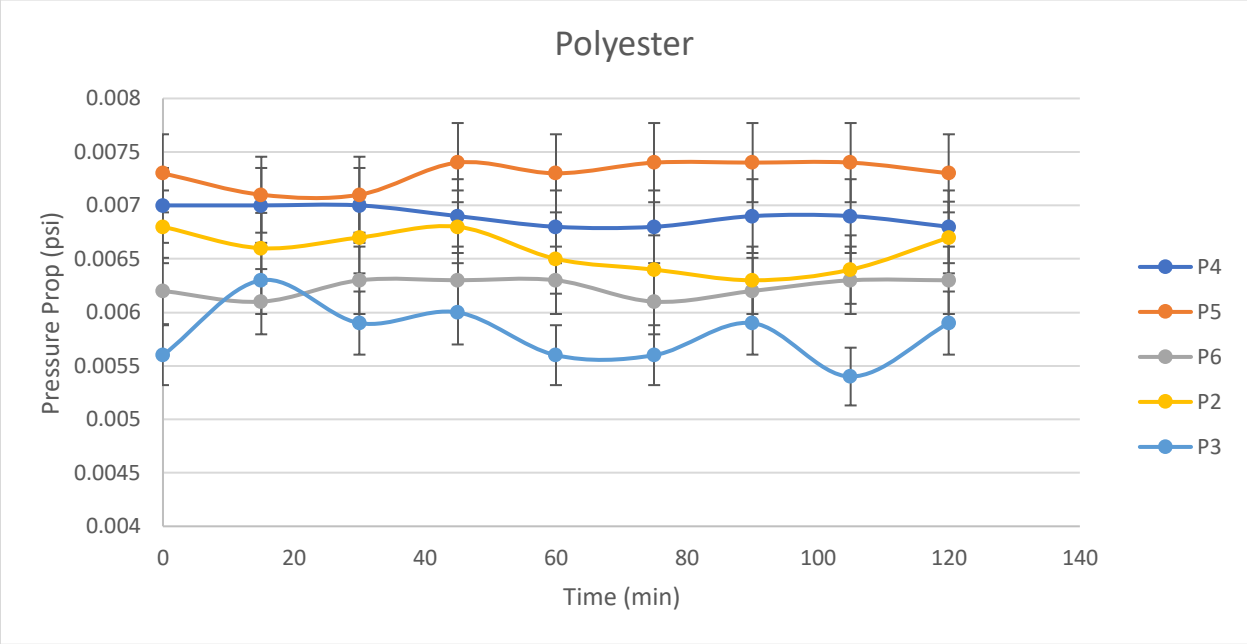


Figure 25: Shows pressure drop (in psi) of Polyester at different relative humilities and a controlled flow of in l/min. P2 is at 40-45% RH (Relative Humidity), P3 is at 50% RH, P4 is at 45% RH, P5 is 43% RH, and P6 is at 43-45% RH. Shows the standard error of the 95% of two standard error.

The Figure above shows that polyester did not have a significant difference in pressure drop (psi) at varying relative humidity levels. A line graph was used for this graph to better show

the changes over time with each sample. This is to be expected because polyester is a natural hydrophobic fiber and thus does not have a high moisture regain. P3 seemed to be lower in comparison to the other samples, this was assumed to be due to fabric variation; there were some defects observed on some of the samples, such as small holes. This could affect the pressure drop due to an increase in pore size in some areas. Gibson et. al. illustrated that polyester show little variation in air resistance with changing humidity. This data was collected using the above procedure method but with some modifications. For humidity levels 50% or higher, the air supply was running through one flow meter into the bubbler providing the humid air. For the lower humidity levels around 40-45% the air supply was being run with both the humid and dry system. Note: it did not have a noticeable impact on the air flow rate.

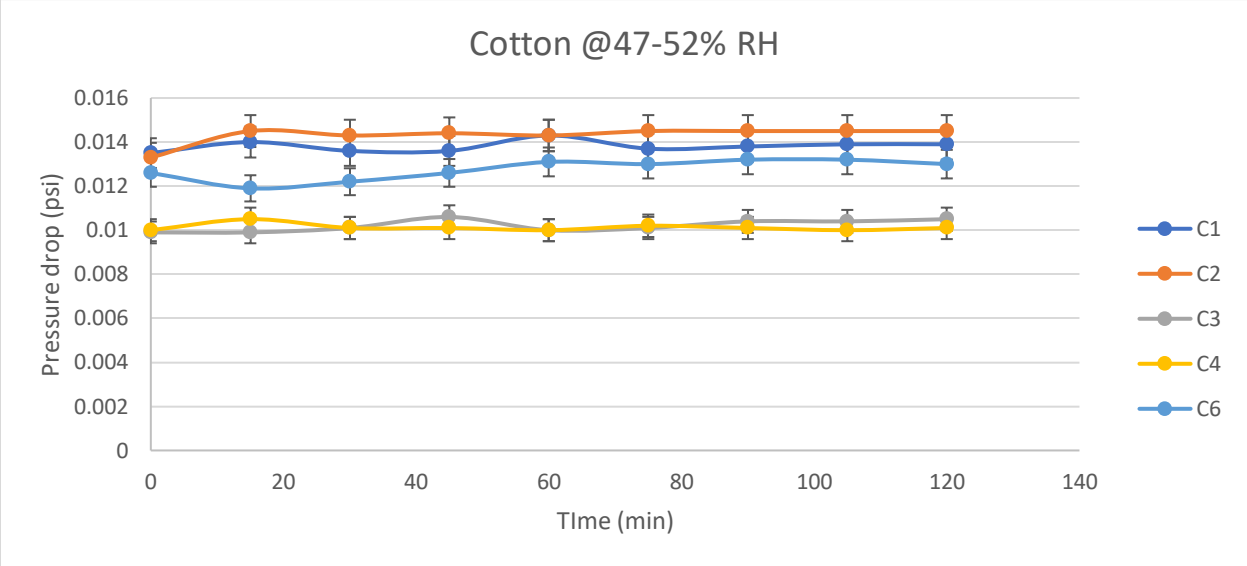


Figure 26: shows the pressure drop (psi) response of cotton at humidity range 47-52% relative humidity. C1, C2, C6 were all ran at a relative humidity around 51%. While C3 and C4 were ran at a relative humidity around 47%.

