ABSTRACT

ABEDIN, FAISAL. Dynamic Breathability: Mapping the Gaps between Static and Dynamic Benefits of Fabric. (Under the direction of Dr. Emiel DenHartog).

High-regain fibers have been shown to have exothermic effects, although there have not been reliable tests to demonstrate these effects on the human body. The ISO 16533 standard test method for determining the exothermic and endothermic behavior of textiles under changing relative humidity (RH) conditions (from 10% to 90%) can only demonstrate the increase in temperature, yet has a number of limitations for sample size, test environments, and test set up. This investigation seeks to understand the relationship between the exothermic and endothermic behavior of textile fibers (wool, cotton, viscose, and polyester) while absorbing moisture and its effect on physiological factors by developing a new fabric test method to characterize the fabric's behavior in transient conditions.

Firstly, all the reliable fabric test methodologies were explored to determine this exothermic behavior. The test includes standard, and dynamic regain tests, ISO 16533, and dynamic hot plate tests. Comparing the test methods allowed us to properly identify the limitations of those methods, which allowed us to consider more practical test protocols for garment testing with manikin and human trials.

The exothermic behavior of the fabrics was investigated using a thermal manikin with a step change in RH (from 45% to 80%). During the transient change in RH, a new evaluation and correction method was modeled to correct the heat loss from different segments of the manikin body. As a result of the heat of sorption, hygroscopic fibers may create exothermic heat, which manifested as a peak during the dynamic shift in the surrounding RH. The investigation was further expanded further to include sweating manikin experiments during a step change in the body metabolic rate (rest-activity-dry) in a controlled environment (temperature 15°C, 50% RH,
The purpose of these experiments was to get a more detailed understanding of physiological traits such as mean skin temperature, microclimate temperature, and humidity, and fabric surface temperature. The findings demonstrated that wool fiber had the ability to maintain a thermal environment more effectively than the other fiber types, thus retaining a warmer microclimate. When the mean skin temperature drops after exercise, a warmer microclimate can act as a buffer against post-exercise chill. Human trials confirmed the validity of the findings.

The subjective trial was conducted with 12 male participants, with five different outfits in a controlled climate chamber of temperature 15°C, 50% RH and 1.7 m/s wind speed. The test protocol was designed to have a continuous process of (rest-activity drying). The human trial showed statistically significant thermal comfort for wool fiber, while polyester was the most uncomfortable for temperature sensation during the post-exercise period.

A novel fabric test method that can simulate changing conditions in a single step was developed by compiling all data from fabric testing, manikin tests, and human trials. This method used a custom-made hot plate to define the exothermic behavior of a fabric and its functionality under changing environmental conditions. The newly developed test procedure can aid sportswear manufacturers in designing clothing that is more conducive to the wearer's comfort while rock climbing, cycling, and exercising under windy atmospheric circumstances. In addition, the use of this test method could contribute to the definition of a new comfort term relating to rapidly changing environmental conditions called "dynamic breathability."
Dynamic Breathability: Mapping the Gaps between Static and Dynamic Benefits of Fabric

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DEDICATION

First and foremost, this dissertation is dedicated to my beloved father, Jainal Abedin, whom I lost during the covid pandemic. I also like to dedicate this to the covid affected people, families, and emergency workers who dedicated themselves to supporting all of us.

I also want to dedicate this-

- To my Mother, Shamima Abedin, for bringing me up, teaching me resilience and patience, and to whom I am always an important one.
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Finally, and most importantly, my wife Nila, without you, I cannot think of my Ph.D. journey at all. Thank you for the two beautiful kids, Hamdan and Hadiqah.
BIOGRAPHY

Faisal Abedin was born to Jainal and Shamima Abedin on September 30, 1990, in Chittagong, Bangladesh. With his father being an overseas businessman, most of his childhood was spent in his aunt's house in Nasirabad, Chittagong. Faisal has a younger sister, Zoairia Abedin.

Faisal completed his Secondary School Certificate from Chittagong Cantonment Public School and College with a G.P.A. 5.00 in 2005. Later, in 2007, he completed his Higher Secondary School Certificate from Chittagong College with a G.P.A. 5.00, a very reputed educational institution in that area. Faisal completed his undergraduate in Textile Engineering from the Bangladesh University of Textiles (BUTEX) in 2013 with distinction and was awarded Prime Minister Gold Medal for his outstanding result in his bachelor's. In 2018, Faisal completed his Master's in Textile Engineering from the same institution. During his education at BUTEX, Faisal was actively involved in various voluntary organizations such as BADHAN and the university soccer team. Following graduation, Faisal joined SQUARE Knit Fabrics Ltd. as an executive in Research and Development for knit products in 2013. With an ambition to bridge academia and industry, Faisal joined the BGMEA University of Fashion & Technology as a lecturer in the department of textile engineering. In 2016, Faisal joined as a lecturer in the department of fabric engineering at BUTEX and was later promoted to assistant professor in 2018. In academia, Faisal worked on several government-funded projects focused on sustainable solutions in the textile industries of Bangladesh.

In 2019, Faisal started his journey at North Carolina State University toward a doctoral degree in Fiber and Polymer Science with a North Carolina Textile Foundation Fellowship. Faisal had an internship with unspun Inc. (San Francisco, California) in the Summer of 2020 on a
textile machine development project as a Textile Research Engineer. He developed a warp knitting machine on the masters, which paved the way for that internship.

Faisal has presented his research on Dynamic Breathability: Mapping the Gaps between Static and Dynamic Benefits of Fabric at several international conferences. He was awarded first place in a student paper competition by the American Association of Textile Chemists and Colorists (AATCC). He will graduate with a Ph.D. in Fiber and Polymer Science in December 2022.

Faisal and his wife Nila were married in April 2015. His wife is also doing her master's in communication at NC State University. Fun fact about being a wolfpack couple they also have two beautiful kids. They are a happy family with a son, Hamdan (February 2019), and a daughter, Hadiqah (August 2021).
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CHAPTER 1

1.1 Research Background and Significance

Ever since the advancement of manufactured fibers, there has been a heated dispute about the relative benefits of natural vs. manufactured fibers for clothing. The hygroscopicity of natural fibers (cotton, wool, and others) and the non-hygroscopicity of synthetic fibers (polyester, acrylic, nylon, and others) are well-established. The extensive usage of non-hygroscopic manufactured fibers for clothing indicates that there may be significant difference between them and hygroscopic natural fibers. Spencer Smith mentioned (Spencer-Smith, J. L., 1976) under steady-state conditions, the main components of natural fibers like keratin for wool and cellulose (cotton, linen) have a very low water vapor transfer resistance. On the contrary, the polymeric materials of manufactured fibers, such as polyester, polyacrylonitrile, and polyamide, have much higher transfer resistance. (Spencer-Smith, 1976). This property, often confused with the term 'breathability' (a term used to define comfort), is boldly highlighted by the non-hygroscopic manufactured fiber manufacturer. Therefore, a significant property of natural hygroscopic fiber did not receive substantial attention in recent days.

However, humans are never in a steady state in real life. Even resting or sleeping, considered the steadiest state of human interaction, also exerts certain metabolic functions that do not enable man to remain in fully steady conditions. In a high-water-vapor-pressure environment, hygroscopic clothing absorbs water vapor, which releases latent heat (Cui et al., 2020). This latent heat raises the temperature of the clothing material and the surrounding air until equilibrium is reached. This phenomenon is called the exothermic effect of fiber. Therefore, in transient conditions, whether it can be the change in the body's metabolic rate or the change in environmental conditions, hygroscopic natural fibers can exert a substantial buffering action in
transient settings by developing an exotherm effect on the clothing surface, which may work in the wearer's favor by providing temporary protection from the effects of changing conditions. Consequently, in non-transient settings, moisture vapor transfer and thermal insulation value may be the two most essential parameters to consider when comparing the performance of the various fiber types. It is also vital to understand how the fiber moisture regain process, and sorption heat, can affect the fiber's properties in terms of human thermal balance and comfort in transitory conditions. Since Cassie published his initial paper in Nature in 1939, describing the concept of thermostatic buffering action of textile fibers, a great deal of experimental and modeling work has been done to this day. The argument over how textile fibers/clothing react under non-steady settings and how this affects human heat balance and comfort continues today. For example, Cassie and Spencer-Smith (King et al., 1940) (Spencer-Smith, J., 1966) conducted extensive studies into the moisture buffering action of hygroscopic fibers, but Lotens (Lotens & Havenith, 1995) showed that such assumptions were not always correct.

Clothing produces a microclimate between the skin and the clothing. The surrounding environment strongly affects the levels of temperature and humidity of the skin microclimate. For example, a change in ambient humidity from low to high, or sweat generation on the skin during exercise may create a damp environment in the microclimate. Clothing may absorb both liquid and moisture vapor; however, depending on the type of clothing worn, vapor transfer via clothing can affect the microclimate, which affects the body's core and skin temperature. Skin sweat evaporation is influenced by several factors, including clothing-related factors such as thickness, wettability, and permeability of clothing. In addition to ambient humidity and temperature, microclimate conditions such as temperature, humidity, and body temperature play a vital role during sweat evaporation from the skin. (Davis & Bishop, 2013) (Berglund &
Gonzalez, 1977) (Pascoe et al., 1994). So, many factors affect the microclimate during regular body metabolism, but unfortunately, no test method that truly addresses these phenomena in transient conditions exists.