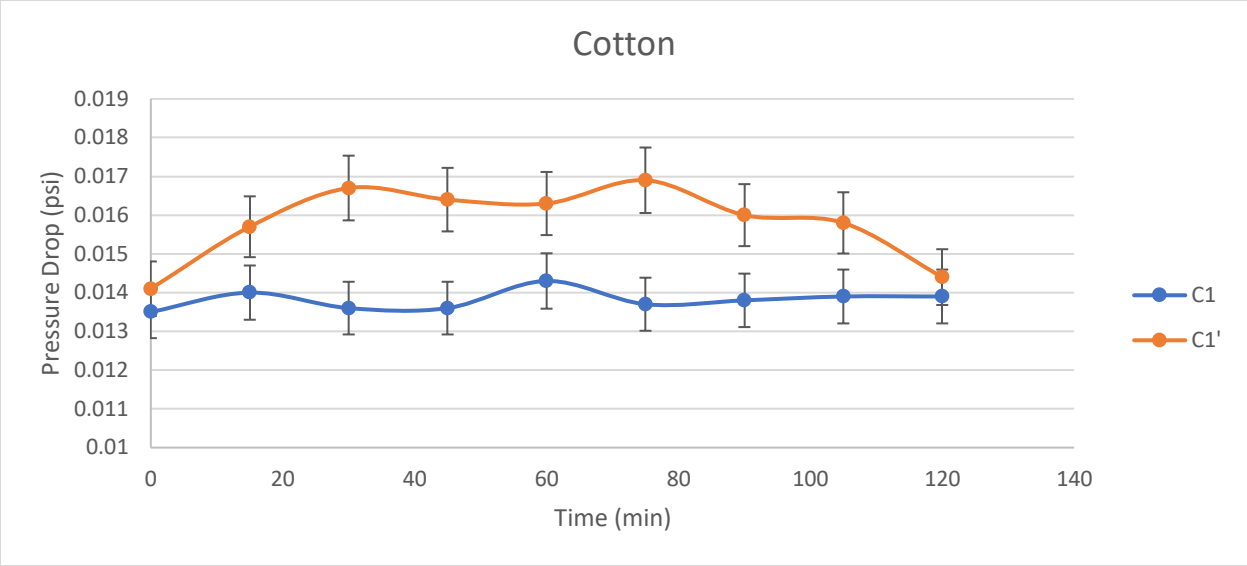


Figure 27: Shows the pressure drop (psi) of cotton samples at different humilities. C1 is at 47-50% RH and C1' starts at 69% RH and drops down to 53% RH.

Figure 26 shows how at different humidity levels cotton responds as well as the variability of the cotton samples. The relative humidity of the samples was not that different and each group was tested at similar humidity levels that remained constant. Figure 27 illustrates the effect of humidity on the C1 cotton sample at different humidity levels. It showed that the pressure drop of C1' prime increased as the humidity level increased and decreased as the humidity level decreased, starting at 69% and ending at 53%. This data was collected using the above procedure method but with some modifications. For C1' the air supply was running through one flow meter into the bubbler providing the humid air and hot water was added to the bubbler to increase the humidity level. For the lower humidity level of C1 the air supply was being run with the humid system but did not have hot water added and airflow was not changed.

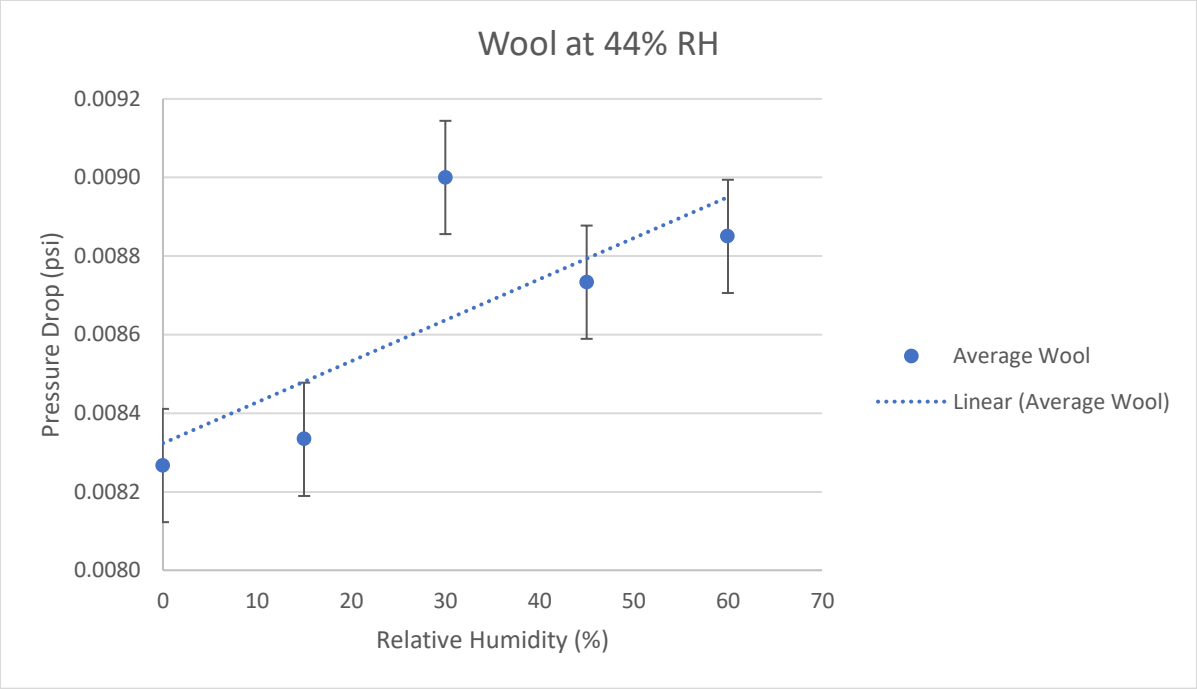


Figure 28: Shows the pressure drop (psi) of the averages of nine points from each of the wool samples W1-W6 at a constant humidity level. Giving the standard error between the nine samples at each point.

Figure 28 shows the variability of the average wool samples as well as the effect of the constant humidity on the measured pressure drop of the fabric. The variability is expected to come from W3 and W1 because they show a slight decrease at a constant level of humidity, in contrast to the other samples. W1 as an outlier is assumed to be caused by miss-use and drifting of the 477AV measuring device because other W1 results did show a slight increase. The 477 AV measuring tool was tested to see if drifting would occur and after letting the device measure a pressure drop without a sample over time drifting did occur. This meant that if the device was not calibrated before a reading the recorded data could have drifted from an accurate reading. These results were obtained by flowing the air through just the dry air line for humidity levels >40%, the humidity ranges tested at 40-50% was tested with the air flowing through both humid and dry air and for humidity levels at 50%< was ran with humid air. Note: the air flow did not change and if the humidity level was 60%< then hot water was added.

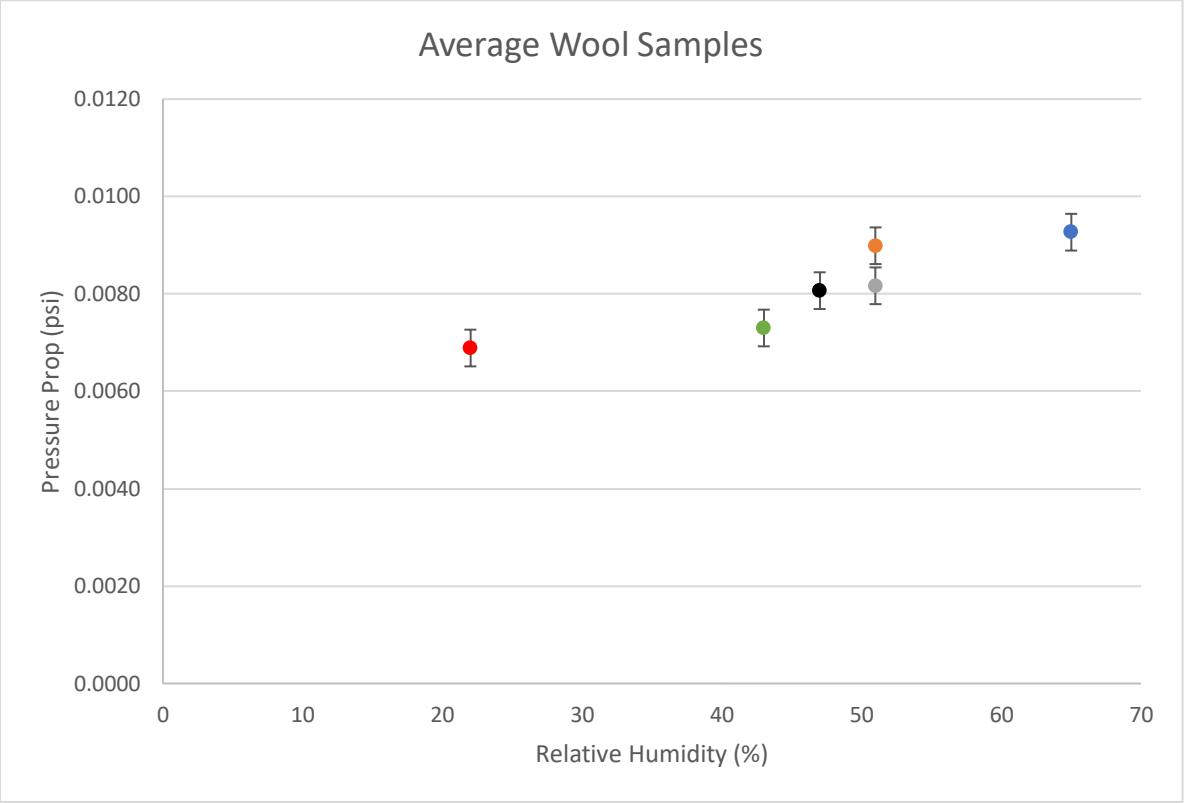


Figure 29: This graph shows the pressure drop (psi) of the average wool samples at different humidity levels. W1 (Green) was at 42% RH, W2 (Grey) and W3 (Orange) were at 51% RH, W4 (Blue) was at a range of 61-67% RH, W5 (Black) was 47% RH, and W6 (Red) was at a range of 20-28% RH. Showing standard error bars indicating the different pressure drop readings during the 2-hour test.

Figure 29 shows the average results of wool samples at different humidity levels ranging from 20% to 70% relative humidity. This graph suggests that as the humidity increased so did the pressure drop (psi). The error bars are the standard error of 95 percentile and show the variability of the different pressure drop readings of the samples at each point during the 2-hour test. This showed that there is an evident increase in air resistance as the humidity increased. These results were obtained by using the above procedure mention in the methods section.

Figure 30: Shows the pressure drop (psi) of wool 3 samples at different humidity levels. W3 at 44% RH, W3' at 52% humidity, W3'' at 51% humidity. Note these are the same sample tested at different humidity ranges.

Figure 30 shows the Wool 3 sample as an anomaly when compared to the other wool samples. At varying relative humidity from 44% up to 52%, the W3 and W3' samples' pressure drop decreased which is in contrast to the other samples when looking at the time dependence. The W3 and W3' samples show that over time the pressure drop across the sample decreased. When compared to the other wool samples at the same humidity level wool 3 when averaged is higher than wool 2 shown in Figure 29. The average of wool 3 is still in line with the expected results of the humidity dependence. The procedure for W3 is the same as the above procedure but W3' and W3'' were modified by only allowing air through the humid air system. Note: the air flow stayed the same.

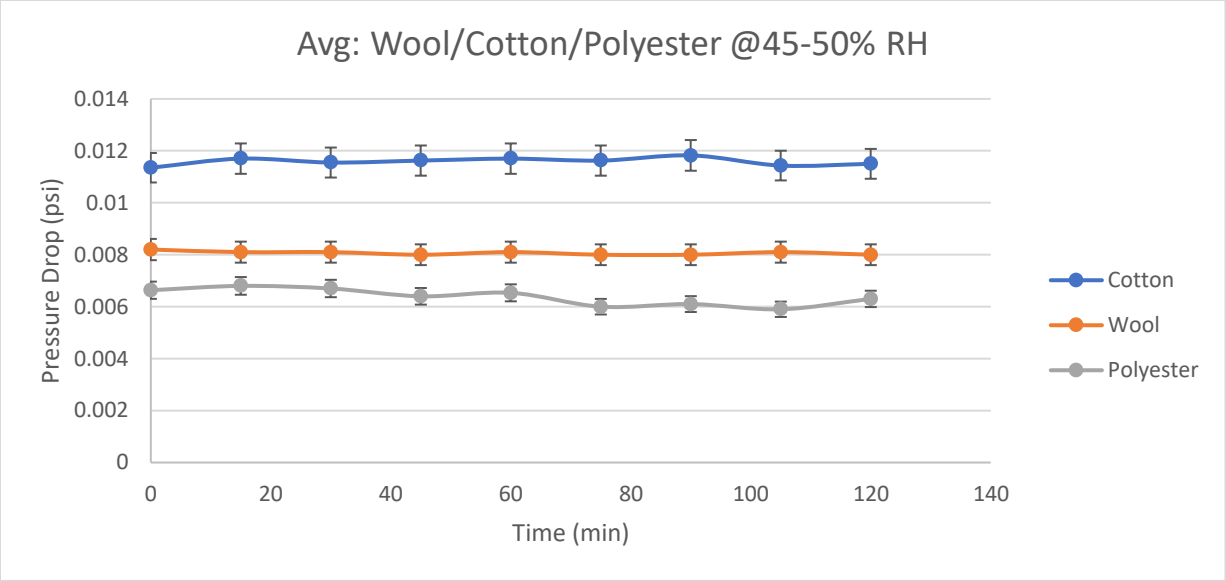


Figure 31: shows the average pressure drop (psi) results of Polyester, Wool, and Cotton at humidity range 45-50% relative humidity.

This graph (Figure 31) above shows the comparison between the fabric samples in terms of pressure drop (psi) and time. It shows that cotton had the higher air resistance in the humidity range which is to be expected because cotton absorption rate is faster than that of wool. These results are all obtained by averaging the results of the fabric samples of the same testing conditions. The air flow for each test remained the same and the humidity level was on average 47%