Most studies were conducted in fabric or garment stage tests using hot plates, manikins, or human trials with few participants. Furthermore, the test materials included a wide range of topics of interest. There have not yet been a comprehensive series of tests conducted to understand the complete theory and mechanism of moisture sorption, vapor transfer, and thermal insulation in the fabric stage, the garment stage, and with human subjects wearing the same type of clothing but with different fiber compositions in transitory conditions. Thus, additional scientific research in this field is still required, and the establishment of a standardized test and evaluation technique is in demand.

1.2 Research Goal

This research aims to develop a test method that can address the differences between the static and dynamic benefits of fabrics. Understanding physiological and clothing characteristics under changing physiological or environmental variables, as well as the regulating factors controlling this process, are necessary for achieving this goal. The research will benefit the clothing industry by better designing clothing for sports under specific environmental conditions considering comfort and functionality.

1.3 Research Objectives

The goal could be achieved by fulfilling the following objectives:

a) Develop a standard and modified test methods to characterize dynamic fabric moisture regain and exotherm behavior of different fabrics.

Detail tasks include:
• Determining and understanding the fundamentals of available standard and modified fabric tests and garment test methods for the exothermic behavior of textiles.

• Investigating the effect of moisture regain of fibers on the exothermic behavior of textiles.

• Analyzing the results of the fabric and garment tests and validating the results with human trials with a suitable protocol.

• Suggesting the best method to test the dynamic moisture regain of fabric and its impact on human comfort by investigating the exothermic behavior of the fabric from the various test results.

b) Obtain an understanding of physiological data of skin-textile characteristics in various ambient and microclimate conditions.

Detail tasks include:

• Understanding skin-microclimate behavior, such as skin temperature and humidity, fabric temperature and humidity, and skin-microclimate temperature and humidity by analyzing the data generated from different fabric and garment level tests.

• Defining the breathability of textiles from a novel perspective while comparing with existing definitions and explanations.

• Combining all the physiological data sets from fabric testing, garment testing, and human subject trial will enable a better understanding of the comfort aspects of the different fiber types.
1.4 Research Questions

On the basis of the above discussion, the following research questions in Table 1-1 will try to be answered throughout the investigation.

<table>
<thead>
<tr>
<th>Category</th>
<th>Main Research Questions</th>
<th>Sub-Research Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Method (Standard and Modified)</td>
<td>What suitable test method can determine the relationship between dynamic regain behavior and the exotherm effect?</td>
<td>i. What are the main measurement differences between fabric tests for determining the exotherm effect and moisture regain?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. How could fabric tests, garment-level manikin tests, and human trials be understood and interpreted in terms of physiological responses?</td>
</tr>
</tbody>
</table>
| Physiological and clothing aspects | What effects do dynamic environmental or physiological changes have on skin-textile characteristics during various fabric tests, garment tests, and human trials? | i. How do skin temperature and humidity respond to dynamic changes (environment or physiological)?

ii. What effect does the dynamic system have on the fabric temperature and humidity?

iii. Is there any evidence of the presence of the exotherm effect? How can we measure and explain it in terms of physiological responses and outcomes if this is the case?

iv. Will we be able to distinguish between hygroscopic and non-hygroscopic fiber types and their responses to transient environmental conditions? |
1.5 Research Approach

Addressing research questions will require understanding the concepts and applications of advanced instruments to measure the dynamic moisture buffering potential in a transient environment setting. For fabric testing, the ISO-16533 test setup and dynamic hot plate were used to gain insight into benchtop testing methods. However, benchtop testing is insufficient as these measurements cannot predict clothing behavior in a realistic environment. On the other hand, the thermal and sweating manikin can simulate physiological responses in a more realistic environment. Thus, both manikin systems have been explored to understand more realistic clothing behavior; finally, it is crucial to validate the findings at the fabric and garment level with human trials. Therefore, a complete cycle of fabric tests, garment tests, and human trials has been utilized to determine a new fabric test method for the dynamic moisture regain and exothermic behavior of the fabric. A graphics of research approach shown in Figure 1-1.
1.6 Thesis Layout

The thesis consists of eight chapters. A summarized lay out of the chapters shown in Figure 1-2.

The research background, research goal, research objectives, and approach have presented in Chapter 1. This breakdown enables a clear understanding of the significance of the research and helps to establish specific approaches to achieving the research goal.

Chapter 2 presents an extensive review of the literature in relevant areas so as to gain a scientific understanding of the basic theory and mechanisms of moisture transmission through skin and clothing. Also, it helps to sort out the available fabric test methods for the exothermic behavior of the fabric and has helped to identify the knowledge gaps. That provides a framework for accomplishing the research goal.
Chapter 3 compares the fabric test methods available by experimentation and validation. Moreover, a valid conclusion can be drawn by addressing the advantages and disadvantages of the available fabric test methods.

Chapter 4 studies the exothermic behavior of textile materials in garment form with the thermal manikin. A novel and detailed correction method for manikin heat loss data has been presented and validated for transient humidity change.

Chapter 5 extends the effect of textile material's exothermic behavior with the sweating manikin and in the presence of wind. A detailed study of the physiological and skin parameters has been examined.

Chapter 6 presents human responses to a specific protocol designed to validate exothermic behavior and its impact on physiological comfort of clothing.

Chapter 7 describes a new methodology to measure heat of sorption of textile fabrics. TAM air iso thermal calorimetry was used in a novel way to measure the heat generated by fabrics while absorbing water in a isothermal condition.

Chapter 8 presents a novel test method by analyzing fabric tests, manikin tests, and human trial results. In addition, some preliminary results have been presented to validate the method's suitability for the fabric's exothermic behavior.

Chapter 9 summarizes the findings and discusses future work.
Figure 1-2 Thesis outline and framework.


2 Chapter-2

2.1 Background Literature and Research Gaps

Clothing comfort is a subjective concept. Numerous attempts have been made throughout the years to quantify and explain human clothing comfort and related properties in various methods (Das & Alagirusamy, 2010b). In his book "Heat and Mass Transfer in Textiles," Haghi mentioned clothing as a second skin, referring to humans as unfinished beings without clothing, which undoubtedly draws attention to how vital clothing is in day-to-day life (Haghi, 2011). Humans, particularly in recent years, have developed an excellent sense of dress for various occasions or activities such as walking, hiking, cycling, running, etc., and are conscientious of the garment's comfort and functionality. The sweating phenomenon plays a vital role in ensuring human comfort and is the primary means of transporting moisture from the human body. The amount of sweat released from the human skin during exercise is approximately 1000 g/m² per hour, while it is only 15 g/m² per hour when the body is at rest. This means that a certain amount of moisture is always evaporating through the skin in the form of sensible or insensible perspiration. It confirms that humans are never in a true steady state situation (Hai-bo & Lu, 2010) (Cui et al., 2020). Therefore, the types of clothing can play a vital role in absorbing moisture and ensuring human comfort in transient situations.

Hygroscopic textile fabrics generate heat during moisture absorption, known as the exotherm effect, and absorb heat during desorption, known as the endotherm effect. The heat of moisture absorption varies depending on the material being used. Wool fiber, which has a high moisture regain, is an example of a fiber whose heat of moisture absorption is significantly larger than that of common synthetic fibers, which has a low moisture regain. According to this finding, the hygroscopicity of textile fibers has a significant impact on the body's thermal balance. As a
result, it is important to study the fundamental theory of the exotherm behavior of textile fibers, the moisture absorption-desorption phenomenon, and methods for evaluating and quantifying these dynamics.

2.2 Moisture transport from the human body and Clothing Interaction

During normal conditions, moisture is transported from the body in two ways. One of the types is sweat in the form of a liquid, which is sometimes referred to as active sweat or sensible perspiration. On the other hand, insensible perspiration has a similar effect on the body in the form of vapor. Figure 2-1 shows a detailed cross-section of human skin and illustrates sensible and insensible sweat loss phenomenon.

![Figure 2-1 Human skin structure and two types of sweat loss on the skin surface (sensible sweat and insensible sweat) (Zhong et al., 2021).](image)

Eccrine sweat glands are the most abundant and ubiquitous type of sweat glands, which create most visible moisture on the skin surface. The nervous system controls the activity of these sweat glands in response to physical, thermal, and emotional stimuli, as well as by the environment. Thermoregulation of the body core and the regulation of skin moisture are two crucial functions of these sweat glands. Insensible sweat in the form of vapor performs nearly identical functions to those of liquid sweat, which is technically known as trans epidermal water loss. Without any external stimulus, the entire body of an individual can produce insensible
sweat. Water within the body diffuses osmotically and unconsciously evaporates from the inner dermis and epidermis to the outer stratum corneum (SC) as a result of the presence of a moisture gradient between the inner and outer dermis and epidermis (Hill, L. W. & Sulzberger, 1935) (Ohhashi et al., 1998) (Baker, 2019) (Hu et al., 2018) (Sotoodian & Maibach, 2012).

2.3 Body Thermal Regulation and Skin-Moisture Interaction

Both types of sweating, sensible and insensible perspiration, play an essential role in maintaining the body's physiological comfort by evaporative heat loss. The heat balance at a low core and skin temperature is in part related to the evaporation of insensible perspiration, which plays an important health function in thermoregulation. In contrast, heat balance at a high core and skin temperature is mainly attributed to the secretion and evaporation of sensible sweat.