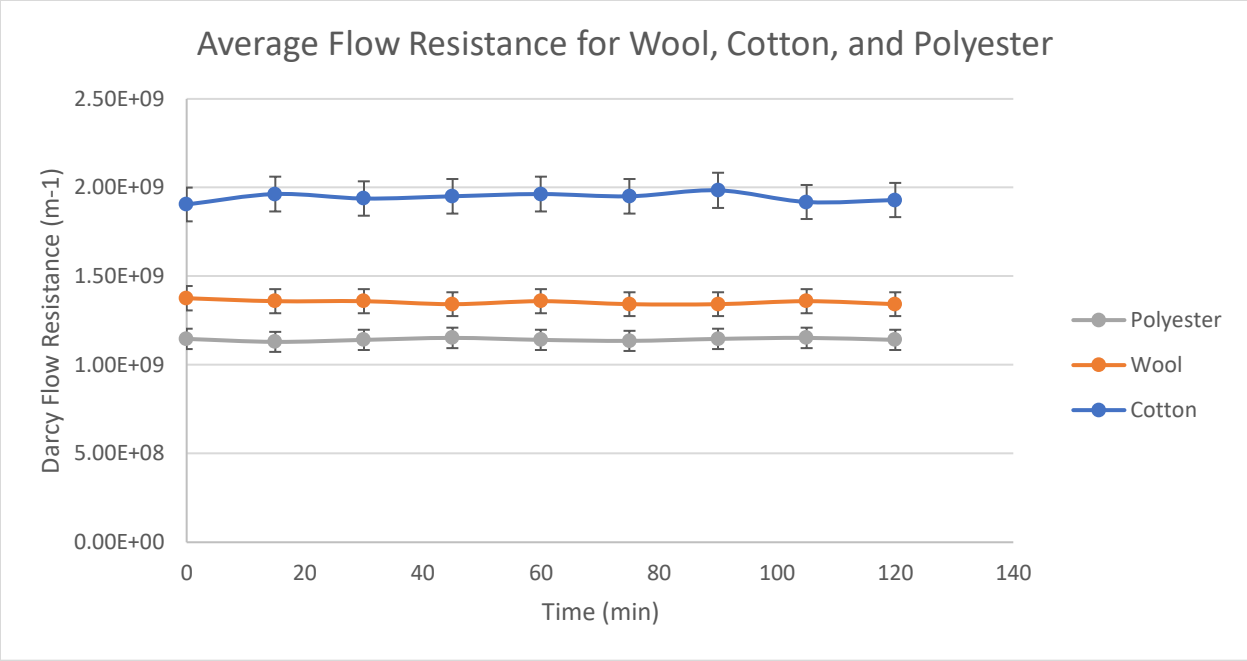


Figure 32: Illustrates the average Darcy flow resistance (m^{-1}) of wool, polyester, and cotton at 45-50% relative humidity range.

Figure 32 resembles a similar pattern shown in Figure 31 pressure drop data. It shows that cotton in terms of Darcy's flow resistance remains the highest in resistance compared to wool and polyester which follows respectively, this is before calculating the thickness of the fabric to ascertain the air permeability expressed by Darcy. Darcy's flow resistance is $R_D = \frac{A\Delta p}{\mu Q}$.

KES Compression data

Table 2: Shows the compression analysis of wool, cotton, and polyester conducted on the KES system. The samples were tested under standard conditions of 21°C and 65% RH.

Sample ID -replicated	Thickness (mm)
C-1	0.8361
C-2	0.8120
C-3	0.8997
C-Average	0.8493
P-1	0.6919
P-2	0.7175
P-3	0.7077
P-Average	0.7057
W-1	1.0555
W-2	1.0459
W-3	1.0335
W-Average	1.0450

*Thickness of a $2cm^2$ area at 0.5 gf/cm^2

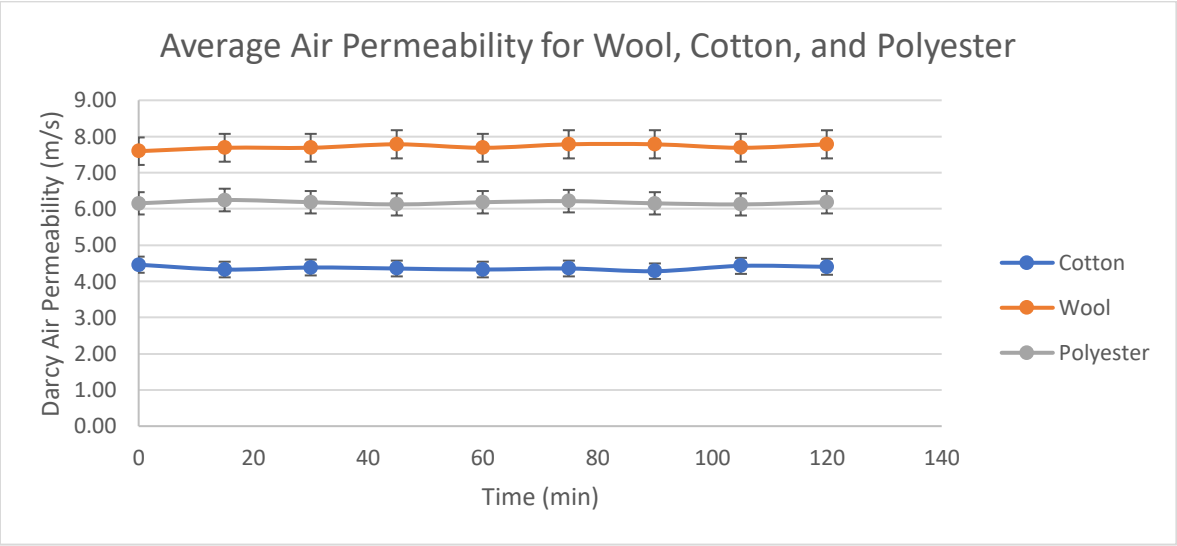


Figure 33: Shows the average inverse air permeability (m/s) of wool, cotton, and polyester based on Darcy's equation.

Figure 33 was obtained by dividing the fabric thickness found in Figure 29 by the flow resistance thus expressing the Darcy air permeability. This graph was the inverse of the flow resistance by Darcy and showed that wool had a higher air permeability than polyester, whereas it was expected to fall between cotton and polyester. Cotton still has the lowest air permeability which was expected. Table 2 shows that wool had the greatest thickness and polyester had the smallest.

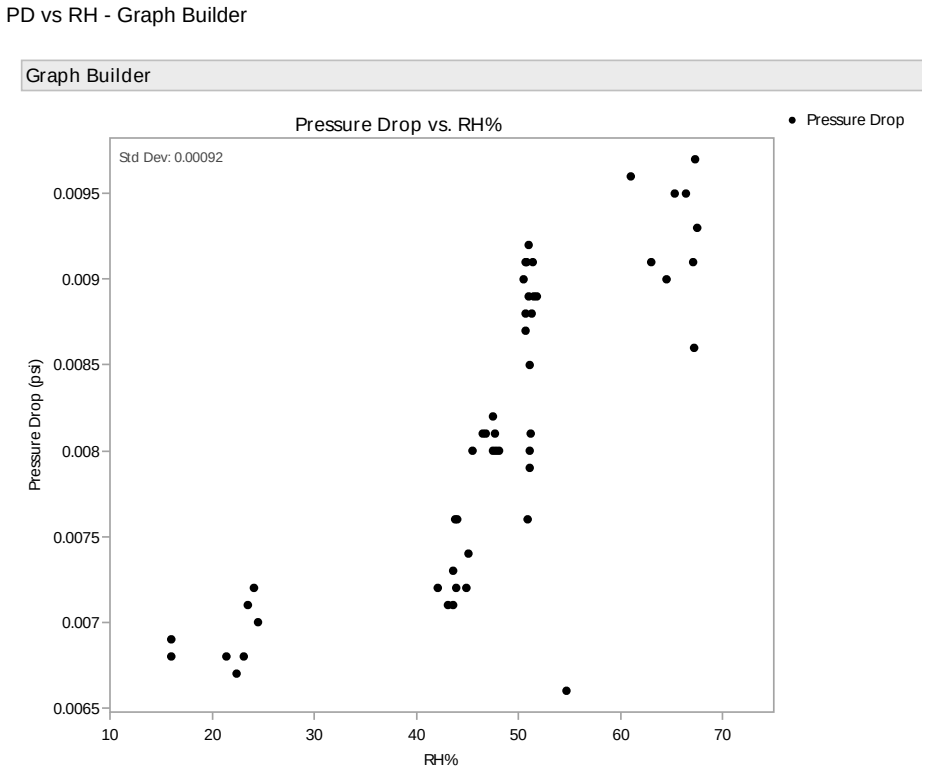


Figure 34: All wool samples W1-6 pressure drop (psi) vs humidity going from 40% to 70% relative humidity.