Normal thermoregulation allows the human body to keep its core temperature between 36-38°C while at rest and between 37-41°C while actively engaged in strenuous physical activity (Katić et al., 2016). The dry human body relies mainly on convection, conduction, and radiation under very mild conditions (e.g., resting, sleeping, and low-intensity exercise). It only needs to evaporate a nearly constant insensible sweat to maintain body temperature. Since the latent heat of evaporation of insensible sweat is inadequate to regulate body temperature, when the thermal load increases and beyond the onset threshold, the sweat glands begin to discharge sensible sweat to the skin surface, where it evaporates for heat dissipation (Baker, 2019) (Gagnon & Kenny, 2012) (Vinken & Bruyn, 1969). For heat balance, the rate of sensible sweat production increases linearly as body temperature rises. In this case, effective cooling of the body is mainly achieved through the latent heat of water vaporization from sensible sweat.

Kim et al. mentioned the high importance of insensible perspiration (moisture vapor) to maintain skin hydration than liquid moisture (Kim, Jayoung et al., 2019). Most insensible sweat
evaporates from the skin surface to the surroundings, whereas a fraction is retained within the SC
to maintain skin hydration. This retained water from insensible sweat is essential for skin health,
including skin barrier function, elasticity, and electrical characteristics. Measurement of
insensible sweat loss has attracted significant attention in the cosmetic, dermatological, and even
psychological fields (Hardy & DuBois, 1937).

2.3.1 Importance of Clothing for Skin-Moisture Interaction

The human body provides limited cooling during very low levels of physical activity,
primarily through the production of insensible perspiration. That is where the actual interaction
of clothing with skin and moisture occurs. It will be more difficult for water vapor to escape into
the surrounding atmosphere when the garment layer does not allow it to pass through. The
relative humidity of the microclimate within the clothing increases, as a result, making the
clothes uncomfortable and unpleasant to wear in certain situations. Over the years, researchers
and the clothing industry. This brings us to a point where we can establish a relationship between
sweat rate and the change in mean body temperature depicted in Figure 2-2.

Under the onset threshold (office work, sleeping, yoga, etc.), insensible sweat is the
primary body sweat, where an initially relatively flat portion characterizes the relationship.
Beyond the onset threshold (eating hot food, sauna, running), sensible sweat emerges and
becomes dominant, where the relationship is linear. Ultimately, sensible sweat rate reaches a
maximal level, leading to a plateau despite mounting mean body temperature (Vinken & Bruyn,
1969).
Although Figure 2-2 from Zhong et al. nicely describes how body thermoregulation is maintained during the increase in activity, they did not mention the aftereffects, i.e., how the body will cool down after reaching the plateau position. During sweating, the humidity in the human body is may be absorbed by clothing. Cooling cannot occur if humidity remains in the fabric and is not transported to the clothing surface for evaporation. If clothing materials absorb moisture, the rate with which the fabric dries after the exercise will be one of our research points of interest. Two salient factors affecting the performance of a garment towards the heat balance of humans are the rate of transport of water vapor and the rate of transport of liquids within the fabric, either by absorption or capillary action (McArdle et al., 2010) (Berglund & Gonzalez, 1977). Therefore, it is important to know the mechanism of moisture transmission from the skin.

### 2.4 Steady-State Moisture Vapor Transfer Mechanism from Skin

Water vapor can interact with textiles and be transported via the following mechanisms (Das & Alagirusamy, 2010a) (Özek, 2018) (Lomax, 1985):

- Water vapor diffusion through air spaces between fibers and yarns and along the fibers.
Absorption and desorption of the water vapor of the fiber.

Transmission of water vapor by forced convection through textiles.

The first stage is dominated by two rapid processes in the air filling the inter-fiber void spaces: water vapor diffusion and liquid water diffusion through the fiber bundles, both of which can achieve new stable states in fractions of seconds. The second step involves fiber moisture sorption, which is slower and takes anywhere from a few minutes to many hours. Water sorption into the fibers occurs during this time as water vapor diffuses into the fabric. Finally, after transmission of water vapor by forced convection, steady state is achieved.

2.4.1 Diffusion

Diffusion is the random movement of a molecule from one part of the system with a higher concentration of vapor pressure to another (Feher, 2017). In the diffusion process, the vapor pressure gradient acts as a driving force to transfer moisture from one side of a textile layer to the other. The diffusion of water vapor through textiles could be divided into diffusion from the surrounding air into the air space between the fibers and the yarns and diffusion from the air around the fibers into fibers. Meanwhile, due to the surface tension force, liquid water begins to flow out of the greater liquid content parts and into the dryer regions (Snycerski & Frontczak-Wasiak, 2002).

The diffusion process was first postulated by Fick, explaining the relation between the rate of moisture flux and the concentration gradient (Hearle & Morton, 2008) (Haghi, 2011).

\[ J = -D \frac{\partial C}{\partial x} \]

Where \( J \) is the material flux through a surface of unit area, \( D \) is the diffusion coefficient, \( \partial C/\partial x \) is the concentration gradient. However, this Fick's first law only applies to the system that diffusant pass through without building up in the region. In the case of some textile materials that
are able to absorb moisture, vapor diffusion follows Fick's first law at the first stage but not at the second stage. The second stage of the diffusion in hydrophilic/hygroscopic material is a slower process, which was found in many studies (Mackay & Downes, 1969). The structural change within the fiber is one reason for the slower diffusion, as the swelling of fiber minimizes the space between fiber, which delays the process (Das & Alagirusamy, 2010). The diffusivity of textile material could be affected by several factors. The volume fraction and fiber shape are essential parameters that influence the diffusivity of water vapor. A higher fiber volume fraction leads to a low porosity fiber assembly, reducing the water vapor diffusivity (Woo et al., 1994a) (Woo et al., 1994b).

2.4.2 Sorption and Desorption

The second step involves fiber moisture sorption, which is slower and takes anywhere from a few minutes to many hours. Water sorption into the fibers occurs during this time as water vapor diffuses into the fabric, increasing the relative humidity at the fiber surfaces. Following the diffusion of liquid water into the fabric, the fibers' surfaces become saturated because of the film of water on them, enhancing the sorption process once again (Prasad et al., 2002).

The process in which substances take up the moisture from the external environment is called sorption. Sorption included both adsorption and absorption. According to the IUPAC definition, absorption is the process of one material being retained by another. In the textile case, the moisture in the air enters the bulk phase of the fiber or reacts with the water affinity group to form a hydrogen bond (McMurry, 2003). The process by which molecules adhere themselves to the surface of the phase is referred to as adsorption. Desorption is the reverse process of sorption in which the substance is released from a surface or the bulk phase. Desorption is the process that
removes moisture in the material, but desorption is not the exact reverse process of sorption. Hysteresis is a phenomenon that always happens when the sorption and desorption processes are compared. When a textile material desorbs moisture, the moisture regain will be higher than when the same condition is achieved by sorption (Cookson & Slota, 1993).

The water vapor sorption behavior of the materials is closely related to the relative humidity and is described by a sigmoidal isotherm curve. A typical isotherm curve is shown in the Figure 2-3, which could be divided into three parts.

![Sigmoidal Isotherm Curve](image.png)

Figure 2-3 Illustration of typical behavior exhibited by a lignocellulosic material when desorbing moisture from a fully water-saturated state and when desorbing moisture from a non-water-saturated cell wall moisture content. Hysteresis between the adsorption and desorption isotherm is also shown (Hill, C. A. et al., 2009).

At a low relative humidity level, monolayer adsorption onto the internal surface of the fiber and absorbed by polar groups in the amorphous area is the dominant process. At a medium relative humidity level, multilayer adsorption happens because fewer polar groups are available. At a high relative humidity level, capillary condensation occurs, and the water breaks up the hydrogen bond, which opens more space for moisture to enter (Hill et al., 2009). This sorption isotherm curve shows that the moisture content change could be different with the same
magnitude of relative humidity change in different relative humidity regions. For example, when a hygroscopic textile material switches from 0% to 20% RH, the amount of moisture content increases is more than switching from 40% to 60% RH. Because of the heat generated or absorbed during sorption/desorption and evaporation/condensation during these two transitory stages, heat transfer is linked with these four types of liquid transport. The efficiency of heat transmission affects both sorption and desorption, as well as evaporation and condensation. Sorption and evaporation, for example, take longer in thick cotton textiles than in thin cotton fabrics to achieve stable states.

2.4.3 Forced Convection

Forced convection is the term used to describe the transfer of moisture vapor that occurs when air flows over a moisture layer. The differential determines the moisture transmission between the moisture concentrations of two different environments, i.e., the surrounding atmosphere and the source of moisture vapor. The following equation governs the course of the process (Incropera et al., 1996).

\[ Q_m = -A h_m (C_a - C_\alpha) \]

Where, \( Q_m \) = the mass of moisture vapor transmitted by convection

\( A \) = Fabric Area

\( C_a \) = Moisture vapor concentration on the fabric surface

\( C_\alpha \) = Vapor concentration in the air

\( h_m \) = convective mass transfer coefficient

2.5 Dynamic Moisture Vapor Transport Mechanism

The steady-state moisture vapor transmission is vital to know the primary mechanism of moisture transmission. However, humans are never in a steady state condition; therefore, the
dynamics of moisture vapor transmission must come into the picture. Moisture transfer in
dynamic circumstances also involves heat transmission because water molecules may undergo a
phase change. As a result, moisture sorption and diffusion during these transient stages are
associated with different forms of moisture transmission because of heat released or absorbed
during the sorption or desorption and the evaporation or condensation process (Chen et al.,
2003).

Many researchers have tried theoretically and experimentally better to illustrate the
dynamic moisture-transport behavior of textiles (Kaplan & Okur, 2010; Kim, Eun et al., 2003).
On the basis of the literature review, we conclude that two transfer mechanisms govern these
dynamics.