Figure 34 illustrates more clearly how as the relative humidity increase so does the pressure drop across the fabric in wool fabric. This shows an increase in pressure drop across the fabric once

samples were tested past about 45% relative humidity. There is one outlier to be noted but this is assumed to be a measurement error at the start of the test for W2. Similarly, to Figure 33 these fabrics were tested for 2 hours under the same total flow rates but at different humidity levels. Hot water was added to the bubbler to produce the increasing humidity level for W4 but for W1 and W3, their humidity levels remained constant for the duration of the experiment. The average increase in pressure drop from 20% RH to 70% RH was 35%

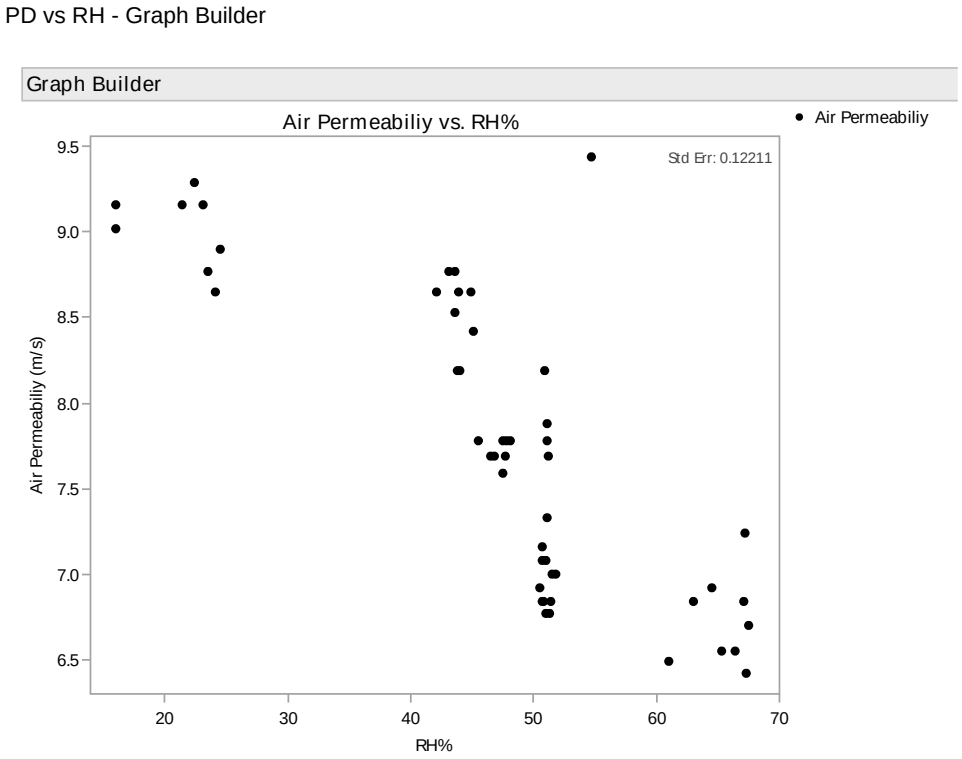


Figure 35: This shows the air permeability (m/s) vs relative humidity of the wool samples W1-6 at different humidity levels. Derived from Darcy's equations

The above graph (Figure 35) displays the Darcy air permeability of the wool samples at different humidity levels ranging from 40% to 75% relative humidity. This further shows that the air permeability decreases as the humidity increases. There is a curve-linear negative trend that is

still evident and within expected results. These fabrics were tested for 2 hours under the same total flow rates but at different humidity levels.

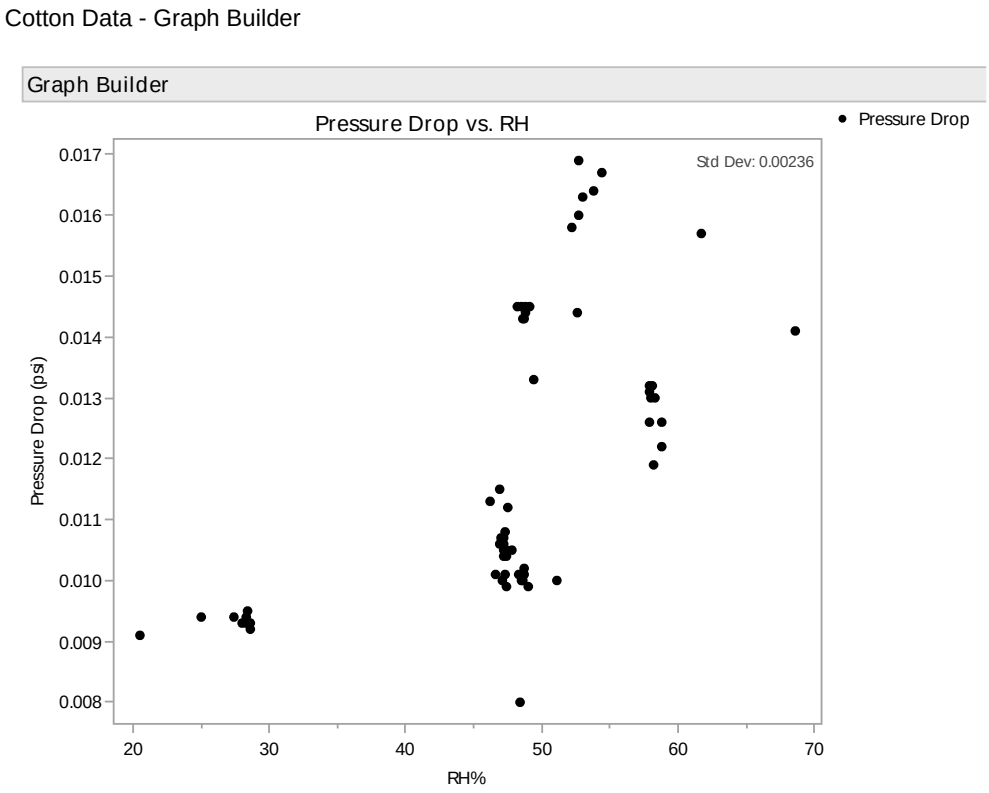


Figure 36: This graph shows the pressure drop (psi) of cotton at different humidity levels from 20% to 70% relative humidity.

In Figure 36 the cotton sample pressure drop (psi) increased as the humidity increase and the standard deviation was .0024 psi. There seemed to be a lot of variability in the higher humidity levels, but an increase was evident when compared to the lower humidity levels. The increase is shown to be steeper in the cotton samples than what was shown in Figure 35 with the wool samples, i.e. the average increase in pressure drop was 56% in the cotton samples versus 35% in wool. These fabrics were tested for 2 hours under the same total flow rates but at different humidity levels.

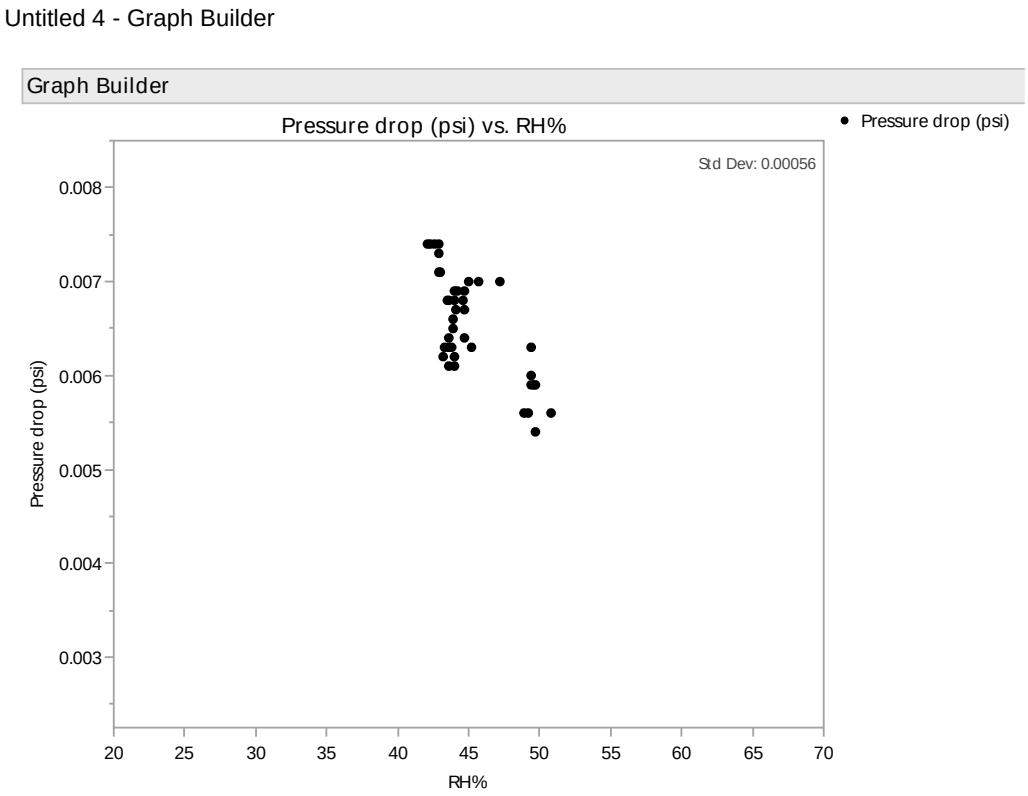


Figure 37: Shows the pressure drop (psi) of polyester at different humidity levels from 40% to 55% relative humidity.

Figure 37 shows polyester samples pressure drop (psi) across the sample at varying humidity levels. It showed that there was little change in the air resistance of polyester when the humidity changed, which correlates to what Gibson et al. found. There seems to be a slight decrease in air resistance looking at the graph, but it is not significant enough to note a change in resistance. The average decrease in pressure drop was 6.3%. The polyester samples did not show changes over time and thus more humidity levels were not tested because the air resistance would not change. These fabrics were tested for 2 hours under the same total flow rates but at different humidity levels.

Table 3: Air Permeability of cotton, wool, polyester using the ASTM D737 test method. The permeability is in cubic feet per square foot per minute for 0.5" water pressure drop (125 Pa).

Air Permeability in CFM			
Sample:	**C**	**P**	**W**
Test Area Diameter (inch):	2.75	2.75	2.75
Orifice Diameter (mm):	8	11	11
n*			
1	116	256	244
2	117	247	244
3	139	270	234
4	140	253	221
5	118	261	-
6	124	266	269
Mean	**126**	**259**	**242**
Std. Dev.	**11.1**	**8.5**	**17.6**

**Limited supply of specimens available reducing the standard n=10 replicas/sample.*

Table 3 shows the results from the ASTM D737 Air Permeability in CFM for polyester, wool, and cotton. This table give a reference to how the proposed system compares to the air permeability readings created by this standard. Cotton average air permeability was much lower than polyester and wool's average air permeability. This was comparable with the Darcy's air permeability with polyester and wool having a close reading. The tests were ran in a lab environment of 21°C at 65% relative humidity with accordance to the ASTM D737 Standard requirements.

Chapter 5: Discussion and Conclusions

Discussion

For this study all the tested fabrics were folded to create a four layered test sample. This was done so that enough of a pressure drop across the fabric could be measured. Gibson et al. showed that layering the fabrics does not significantly affect the air permeability it only creates an added process of the layers. This method by Gibson et al. was only shown for polyester but it was assumed to be the same for other fabrics. Based on the results in Figure 25 polyester fabrics do not have much moisture uptake and maintains a constant air permeability even at different humidity levels. This is to be expected due to the hydrophobic nature of polyester but P3 showed some fluctuation in the readings, and this was assumed to be due to the defects in the fabric (refer to Table 1) and improper reading of the measuring device. This accounted for the low air permeability level and the sudden changes in air permeability at the various time stamps. When looking at the average of all the samples it became clear that polyester remained relatively constant with slight variability in the fabric samples because there was only a 6.3% difference between 40% and 55% relative humidity. The polyester data provided a baseline to evaluate the accuracy of the system when comparing other fabrics. The data on polyester provides some confidence that the measuring devices are measuring the fabric correctly. This can be stated because the polyester fabrics were tested at the same relative humidity level of 45% and again at 55%, with identical methods, which provided similar results.

Looking at Figure 27, the cotton 1 sample was tested at different humidity levels. C1' which was tested at near 70% relative humidity and showed a steady increase in pressure drop and then as the humidity starts to decrease so did the pressure drop. The increase in cotton

aligned with previous data collected by Gibson et. al. and for the decrease it could be assumed to be caused by the high temperature and moisture being evaporated off the fabric. This is suggested because fabric temperature, taken for some of the tests with a thermocouple between the fabric layers, would start at a lower temperature but by the end of the 2-hour test, it would be at or near 30 °C, which was the measured oven temperature. Barnes and Holcombe mentioned the ideal scenario where there would be little moisture absorption due to the temperature of the fabric. Fabric temperature was measured on cotton and wool samples. The fabric temperature over the course of the test rose to the environment temperature of the oven with a ± 0.5-degree difference between the fabric and the measured oven temperature. Therefore, it was likely that as the temperature of the fabric increased, and the relative humidity decreased the C1' sample lost moisture due to evaporation. This could possibly be used to test for a certain heat loss caused by fabric temperature and humidity changes but that was beyond the scope of this paper. The ASTM D737 test method for air permeability of textile fabrics was conducted on the fabric samples and is shown in Table 3. The air permeability data was used as a reference and compared with the results from the proposed system. The air permeability of the ASTM and proposed method data was converted to L/min/cm^2 at 125 Pa for better analysis of the comparison. The average cotton sample for the ASTM method was 1.26 L/min/cm^2 and for the average proposed method it was 1.47 L/min/cm^2. The results were close to each other and provided a good reference to show the capability of the proposed method becoming a test method. Polyester samples for the ASTM data were 2.59 and 2.5 L/min/cm^2 respectively and for the proposed method the polyester results were 2.3 and 2.5 L/min/cm^2 respectively. The difference in the data was about ±0.2 except for polyester which was .09. The difference in the polyester sample is expected because its air resistance does not change much with changing humidity. For cotton and wool, the difference