Dynamics of moisture transport

- Fiber Regain and Equilibrium Kinetics
- Hygroscopic and non-hygroscopic behavior

Dynamics of Heat Transport

- Concept of Exotherm Effect
- Heat loss (Dry and Evaporative) and buffering effect.

Steady-state metrics cannot represent the dynamic heat and moisture from clothing.

Although these two factors never happened separately, we tried to break them down into several
concepts for our research perspective to understand the dynamicity of fiber behavior better.

Moisture may be absorbed in the form of moisture vapor form to evolve a heat of $Q_v$ (J/g) and in
the form of liquid to generate $Q_l$ (J/g). According to the first law of thermodynamics,

$$Q_v = Q_l + L$$
where $L$ is the latent heat of condensation of water in J/g, this can be depicted in the Figure 2-4.

![Figure 2-4 Heat of sorption from vapor and liquid (Hearle & Morton, 2008).](image)

Clothing can dynamically transfer dry heat and moisture (mass transport). It is vital to note that the thickness of the enclosed air layers in an ensemble has a considerable effect on both the insulation and moisture vapor permeability of the system. It is possible for the air contained within clothes to enter a dynamic state while a person is in such a condition. The intensity and pattern of activity and the size and number of openings in the garments are critical factors in the final stage of thermal and vapor exchange. High air velocity can compress clothes in a severe windy environment, reducing their insulation. Clothing can also lose its thermal insulation properties if it becomes wet with perspiration or water (Das & Alagirusamy, 2010).

### 2.5.1 Fiber-Regain and Equilibrium Kinetics

Moisture regain (MR) is the term used to describe the absorbed moisture content of fibrous materials. Moisture regain is calculated by dividing the mass of moisture adsorbed by the dry mass. Although certain fibers may have a residual amount of moisture in this state, the dry mass of the fiber is the mass of the fiber when it is in equilibrium with entirely dry air. This residual moisture in the dry state is not included in the mass of moisture absorbed (Hearle & Morton, 2008) (Pan & Gibson, 2006). The regain (R) is defined mathematically as following and often expressed as a percentage.
The MR of the textile fiber is mostly depending on the RH of the ambient environment; it could be the surroundings or the body that covers the surface. Jones et al. (Jones et al., 2006) clarified the equilibrium condition of textile fiber. The RH of the air in the ambient microclimate around a fiber determines the equilibrium moisture regain of most fibrous materials. Assuming that the ambient relative humidity is the same, the equilibrium will be approximately the same at different temperatures. Regardless of relative humidity, ambient temperature and atmospheric pressure might have a small influence. At typical indoor and outdoor ambient temperatures, relative humidity, on the other hand, is obviously the most important variable for most human conditions. The link between relative humidity and regain may not hold up under more severe circumstances, such as those found in manufacturing operations.

\[
R = \frac{\text{Mass at given condition} - \text{Mass at dry condition}}{\text{Mass at dry condition}}
\]

Figure 2-5 Typical moisture regain curve for popular fiber types in raw stages (Hearle & Morton, 2008).
Natural fibers, on average, have larger regains than synthetic fibers, with some of the latter having almost no regain. Figure 2-5 shows the standardized moisture regain relationships for several popular fabrics (raw fibers) adapted from (Hearle & Morton, 2008). Because the regain is measured in terms of adsorbed moisture vapor, the curves cease at 100% relative humidity. Although the curves look to end at 100% RH, it is impossible to set an upper limit for individual fibers. The maximum limit for fabrics in a fibrous medium is determined by various factors, including the porosity and structure.

2.5.2 Hygroscopic vs. Non-Hygroscopic Fiber Regain Behavior

Textiles composed of hydrophilic fibers, such as cotton and wool, build up moisture at the inner fabric surface exposed to sweating skin at a relatively moderate rate, while fabrics made of hydrophobic fibers, such as polyester, build up moisture rapidly.

When textiles with varying degrees of hydrophilic nature were compared, it was observed that the period of transitory behavior was highly influenced by the moisture sorption capacity of the fabric. When wool fabric subjected to a humidity gradient because of its higher heat of sorption it retains heat, making it ideal for climates with extremes. Total quantity of moisture transported from a high humidity environment is more prominent with a highly hygroscopic fabric such as cotton than with a weakly hygroscopic fabric such as polyester during the transitory time. A study comparing wool and polyamide (Figure 2-6) clothing found that a wool garment allowed for more heat loss. Perspiration and clinging sensations were delayed when wearing a wool garment (Li, Yi, 2001) (Das & Alagirusamy, 2010).
In their study, Li and Holcombe (Li, Y. & Holcombe, 1993) used temperature and moisture gradients to determine the dry and evaporative heat fluxes that occur at the outside surface of the garment during exercise while wearing different types of clothing. In Figure 2-6, there is no change in the heat flow between dry and evaporative conditions before sweating occurs. When wearing wool rather than polyester, the dry heat flux at the outside surface of the garment was considerably higher after sweating than when wearing polyester. There was no substantial difference in evaporative heat flow between wool and polyester, according to the findings.

2.5.3 Exothermic Behavior of hygroscopic fiber

The influence of exothermic behavior on fabric is governed by the moisture absorption of the textile material when it is in a transitory state. The absorption and desorption of moisture will be described in more detail later. Spencer Smith's series of publications on the "physical basis of clothing comfort" provided an excellent description of the detailed mechanism of the exotherm.
effect of hygroscopic fibers (Spencer-Smith, J. L., 1978). When a hygroscopic textile material is exposed to greater humidity levels, moisture is absorbed, and latent heat is released, increasing the fabric's temperature and the temperature of the local air, which is known as the exotherm effect. This gradual increase in temperature continues until an equilibrium is reached between the temperature and water vapor pressure of the local air and the regain of the clothing material. The latent heat of absorption of water vapor is around 2260 KJ/kg. The specific heat of the clothing is relatively low (0.3 J/g K). The author implies that this immediate impact of an increase in water vapor pressure causes a substantial increase in the temperature of the clothing material coupled with a relatively slight increase in the regain, depending on the level of moisture regain of the material. The procedure is followed by a progressive drop in the clothing’s temperature and an increase in its moisture regain until an equilibrium has been attained. Spencer Smith described that the buffering action could act as a wearer advantage while changing the conditions, whether it can be environmental or in body activity. The conditions are depicted in Figure 2-7.

![Figure 2-7 Conditions for showing exotherm effect by hygroscopic fibers.](image)

King and Cassie (King et al., 1940) also Henry (Spencer-Smith, 1978) showed the influence of a change in ambient parameters on a hygroscopic textile material experimentally as
a rapid diffusion of a change in the temperature through the cloth followed by a much slower diffusion of a change in regain. Cassie showed that wearing hygroscopic clothing, such as wool, had a significant buffering effect when moving from a warm, dry environment to a cold, damp environment. According to the authors, hygroscopic clothing gradually absorbs moisture from the air and emits heat in the process, temporarily limiting heat loss from the wearer's body. After conducting direct tests on wool suiting that clothed an ephemeral body, David concluded that the heat loss through the fabric was reduced by about 12 percent immediately after the system was switched from a 50% RH to an 80% RH atmosphere and that this buffering effect was reduced to about 3% after 20 minutes. In these circumstances, the author has made estimations that just 30 to 50% of total sorption energy is beneficial in limiting body heat loss.

For testing the buffering action of hygroscopic textile material (worsted, linen, acrylic) at the onset of perspiration, Spencer-Smith (Spencer-Smith, J., 1966) utilized an artificial body comprised of a guarded hot plate. Perspiration was imitated with a recessed top surface and water kept inside that body; after obtaining the plate temperature at 37.4°C, water was introduced into the recess. The heat required to maintain constant body temperature was measured and plotted against time. The results revealed that, after introducing water, the heat loss in the linen and worsted yarn increases immediately. It then progressively dropped to a steady-state value whereas no mentionable change occurred in the case of acrylic fabric. The author also reported and exhibited that the surface temperature in the fabric showed a similar response.

The wettability of the textile material also affects coupled heat and moisture through the fabric, which ultimately contributes to the wearer's comfort. As the regain of the fabric increases, the ability of water to condense and spread across the fiber surface will allow liquid-assisted heat and water vapor transmission to occur, as described by Phillip and de Vries (Philip & De Vries,
This will reduce the resistance to both heat and water vapor transfer. The wettability allows it to absorb water from perspiring skin and become saturated, resulting in high maximum heat loss via wet fabric assemblies. As a result, water vapor can begin to condense in the micropores and crevices of the fibers at relative humidification well below saturation, and the material will behave in much the same way as a hygroscopic fiber, providing some buffering effect at the onset of perspiration, as long as the fibers are easily wettable.

2.5.4 Heat-loss During Transient Condition

Clothing, that is primarily made of hygroscopic fibers such as cotton and wool, significantly influences heat transfer in the dynamic state between the body and the environment (King et al., 1940).

Clothing acts as a barrier for the transport of heat and vapor between the skin and the environment. This barrier is formed by clothing materials, the air they enclose and the still air around outer surfaces (Havenith, 1999). Heat transmission through clothing is critical in environmental engineering and functional clothing design because it is directly related to thermal comfort. Heat transmission through clothes is typically thought of as the sum of two different types of heat transfer: dry heat transfer and evaporative heat transfer.

\[
\text{Dry heat loss, } R_{ct} = \frac{T_{sk} - T_{air}}{I_T}
\]

Where, \(T_{sk}\) = Skin temperature
\(T_{air}\) = Air temperature

\(I_T\) = Clothing insulation, including an air layer

\[
\text{Evaporative heat loss, } R_{et} = \frac{P_{sk} - P_a}{R_T}
\]

Where, \(P_{sk}\) = Skin vapor pressure
\(P_a\) = Air temperature
\( R_T \) = Clothing vapor resistance, including an air layer

Figure 2-8 Heat and mass transfer from a human body covered with tight-fit and loose-fit garments (Das & Alagirusamy, 2010).