was larger, and is assumed to be due to the nature of each test. The ASTM Standard test the fabrics at a lower temperature (21°C) with the environment's relativity humidity at 65% and for one instant of time. The proposed method averaged the data over time at varying humidity ranges and for a 2-hour period at 30°C which gave time for the air resistance to change. The flow rate effects the air permeability results as well; the ASTM method flow rate is much higher than that of the proposed system. The lower the flow rate the more difficult it is to obtain a steady air resistance from the fabric therefore, this could also give insight into the difference in air permeability results.

Stability of Resistance Measurements with Constant Humidity

Figure 26 showed that there was little increase in cotton's pressure drop at a constant humidity level. This was concluded based on the observation that cotton reached equilibrium much quicker. This was likely due to a higher rate of moisture absorption, which was supported by Figure 27 showing the increase in pressure drop of cotton with rising humidity and decrease in the pressure drop with the lowering of the humidity. The results presented in Figure 27 were conducted with the same C1 cotton sample but at different relative humidity levels within one experiment. C1 was held at a constant humidity level around 48% and C1' was tested under an increasing humidity level from 50% to 70% relative humidity. Hot water was added to the bubbler increasing the humidity level to about 70% and over time the humidity slowly decreased to about 53% which is close to the constant level for C1. The results showed that cotton had a high moisture sorption and with increasing humidity, the air resistance of cotton increased which was assumed to be because of the swelling of fibers. In reference to Figure 27, it was observed that the rate of absorption increased with humidity levels but as the humidity decreased, the rate

of desorption increased as well. This was slightly different with the wool samples (Figure 28) which showed a slight increase with steady humidity levels. The issue with this was that the incoming air had a higher humidity reading than the outgoing reading. This was an unknown issue prior to the experimentation and was later fixed by increasing the tube line length in the oven. This may have been the reason for the steady increase in the wool samples but W1 and W3 showed major inconstant readings. W1 may have been missread by the device due to drifting or calibration error. Or, the errors were due to the different humidity readings, although this was unlikely because of the constant behavior of the other samples. After remeasuring the samples once, the humidity difference was solved and W1 was more stable and around the same readings as the other samples but W3 still showed a slight decrease in air resistance over time. This gives insights into how wool may have had a much slower moisture absorption than cotton and therefore showed a slight increase over time. Unlike the cotton samples, which showed a rapid difference in air resistance and steady readings at those levels, the wool samples seem to have a slow increase in air resistance over time at different humidity levels but starting near the same air resistance reading. Wool is also stated by Wehner et al. [7] that it takes several hours to absorb moisture with changing humidity levels therefore this can explain the slow increase in air resistance compared to the cotton samples. As a consequence, the 2-hour test duration per sample was used to obtain stable measurements. This may limit the practicality of the measurement method as multiple RH measurements may take a long time (4 per day).

The wool samples did not increase as much in air resistance as the cotton samples, but there were more fluctuations observed in the wool samples. This could also be due to drifting or improper reading of the measuring device. W3 was a sample that showed deviating behavior. The W3 sample was tested 3 times and for W3 and W3’ a decrease in the pressure drop was

measured over time. But the average of the W3 wool sample was still in line with the expected results when compared to the humidity dependence. The decrease over time was unexpected and controversial to the other samples' time dependence where the sample either increased or remained relatively the same. Only an experiment by Iqbal et. al. showed knitted unscaled wool fibers to have a low air permeability at higher humidity. Iqbal et. al. discussed how descaled jersey knitted woolen fabric can become more open when saturated with water. But in their study, the wool was descaled with nanoparticles of calcium carbonate and prepared specifically to have this behavior [17]. This is due to the fibers opening during the wetting process but the detailed finishing of the fibers and fabrics in this study were unknown and all the wool samples are of the same properties. Therefore, it is unclear why wool 3 behaved in this manner, whereas the other samples had an expected air resistance increase over time.

In Figure 31 the averages on cotton, polyester, and wool are compared at around the same relative humidity. It showed how cotton had the highest pressure drop followed by wool and then polyester. This was to be expected based on previous data expressed in the literature. The graph also depicts the averages of each sample illustrating the repeatability of this system validating its accuracy with the CV% of cotton being 1.3%, wool was 2.1% and polyester was 5%. To find the apparent air resistance the Darcy apparent resistance (R_D) method was used, and the results mimic the pressure drop data trends. The equation used was:

$$R_D = \frac{A\Delta p}{\mu Q}$$

Where (A) the apparent sample flow area, which is the area of the test cell, is 3.81 x 10^{-2} m^2, the (μ) gasses viscosity is 1.886 x 10^{-5} for O_2 at 30^{o}C, (Δp) is the recorded pressure drop across the sample converted to N/m^2, and (Q) the total volumetric flow rate was found by converting the reading on the flow meters which were in standard liters per minute to m^3/s. Data ascertained

from the apparent flow resistance mimic the data presented by the pressure drop (Δp), as all three other parameters (A, μ, Q) were kept constant in these experiments. The R_d was then applied to the Darcy air permeability equation:

$$k_D = \frac{\Delta x}{R_D}$$

The data became inverse of the apparent flow resistance showing the air permeability of the fabrics at the desired relative humidity, but the data was at the same time normalized for fabric thickness, which varied between the cotton, wool, and polyester samples. Cotton had the lowest Darcy air permeability, which was expected but wool showed to have a higher Darcy permeability than polyester. This was assumed to be due to the measured thickness of wool used for Darcy's air permeability equation being 30% higher than polyester. Therefore, even with the higher pressure drop than the polyester samples, the wool samples showed a higher Darcy (effective) permeability. Wool's Darcy air permeability (6.5 m/s) at the highest measured humidity which was higher than polyesters Darcy air permeability (6.8 m/s). The data still supported that there was moisture absorption with changing humidity within the experiments, causing the fabric's increasing air resistance (Figure 32).

Changes in Resistance with Humidity

After confirming the reliability of the experiment setup with constant humidity, the setup was used to evaluate the fabrics for changes in air flow resistance at different humidity. Figure 33 gives a better analysis of the effect of humidity on the fabrics over time. It was shown that there was an increased air resistance on the wool and cotton samples with humidity changes. The negative slope in the air permeability graphs shows that there is an increase in air resistance due to the swelling of fibers. Figures 33 further verifies how the constant humidity level changes the

air resistance of both wool and cotton to a significant degree. But for polyester, similar to the results discovered by Gibson et. al., did not have any significant changes over time with relative humidity [4].