The difference in fabric thermal insulation in non-perspiring and perspiring situations may result in inconsistencies when calculating dry heat loss during sweat. As a result, anomalies occurred when calculating the evaporative heat loss and measured the resistance to water vapor over the same period. Most people think that sweat reduces clothing thermal insulation because it increases effective thermal conductivity, liquid water transport, and evaporation inside wet clothing assemblies, all associated with perspiration. Due to the loss of evaporative heat, perspiration causes a significant increase in total heat loss. The thermal insulation provided by clothes decreases during sweating, with the degree of loss varying from 2% to 8% depending on the amount of water accumulated within the textile ensembles (Das & Alagirusamy, 2010) (Chen et al., 2003). Figure 2-8 explains how combined action of heat and mass occurred while wearing both tight-fit and loose-fit garment.
2.5.5 Moisture Buffering Effect

Cassie first postulated the concept of "buffering" moisture in 1939 (Cassie et al., 1939) In transient humidity conditions, hygroscopic fibers can absorb or desorb moisture from or to the surrounding environment, delaying the moisture change in the microclimate of clothing. Theoretically, this effect often acts as a buffer against sudden humidity changes in favor of the wearer. Under experimental conditions, wearers are regularly subjected to significant and abrupt changes in the external environment. Clothing is a critical barrier to protecting the body from such abrupt environmental changes. Because of the moisture-wicking properties of hygroscopic materials, clothing composed of these materials has a substantial impact on the thermal balance and comfort of the user (Woodcock, 1966) (Kim, J. O., 1999) (Li, 2001).

With simultaneous heat and moisture vapor transfer via fiber assemblies, two transitory phenomena, buffering and chilling, are linked with the process. The cooling effect, also known as the buffering effect, is induced by perspiration in hot climates. However, the cooling effect is also induced in cool climates by sweating after exercise, known as the chilling effect. When the climate experiences a rapid increase in relative humidity, textiles absorb moisture to maintain a microclimatic state while generating heat. A thermostatic or buffering action is induced in the individual wearing the fabric in clothes because of this. Heat-induced cooling would occur at the onset of perspiration, whereas cold-induced cooling would occur after the end of the activity, depending on the environment's temperature. This post exercise chill is caused by continuous evaporative cooling from the adsorbed liquid sweat from the fabric, when the person cools down after the exercise. It has a negative effect on productivity and might cause hypothermia. When vapor sweat comes into contact with fabric surface, in this case, the fabric moisture condenses,
reducing the thermal insulation provided by the garment. Both occurrences are very dependent on the temperature and humidity levels in the surrounding environment.

2.5.6 Concept of Breathability

In general, the term 'breathability' refers to the ability of a substance to breathe while being ventilated. If we are talking about textiles, a breathable fabric should passively enable water vapor to diffuse through it. This is definition of breathability that is nowadays often found in the textile industry.

The sweat from the human body must vaporize to provide cooling and it is more difficult for water vapor to escape into the surrounding atmosphere when the garment layer does not allow it to pass through. The relative humidity of the microclimate within the clothing increases, as a result, making the clothes uncomfortable and unpleasant to wear in certain situations. The loss of water vapor through clothing is fundamental to the heat balance of the body and comfort. If a fabric has poor breathability, liquid moisture is formed by condensation of water vapor, leading to a feeling of clamminess (Mukhopadhyay & Midha, 2008). That brings us to think of redefining the breathability of clothing and materials, which is critical for both garment comfort and, more significantly, keeping a constant body temperature.

In this study, breathability is considered as the combination of air permeability, and water vapor transmission For the human body heat loss, air must be transported away from the body as, in general, the environmental air is cooler and dryer, and with the moving air, heat is taken away from the skin (dry cooling), and sweat is evaporated from the skin (evaporative cooling), the latter being the dominant cooling in warm conditions. Therefore, an expanded definition of breathability should include the effects of fabric on convective heat loss, i.e., air
permeability of fabrics. In summary, static breathability is defined as the ability of the material driving the water vapor from the skin and pass through the air to maintain a dry surface.

2.6 Evaluation of Moisture Transmission Properties

2.6.1 Steady State Moisture Vapor Measurement

The equilibrium states of moisture vapor transfer are dealt with in static moisture vapor transfer measurements. Because of the relative simplicity of equilibrium measurements in terms of consistency, the laboratory equipment required is frequently used in research. Even though this knowledge may not accurately describe the interaction between clothing and humans, it provides essential materials to understand the basics of dynamic moisture vapor transfer measurement.

2.6.2 Fabric Test Methods

The moisture vapor transfer characteristics of textile fabrics are measured in various ways using different terminologies. The results produced by different procedures are not necessarily comparable due to differences in testing settings and measuring units among the various methods available. The terminology and related units are used to express the moisture vapor permeability of fabrics presented in the Table 2-1 (Ghali et al., 1994) (Lomax, 1985) (Ren & Ruckman, 2004) (Hes & Williams, 2011):

Table 2-1 Steady-state measurement methods of moisture vapor transmission.

<table>
<thead>
<tr>
<th>Test Methods</th>
<th>Standards/Inventors</th>
<th>Determining Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric/Cup method</td>
<td>ASTM E96-66</td>
<td>Moisture vapor transmission rate (g/m²/day)</td>
</tr>
<tr>
<td>Evaporative dish method</td>
<td>BS 7209</td>
<td>Percentage water vapor permeability index</td>
</tr>
</tbody>
</table>
Table 2-1 (continued).

<table>
<thead>
<tr>
<th>Method</th>
<th>Standard</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweating guarded hot plate</td>
<td>ASTM 1868-17</td>
<td>Resistance to evaporative heat transfer (Ret) (m²Pa/W)</td>
</tr>
<tr>
<td>Permetest skin model</td>
<td>ISO 9920/ BS 7209</td>
<td>Water Vapor Permeability (%)</td>
</tr>
<tr>
<td>Holographic visualization</td>
<td>---------------------</td>
<td>The resistance of equivalent standard still air (cm)</td>
</tr>
<tr>
<td>Moisture vapor transmission cell</td>
<td>ASTM E96</td>
<td>Moisture vapor transmission rate (g/m²/day)</td>
</tr>
<tr>
<td>Turl Dish</td>
<td>CGSB M49</td>
<td>Resistance to water vapor transmission (mm of still air)</td>
</tr>
<tr>
<td>DND Apparatus</td>
<td>Farnworth and Dolhan</td>
<td>Water mass transfer</td>
</tr>
<tr>
<td>Van Beest and Wittgen Apparatus</td>
<td>Van Beest and Wittgen</td>
<td>Volume change in water</td>
</tr>
</tbody>
</table>

In the evaporative disc method, the percentage of water vapor permeability index, WVP (%), is used to measure water vapor permeability (BS 7209). This method uses water at 20 degrees Celsius, an ambient temperature of 20 ± 2°C, and relative humidity of 65 ± 2%. The control dish method (CAN2-4.2-M77) and the Gore modified disc method (BPI 1.4) are the foundations of this standard. The cup method (ASTM E96-66) uses a moisture vapor transmission rate (g / m² / day). During the sweating-guarded hot plate test, the resistance to evaporative heat transfer, Ret (m²Pa/W), is measured (ASTM 1868-17). When determining the vapor transmission property of the fabric, this method is used indirectly. This test procedure conducts the experiment in an isothermal environment under standard atmospheric conditions.
Das & Alagirusamy, 2010). Figure 2-9 shows a list of methods for measuring moisture vapor transmission properties.

Permetest was developed by Hes and team (Hes & Williams, 2011) to measure the permeability to water vapor of textile fabrics, garments, nonwoven webs, and soft polymer foils. It operates on the principle of heat flux sensing, which explicitly measures the evaporative heat resistance of the water. For isothermal conditions, the temperature of the measuring head is kept constant at room temperature. It is necessary to measure the amount of heat supplied to maintain the temperature of the measurement head, from where the supplied water evaporates. The Permetest can be utilized under the BS 7209 and ISO 9920 international standards. In the holographic visualization method, the resistance of the equal standard still air (cm) is used to measure the resistance. It is feasible to measure the resistance of the cloth and air layers separately using this method. The resistance of the fabric can be stated in terms of the standard still air (cm) that provides the same vapor resistance as the fabric under consideration. The moisture vapor transmission cell offers a faster and more straightforward way to test the water vapor transmission behavior of fabrics than other methods. To put it simply, the humidity created...
under regulated conditions is measured as a function of time by the cell, in principle. There are two cells, which are called the bottom and upper cells. The test specimen acts as a barrier between cells. At the beginning of the test, the lower cell is partially filled with water, while the upper cell is almost completely dry. The relative humidity of the upper cell increases with time as the moisture vapor is transported through the fabric sample and into the atmosphere. The change in humidity over a certain time interval shows the rate at which moisture vapor is transmitted through a piece of fabric (Das & Alagirusamy, 2010).

2.6.3 Garment Test Methods

Beyond fabric testing, thermal and physiological tests on manikins and human subjects can provide data considering real-life scenarios. Because clothing, air layer, and mobility factors all impact heat exchange and moisture management of fabrics.

2.6.4 Thermal Manikin

A thermal manikin with sweating skin can represent the human body (Figure 2-10). Manikin simulates a natural three-dimensional body and works as a heat and moisture transfer sensor. It detects the processes of heat loss through sweat evaporation, conduction, convection, and radiation, all of which are significantly influenced by the local microclimate. The manikin can also be dressed to simulate perspiration transfer in a clothed human and investigate other clothing effects. Although it is only possible to assess dry heat flow in both transient and steady-state situations using a dry manikin, it is possible to measure both evaporated and dry heat loss in both transitory and steady-state conditions using a sweating manikin (Rugh et al., 2004). There are two standard methods available, in the US, to measure clothing insulation and evaporation resistance with a thermal manikin. These are ASTM F1291 (for evaluating thermal resistance) and ASTM F2370 (for evaluating evaporative resistance) to measure thermal insulation and
evaporative resistance, respectively, in steady state. The clothing ensembles are tested using the ASTM F1291 procedure to determine their insulation value. It determines the resistance to dry heat transfer from a heated manikin to a quiet, cool environment. In ASTM F2370, the evaporative resistance of clothing ensembles can be determined. Thermal manikins are heated and then sweated in a comparatively controlled atmosphere, and the resistance to transmission of evaporative heat is measured. Although the sweating option is enabled in this test, this does not simulate the real-life scenario of transient conditions.

Figure 2-10 Different types of manikins available for measuring thermal and evaporative resistance for clothing ensembles (Mandal et al., 2017).
2.6.5 Human Trials

The ultimate goal of investigating moisture transport through fabrics is to identify factors that may be used to simulate human comfort sensations under various climatic conditions. Subjective testing, in this sense, provides comprehensive information about the performance of clothing materials under all conditions. One of the research tools has been the use of wear trial studies. The traditional method of conducting these tests was in real-world circumstances where the experimental conditions were not controlled. Although wear studies are helpful in evaluating real-world scenarios, the results may be misinterpreted since they are difficult to quantify scientifically, as human subject trials usually include several variables (Adler & Walsh, 1984) (Behmann, 1962).

In order to meet the criteria of thermal comfort, the heat produced, and loss of the human body should be at equilibrium, human skin temperature remains within a narrow range, and perspiration remains within a given range (Bartal et al., 2012) The thermal balance equation describes the dynamic equilibrium of the human body, which is expressed as:

\[ M - W = R + C + E + L + K + S \]

\( M \) is metabolism, \( W \) is the external workload, \( R \) is radiation, \( C \) in convection, \( E \) is evaporation, \( L \) is respiratory, \( K \) is conduction, \( S \) is the heat storage in the body. This balance could be influenced by both environmental change and personal parameters (Hensen, 1990). The environmental change includes changes in ambient temperature, changes in relative humidity, and wind speed change. Personal parameters include metabolic rate and clothing interaction. Once the thermal balance is interrupted, the discomfort will appear. According to the adaptive principle, people would react in ways that tend to restore their comfort. Therefore, in a transient
condition, a faster way to respond to the change or buffer the change could help to obtain a better thermal comfort condition.

2.7 Moisture Vapor Measurement in Transient Condition

2.7.1 Fabric Test Methods

When it comes to measuring the water vapor permeability of breathable textiles under transient conditions, there are numerous methods described in the literature: some are national standards, while others have been developed independently by clothing manufacturers, often in order to portray their own products in a more favorable way (Hes & Williams, 2011). A list of some methods is given in Table 2-2.

Table 2-2 Transient measurement methods of moisture vapor transmission.

<table>
<thead>
<tr>
<th>Test Methods</th>
<th>Standards/ Inventors</th>
<th>Determining Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>The dynamic moisture-permeable cell</td>
<td>ASTM F 2298 (withdrawn 2015)</td>
<td>Relative pressure drops</td>
</tr>
<tr>
<td>Measurement of Exothermic and Endothermic Property Under Humidity Change</td>
<td>ISO 16533</td>
<td>Exothermic and endothermic property</td>
</tr>
<tr>
<td>The dynamic hot plate system</td>
<td>Naylor</td>
<td>Moisture buffering potential</td>
</tr>
</tbody>
</table>

The dynamic moisture-permeable cell (DMPC) (Figure 2-12) method can evaluate textile moisture transfer characteristics under diffusion, combination diffusion and convection, and pure convection (Gibson, Phillip et al., 1995) (Gibson, Phillip W., 1999). The relative pressure drop at the bottom exit measures the convective flow. Convective flow in hygroscopic porous materials is complicated by the fibers' ability to absorb water vapor and swell. The fabric connective flow
characteristics fluctuate with relative humidity. The DMPC can collect data in both static and dynamic states. Dry or saturated nitrogen gas can control the humidity on either side of the inverted fabric under test, typically 95% RH above the sample and 5% RH below the sample. To calculate the diffusion resistance of water vapor, the relative humidity of the gas flows entering and exiting can be known from the meter reading of the apparatus (Hes & Williams, 2011). This test method was previously adopted by ASTM and later withdrawn. A probable reason could be the use of nitrogen gas and complex computing procedures considering many variables.

2.7.2 Measurement of Exothermic and Endothermic Property Under Humidity Change

The exothermic and endothermic properties of textile materials occur when there is a change in the external relative humidity. Materials can absorb or desorb moisture, which leads to energy exchange. ISO 16533 is a standard testing method to measure the exothermic and endothermic properties of textile materials when relative humidity changes. Two constant containers with 65% and 20% concentrated sulfuric acid solution is used to create the environment of relative humidity of 10% and 90%. The test specimen is clipped to the temperature sensor to record the temperature change over the transient relative humidity. A detailed sketch of the setup is shown in Figure 2-11.
The test sample should be cut into 5 cm x 5cm and dry in the oven at 105 °C for two hours. Then, a desiccator’s condition is needed immediately before testing. The test specimen should be folded in half and placed in the temperature sensor probe in the center of the upper half. In order to wrap the temperature sensor probe, the specimen should be folded again. The fabric with the sensor clipped has to be placed in the constant humidity container to condition for a minimum of 3 hours. After more than 3 hours of conditioning, all three sensors in two flasks should be started, and the temperature and relative humidity should be recorded for 30 minutes. Then, after the plug with the test specimen, the sample has to be transferred to the mouth of a high-humidity container. This recording should continue for another 1 hour. \( T_{\text{peak}} \) can be read from the sensor mounted with the specimen and the \( T_{\text{blank}} \) can be read from the sensors without the specimen in the flask. \( \Delta T_{\text{exo}} \) can be calculated from the following formula.

\[
\Delta T_{\text{exo}} = T_{\text{peak}} - T_{\text{blank}}
\]

Where, \( T_{\text{peak}} \) is the peak temperature, determined using a temperature sensor with the test specimen mounted on the sensor probe in the second constant humidity container during the hygroscopic and exothermic property test, in degree Celsius (°C).
\(T_{\text{blank}}\) is the peak temperature, determined using a temperature sensor without the test specimen mounted on the sensor probe in the second constant humidity container during the hygroscopic and exothermic property test, in degrees Celsius (°C).

\(\Delta T_{\text{exo}}\) is the difference in the peak temperature, determined between a state with and another without the test specimen mounted on the sensor probe during the hygroscopic and exothermic property test, in degree Celsius (°C).

### 2.7.3 Dynamic Hotplate Test

A sweating guard hotplate measures the thermal resistance and evaporative resistance of fabrics under steady-state conditions. In the dry hotplate test, a piece of fabric sample is placed on the plate, which is 35°C. The ambient temperature is set to 21°C, and the relative humidity is 65%, which is the standard testing condition. The hotplate's power input to maintain the plate surface temperature is recorded every 1 minute for a minimum test period of 30 minutes when the fabric system becomes constant. The total thermal resistance of the fabric plus the air layer could be calculated using the following equation.

\[
 R_{ct} = \frac{(T_s - T_a)A}{H_c} 
\]

where \(R_{ct}\) is the total resistance to dry heat transfer provided by the fabric system and air layer (K*m²/W), \(A\) is the area of the plate test section (m²), \(T_s\) is the surface temperature of the plate (°C), \(T_a\) is air temperature (°C) and \(H_c\) is power input (W). The sweating-guarded hot plate mimics heat and moisture vapor transmission from the body surface to the environment via the clothing layers. It determines a fabric's thermal and water vapor resistance (McCullough, Elizabeth A. et al., 2004)
Based on the operation of a sweating-guarded hotplate, Naylor (Naylor et al., 2017) (Naylor, 2019) developed a novel approach to measure the dynamic moisture buffering potential of fabrics. The hotplate operation mode is the same as the dry hotplate test (Figure 2-12), while the relative humidity in the chamber becomes dynamic instead of static. The fabric sample is first equilibrated on the hotplate in an environment with low relative humidity (45%). Once the heat flux becomes stable, the relative humidity is rapidly raised to 85%. With an increase of relative humidity, the fabrics absorb the moisture and generate heat, reducing the heat flux applied to the plate. The area of the transient peak of the heat flux is a measure of the moisture buffering potential.

The transient heat flux peak area was calculated using a simple numerical integration over the peak period (example shown in Figure 2-13). It was found convenient to use this calculation method in Excel, and the result was in good agreement with that obtained using a more elaborate peak fitting routine.

The detailed calculation step has shown below.
\( Q_{\text{start}} \) is the steady-state heat flux at 45% RH prior to the peak, which is obtained by averaging the Q values manually chosen at least 500 seconds before the peak.