Based on the data in Figure 36 cotton seemed to have a quicker moisture absorption rate than wool. In figure 34 wool continued to increase in pressure drop as the humidity increases but in Figure 36 cotton seemed to have already reached its capacity at around 50-55% relative humidity. This can suggest that cotton reached its max absorption and stabilized, and wool did not. This suggest that wool has a higher moisture absorption than cotton but at a slower rate. The results together give insight to the relative humidity dependency but also a slight time dependency on how the air resistance is affected. The air permeability of the wool samples in figure 35 shows similar results to the cotton samples that once past the 50-55% relative humidity the air permeably begins to stabilize but because wool takes longer to stabilize and has a higher moisture absorption it continued to show an increase [1],[7]. The result tested under this system's methodology for wool and cotton fabrics aligns with what was observed by Whener et al. and Gibson et al. in previous literature. They show a humidity dependence over time at both changing and constant relative humidity. The system has the potential to support and express the temperature-humidity effects on textiles materials.

Limitations

There were a few limitations of this design and one being the AALBORG flow meters. The main issue was that the changes made on the command module did not create significant change in flow rates to accurately change the humidity fully to the user's desire. When the flow rate was set and changed on the module the observed air flow did not seem to change and if it did the change was minuscule (unable to measure). This made it difficult to set a variety of desired humidity levels when testing the fabrics, but the module was able to maintain the flow and sustain a constant humidity level. There was a change in flow caused by the flow meters because the flow was lower when the module was hooked up to the air supply unit versus the air supply alone. Another limitation of this system was how data was recorded in the oven. To record the pressure drop of the sample at different time intervals the oven had to be opened and kept open until the reading was done. During this process, the oven quickly lost heat and took about five minutes to return to the set temperature. At this time there was a possibility of affecting the sample temperature and therefore affecting the possible moisture regain and thus its air permeability. This was not certain, but it should be considered because the temperature affects moisture regain of fabrics and relative humidity. Another limitation to consider was the use of an environmental air supply with limited pressure control. This meant that the air coming in already had some level of humidity and the desiccant may not have been able to fully dry out the air. This could also have affected the readings in the flow meter since the air is not pure oxygen and the parameters on the flow meter were set for pure oxygen. This could provide some errors in the calculations but at this point, it was not possible to assess the size of these errors. There was also little knowledge on the structural and characteristic properties of the tested fabric which could have given better insight on explaining any outliers that occurred, referring to the result of W3 samples. Where the W3 showed a slight decrease in air resistance compared to the other wool

samples tested. Although there are some limitations to this system it still provides good data on analyzing the temperature-humidity dependence on textile materials.

Conclusion and Future Research

In conclusion, the recreated system was able to evaluate air permeability and air resistance of knitted wool, cotton, and polyester fabrics. And with a few modifications could be set as a standardized test. The system was able to record accurate and expected response of the samples under relative humidity conditions. Polyester did not show any change with humidity dependence which was expected because of its hydrophobic behavior. Cotton showed that at a constant humidity level the air resistance increased until equilibrium was reached. When the humidity level changed from low to high back to low the cotton sample air resistance followed the same trend. Wool showed a similar trend as well with a humidity and time dependency on the samples. For wool, it took much longer than for cotton to show a significant change in the air resistance of the fabric. The wool and cotton fabrics increased in air resistance when tested at higher humidity levels. The system was able to show desired results in showing that wool and cotton would increase at high humidity levels such as above 50% relative humidity.

Recommendations

Looking forward; with updated flow meters and automated pressure differential measuring tools, this system has the potential to be developed into a test method for evaluating air permeability of fabrics at various and constant humidity levels over time. The test could also be revised for a new test method that allows fabrics to be tested for air resistance under dynamic changes in temperature and humidity. The temperature could prove to affect the desorption of

fabrics changing the air resistance. Temperature affects humidity changes therefore, changing the temperature can affect air permeability by rapidly changing the humidity. The oven can be used to test at different temperature levels and test how fabric behaves at similar humidity levels but at higher or lower temperatures. The test showed that there was a time dependent on how long it took to show a humidity effect. This could be explored more by optimizing the time it takes for air resistance to change under rapid humidity changes. The length of each test could vary for different fabric samples such as how wool needs a long time to stabilize, and cotton needs a short time. Providing more information on fiber type and structure could also assist in understanding humidity effects on air permeability. The ASTM data gave a good reference in testing how different temperature and humidity can affect the air permeability between an instant one time reading versus a constant dynamic reading.

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APPENDIX

Appendix A: Standard Operation Procedure

Instructions For Running Test

Before conducting a test, check and verify that all the connections are correct, and all systems are running. Turn on the AABLORG module opening the desired channels and set the flow rates and adjust for humidity levels. Once a channel is selected follow the on-screen direction to set parameters use the AABLORG manual, the mass flow versus volumetric flow, and flow rate unit conversion tables to understand what desired parameters to set [5]. For this experiment the density of oxygen used was set at 1.427 g/L and the flow rate was set in standard liters per minute. The channels used for this experiment are channel 1 and channel 2 for dry and humid air. The humid air is created with the use of a bubbler filled with distilled water and as air flows though it begins to bubble creating humid air flowing out. An increase in humidity can be reached if warm to hot water is used but it was observed if the water is too hot then condensation will build up in the flow lines and make it difficult to control the humidity. The dry air is created with silicone gel beads in a container, before desiccant crystals were used. But they were extremely overused even when dried out only lowered the humidity to about 30% relative humidity. Therefore, research into other dry methods was explored and silica gel was chosen as the best method to use. After obtaining the silica gel a safety protocol, based on the safety data sheet on desiccant by Ted Pella Inc., was made to ensure correct storage and usage of material in the lab [14]. Once all system parameters are set and components have been set up and checked the next step is to set up the test cell. The test cell as shown in previous figures has four components and the fabric will sit between them (see figure 21). Once the fabric is placed on the test cell attach the top two components onto the fabric closing the test cell and tighten the screws. When placing the test cell in the oven make sure that the 477AV manometer is connected to the

incoming and outgoing ports. Next measure the humidity of the incoming air before connecting the test cell. This will tell the observer if the incoming and outgoing humidity are the same.

Instruction for AALBORG Module

The flow meters are controlled via control module and can be navigated with 4 buttons. Module is set up to control four channels but for this test two will be used. When on the main screen of flow readings use the third button to reach the channels and then select desired channel by pressing corresponding buttons. Make sure the channels are open before setting parameters. To set the flow and parameter of the air flow, press the third button when on the initial screen and once that has been done you will set the flow type to external and then set the density of the gas/fluid and then next set the flow rate in terms of standard liters per minutes (range: 0-9 SLPM). The desired parameters can be found in the AALBOR module manual. This can be done for all channels. The second button can be used to navigate through the module to check the readings of the flow. The button will correspond with the item in section above the button when setting parameters and navigating selected channels. For the test cell assembly make sure to tighten the screws on top diagonal from each other and don't tighten until all the screws are on. Note a wretch may be used to ensure tightening of screws.

Safety Protocol for Silica gel use

The safety data sheet required gloves and safety goggles to be worn when handling the silica gels and suggest that improper handling of the gels can cause dryness and irritation of the hands and eyes [14].