\( Q_{\text{finish}} \) is the steady-state heat flux at 85% RH after the peak, which is obtained by averaging the Q values manually chosen at least 500 seconds before the peak.

\[ \text{Peak Area} = \sum \left\{ \frac{(Q_{\text{start}} + Q_{\text{finish}})}{2} - Q_i \right\}, \]

\( Q \) is the measured heat flux over the region containing the peak. A typical example of the curve has shown in below.

![Figure 2-13 A typical example of a transient peak for a wool fabric found during a dynamic hot plate experiment (Naylor, 2019).](image)

The standard static hotplate testing is a good tool for assessing thermal transfer and vapor transport through fabrics. Thermal and water vapor resistance measured in steady state are mainly determined by fabric thickness and density but independent of fiber type. However, in the novel dynamic hot plate test, the moisture buffering potential could distinguish different fibers as it strongly links the amount of water vapor absorbed by the fabric.

### 2.8 Garment Test Methods

#### 2.8.1 Thermal Manikin

With the development of thermal manikins after World War II, researchers have made significant progress on heat strain and other clothing-related issues. Barely a handful of literature is still found, however, on dynamic moisture transmission and human physiological comfort.
Many studies on automotive comfort applications have been conducted, but these do not genuinely feature the thermal and physiological aspects of clothing. Table 2-3 below highlights some of the papers:

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Transient Condition</th>
<th>Environmental Condition</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Skin Temperature</td>
<td>Environmental</td>
<td>25°C, 20% RH, 80% RH</td>
<td>(De Dear, 1989)</td>
</tr>
<tr>
<td>Skin Temperature Changing Rate Index</td>
<td>Physiological</td>
<td>21°C, 70% RH, Wind 0.22 m/s</td>
<td>(Wan &amp; Fan, 2008)</td>
</tr>
<tr>
<td>Thermal Insulation</td>
<td>Physiological (3 different in walking speed) and Environmental (3 different wind speeds)</td>
<td>Not Mentioned</td>
<td>(Lu, Wang, Wan, Song, Zhang et al., 2015)</td>
</tr>
</tbody>
</table>

De Dear's study (De Dear, 1989) utilized a manikin that was either naked or dressed in 1 clo woolen or polyester suit. Most likely, it was the first experiment with the manikin on a dynamic stage to measure clothing performances. The experiment was carried out in a dual climate chamber (Figure 2-14), with one at 20% relative humidity and the other at 80% relative humidity. The manikin spent approximately half of the total time duration in each chamber. Thermal and physiological responses to changes in relative humidity were studied. According to the manikin experiment, the thermodynamic response to step changes in RH influenced the
wearer's sensible heat balance by between 37% and 42%, while the effect on the polyester was minimal. Although this experiment talked about the general clothing of all subjects, however not specified about the variation of fiber types. Focusing on physiological experience with the effect of ambient variables, these tests probably ignored the effects of the garment. Although the research goal may not depend on clothes, different types of clothing could influence the above-stated findings.

Figure 2-14 Twin climate chamber used by de dear for thermal manikin experiment in transient condition (De Dear, 1989).

Wan et al. (Wan & Fan, 2008) measured the dynamic thermal characteristics of garment ensembles crucial for transient thermal comfort. Their study proposed the use of the changing rate of the mean skin temperature of the clothed manikin-Walter as an objective index which is the Skin Temperature Changing Rate (STCR) for quantifying the dynamic thermal properties of clothing ensembles because a clothing item that causes a greater temperature rise on the manikin would impose greater thermal stress when worn on a human. With a higher index value, the user might expect a faster change in body temperature and a shorter period before reaching a potentially dangerous thermophysiological condition. The author suggested that clothes should be created to reduce the index value. According to the results of the experimental work
conducted by them, the changing rate of the mean skin temperature of the clothed manikin-Walter when switching from the "resting" to the "exercising" mode is related to the changing rate of the body temperature of a wearer wearing the same type of clothing and engaging in a similar change of body activities, which supported the validity of a proposed objective index for quantifying the dynamic thermal properties of clothing ensembles. However, their experiments were conducted with seven different types of garments, and only one human subject was used to validate their results. The environmental conditions for the manikin and human subjects were different, and it is surprising how they validated their result with two different environmental conditions and came to the conclusion of designing clothing of low STCR value without considering any particular activities such as walking, running, and cycling.

Research by Lu et al. (Lu, Wang, Wan, Song, Shi et al., 2015) provides some data for future studies on thermal comfort, human thermal strain modeling, and the design and engineering of functional clothing. In that investigation, the effects of air velocity and walking pace on the thermal insulation of the total and local clothing were examined in the investigation using 486 thermal manikin tests. The research was carried out on 17 different clothing ensembles with varying numbers of layers. Three different wind speeds (0.15, 1.55, and 4.0 m/s), as well as three different walking speeds (0.75, 1.2 m/s), were used. As a result, there are nine distinct testing scenarios. Under these nine circumstances, researchers looked at the total and local insulation in various body areas. Part I produced empirical equations to predict total garment insulation as a function of static thermal insulation, relative air velocity, and walking speed. For each body component, correction equations on the resulting local insulation were constructed in Part II, which examined the local thermal insulation of different clothes. However, they did not
mention the real environmental condition of the chamber, and their focus might be on generating and validating data from thermal manikin experiments.

### 2.8.2 Subjective Wear Trials in Transient Environments

In contrast to manikin tests, many subjective human trials have been conducted to better understand physiological reactions and human comfort levels. The findings are somewhat surprising, and, in some situations, they are opposed to each other. The reason might be the location and individual differences of humans. Many studies focus on thermal responses in humans during a step change in humidity; surprisingly, their lack of attention to clothing reveals that their research focus was different (Fountain et al., 1999) (Tsutsumi et al., 2007). A synopsis of the literature survey has been provided in Table 2-4 in an attempt to cover some of its main points.

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Transient Condition</th>
<th>Environmental Condition</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Perception</td>
<td>Environmental</td>
<td>20°C, 43% RH and 6°C 93% RH</td>
<td>(Rodwell et al., 1965)</td>
</tr>
<tr>
<td></td>
<td>Change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Sensation</td>
<td>Environmental</td>
<td>25°C, 20% RH and 80% RH</td>
<td>(De Dear, 1989)</td>
</tr>
<tr>
<td></td>
<td>Change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweat loss, Evaporation of Sweat</td>
<td>Physiological</td>
<td>5°C, 54% RH</td>
<td>(Nielsen &amp; Endrusick, 1988)</td>
</tr>
<tr>
<td></td>
<td>Change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Temperature, Heart rate, $\dot{V}_{o2\text{max}}$, Comfort Sensation</td>
<td>Physiological</td>
<td>30°C, 30% RH</td>
<td>(GAVIN et al., 2001)</td>
</tr>
<tr>
<td></td>
<td>Change</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2-4 (continued).

<table>
<thead>
<tr>
<th>Heart rate, Core Temperature, Thermal comfort, Thermal Sensation, Wetness Sensation</th>
<th>Physiological Change</th>
<th>32°C, 20% RH, and 8°C, 40% RH</th>
<th>(Laing et al., 2008)</th>
</tr>
</thead>
</table>

By mimicking the step shift between 20°C, 43% RH inside and 6°C, 93% RH outside in the British outdoors during winter, Rodwell et al. (Rodwell et al., 1965) examined the effects of clothing sorption heat on human skin temperatures and thermal sensations. Comparing the thermal perceptions of people wearing woolen and polyester ensembles with matched hygroscopic and non-hygroscopic fibers, Rodwell found no significant variations in skin temperatures and concluded that the buffering effect was of limited practical use. Nevertheless, the null results may be due to end-point issues with the five-point scale of thermal sensation utilized and the enormous 14-degree-C temperature step in their research design, which confused the influence of humidity step changes.

Humidity step changes have a more significant thermal impact when people wear wool (or other hygroscopic textile materials) because of the clothing's ability to absorb and release moisture on demand. These humidity transients have a very similar pattern on human skin. The thermal, physiological, and subjective responses of twelve male college-age participants and a thermal manikin to humidity step changes were investigated by de Dear and the team (De Dear, 1989). Using two climate chambers, volunteers spent half of the three-hour trial at a humidity of 20% and the other half at a humidity of 80% while the operative temperature was maintained constant at 25°C. Humidity levels rose and fell in tandem during the investigation. The manikin
and subjects were tested both on naked and clothes of 1clo woolen or polyester outfits. Manikin measurements revealed that the woolen ensemble's thermodynamic response to humidity step changes affected the wearer’s sensible heat balance when clothing humidity reached 37% to 42%.

In contrast, the response of the polyester ensemble was minimal. Humidity fluctuations in wool, polyester and bare cases affected the mean skin temperatures, but the effect was largest when wearing wool. When individuals were dressed in wool, their responses to humidity variations were strongest, although humidity decreases had significant short-term impacts for bare and polyester clothing, demonstrating that human skin tissue has a thermodynamic sensitivity to humidity transients. Humidity decreases have a more significant impact on temperature sensations than humidity increases, overall.

One of the first studies on the role of textile materials in thermoregulation for intermittent exercise was by Nielson and Endrusick in 1988 (Nielsen & Endrusick, 1988). Underwear consisting of five different types of fiber was tested in a standardized military clothing system in a cold environment \((T_{air} = 5^\circ C)\). The males twice repeated an interval of 40-minute cycle exercise (54\% \(\dot{V}_{o_2} \text{max}\)) followed by a 20-minute rest break. Sweat loss, sweat evaporation, and the amount of non-evaporated sweat absorbed in underwear were found to vary between the different types of fibers. The amount of sweat absorbed for natural wool and cotton fibers was greater than from underwear made from synthetic fibers. In general, neither the core temperature, mean skin temperature, onset of sweating, nor average skin wetness exhibited any difference between the underwear. Thus, for underwear and the conditions that were tested, it appears that different textile materials do not affect the heat balance of humans.

Gavin et al. (Gavin et al., 2001) compared the effects of thermoregulation on cotton and synthetic clothing ensembles that included the following: crew neck, short-sleeve T-shirts,
cycling shorts, and anklet socks. Eight males carried out an exercise regimen of 15 min rest, 30 min running (70% \( \dot{V}_{o_2 \text{max}} \)), followed by a 15 min walk (40% \( \dot{V}_{o_2 \text{max}} \)) and 15-minute seated rest at an environment of 30°C and 35% RH. The researchers also used a semi-nude clothing ensemble composed of a lycra swimsuit and PET socks. During the pre-exercise rest period, the semi-nude ensemble demonstrated a statistically significantly lower skin temperature than the clothed ensembles. During the exercise and post-exercise phase, no differences in bodily temperatures, physiological responses (heart rate and \( \dot{V}_{o_2 \text{max}} \)) nor comfort sensations were found. Synthetic clothing ensembles provided a statistically higher sweat efficiency. Although the work of Gavin et al. was performed in a relatively hot environment, the conclusion parallels the work of Nielson and Endrusick.

The results of human trials have revealed confounding effects from other studies. It should be noted that most of these studies were conducted only at the garment level, with no benchtop test data presented. As a result, there is no conclusive evidence that the fabric of one fiber type can significantly impact the other type of fiber and lead to a human temperature equilibrium.

2.9 Summary of Discussion and Proposed Study

Both test methods are capable of showing the exothermic phenomenon of textile materials when relative humidity is low to high. ISO 16533 uses the temperature increase to interpret the exothermic phenomenon, while the Naylor SGHP method uses heat flux (which can also be converted to generated heat). The temperature increase could only tell the highest temperature in a particular time but could not tell the heat generated in the long term, as the temperature increases are minimal after 60 minutes. Furthermore, ISO 16533 only measured the surface of one point in the sample, leading to a significant variance. The Naylor SGHP method
measured the average heat release on a 60±1cm × 60±1cm plate. In addition, the testing environment is quite different between these two methods. ISO 16533 measures the fabric in an environment with a single temperature, whereas Naylor SGHP has fabrics measured on the hotplate that has a different temperature from the ambient environment, similar to the fabric condition in daily use that contacts human skin.

However, ISO 16533 had an easy-to-make setup that was inexpensive. Furthermore, it was easier to control the relative humidity at low temperatures and implement a rapid relative humidity change ('step change'). The Naylor SGHP method had higher equipment requirements. The increase in relative humidity was much slower and was not as well-controlled at lower temperatures.

Using a sweat-guarded hot plate, the thermal and evaporative resistance can be measured without considering the other realistic environmental and physiological conditions that the manikin would meet. Manikin measurements are realistic in that they quantify the influence of a clothing system on the heat exchange between the entire body and its surrounding environment. Among the factors considered in manikin testing is the amount of body surface area covered by clothing and the amount of skin exposed, how body position and movement effects, the fit of garments, the effect of clothing layers, product design and features, temperature, and heat flux variation on different body segments (McCullough, E. A., 2005).

Manikins are a good starting point for testing in real-life scenarios, but they cannot be used as a gold standard because they do not deliver the best results considering all of the physiological aspects of humans. Human subject trials should be performed to fill in the gaps left by varied fabric and manikin tests. Enough human trials can shed light on the human thermal environment and comfort aspects of clothing. A type of testing (for example, fabric or garment)
that uses only one piece of equipment could not comprehend the complex thermal and physiological components. No other study has consistently described this complicated phenomenon of human thermal heat balance and comfort concerning all physiological and environmental circumstances. In addition, many manufacturers of commercial sports gear (hikers, cyclists, and others) use the term 'breathability' to describe their business advantages rather than focusing on this dynamic component of comfort and breathability.

In summary, the research described here tries to tie together the gaps identified throughout various stages of testing while taking into account various environmental and physiological variables. A series of tests will be conducted using regular fiber types with relatively same thickness level, including an ISO 16533 setup, the Naylor hotplate test, the dynamic hotplate test, thermal and physiological manikins, and human trials under a variety of test conditions and environments. This research will assist active sportswear manufacturers and consumers in designing their products better to accommodate transient physiological and environmental changes as a result of the findings. The breathability in a dynamic condition can be determined by examining the mean skin temperature, skin-microclimate temperature and humidity, fabric temperature and humidity, and heat loss data from different test results. The overall summary can be depicted in the following Figure 2-15.
Figure 2-15 Mapping the gaps between the static and dynamic benefits of fabric.
References


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CHAPTER 3: The Exothermic Effects of Textile Fibers during Changes of Environmental Humidity: A Comparison between ISO:16533 and Dynamic Hot Plate Test Method

Abstract

The exothermic effects of high regain fiber types have been described before, yet there have not been reliable tests to demonstrate these effects on the human body. Most test methods focus on steady-state measurements; therefore, these exothermic effects during changes in environmental humidity are typically not analyzed or quantified. We have conducted a set of fabric tests that shows the connection between the exothermic effect of water vapor uptake and its consequence for heat loss through the fabric in transient conditions. We have performed the ISO:16533 standard test, a dynamic hot plate test developed by Naylor to measure the exothermic property of the fabric, and dynamic regain tests to connect the dots between these tests and the water vapor uptake phenomenon. So far, these test methods have proven to be the most reliable for determining exothermic behavior of textile fiber. However, those test methods still have limitations and cannot simulate realistic environmental conditions considering an instantaneous change in the environment. This paper reflects the comparison between the two test methods and recommends directions to accurately address the theory of water vapor uptake under dynamic conditions.

Keywords

Hygroscopic fibers, exothermic property, moisture, relative humidity, clothing

3.1 Introduction

Clothing comfort is a subjective concept. Numerous attempts have been made throughout the years to quantify and explain human clothing comfort and related properties in various
methods (Das, A. & Alagirusamy, 2010). Haghi referred to clothing as the second skin and described humans as unfinished creatures without clothing, which undoubtedly draws attention to the vitality of clothing in everyday life (Haghi, 2011). Humans, particularly in recent years, have developed an excellent sense of dress for various occasions or activities such as walking, hiking, cycling, and running, and are conscientious of the garment's comfort and functionality.

Sweating is vital to ensure human comfort and is the primary means of transporting moisture from the human body. The amount of sweat released from human skin during exercise is approximately 1000 g/m²/hour, while it is only 15 g/m²/hour when the body is at rest. This means that a large amount of moisture may evaporate from the skin in the form of sensible perspiration. It supports the notion that that humans are never in a true steady state situation (Cui et al., 2020; Hai-bo & Lu, 2010). Therefore, clothing fibers may have an impact on human comfort in transient situations by absorbing and desorbing moisture.

The property of absorbing water vapor, regarded as moisture regain, is a significant feature of clothing materials. The vapor absorption may make the fabrics act as a heat reservoir, protecting the body from being exposed to more humid conditions. Gao et al. (Gao et al., 2022) mentioned in a high-water-vapor-pressure environment, hygroscopic clothing absorbs water vapor, which releases latent heat. This phenomenon raises the temperature of clothing material and the surrounding air until an equilibrium is reached. That is called the exothermic behavior of clothing materials. Thus, fibers with high moisture regain would better buffer humidity and temperature variation when switching the environment.

The exothermic and endothermic properties of textile materials occur when there is a change in the external relative humidity (RH) so that the materials can absorb or desorb the moisture, which leads to energy exchange. The exotherm effect of a textile is may directly
affects physiological comfort. Clothing creates a microclimate between the skin and the clothing. The surrounding environment and the conditions at the skin determine the levels of temperature and humidity of the skin microclimate. For example, a change in ambient humidity from low to high can create a sticky perception of the microclimate; similarly, perspiration generation during exercise can create a damp environment in the microclimate. Clothing may absorb both liquid and moisture vapor; however, depending on the type of clothing worn, vapor transfer via clothing will affect the microclimate, which affects the body's core and skin temperature. The evaporation of sweat from the skin is influenced by several factors, including thickness, wettability and permeability of the clothing. In addition to ambient humidity and temperature, microclimate conditions are determined by the sweat evaporation and fabric properties (Berglund & Gonzalez, 1977; Davis & Bishop, 2013; Pascoe et al., 1994).

However, no test method currently exists to address such issues in dynamic conditions, specifically during a change in environment. Multiple authors have recognized that the thermophysiological components of clothing comfort cannot be entirely described by laboratory measurements of steady-state heat and moisture vapor resistance (Barker, R., 2011; Barker, Roger L., 2002; Huang, 2006; Huang, 2016; Kaplan & Okur, 2010; Kim et al., 2003).

Few attempts have been made to quantitatively assess comfort attributes in a changing laboratory environment (Naylor, 2019). Among them, ISO 16533 (ISO, 2014) and the dynamic hot plate method developed by Naylor (Naylor et al., 2017) are the most reliable in attributing these properties. However, those methods still have limitations and may be modified instead. This paper addresses the limitations and recommends changes based with experimentation on the above-mentioned methods.
3.2 Materials and Methods

3.2.1 Materials

*Test Materials and Physical Properties*

Knitted fabrics made from wool (yarn diameter \( \leq 17.5 \) \( \mu \)), cotton, viscose, and polyester were received from Australian Wool Innovation for experimentation. The materials were selected based on their moisture regain behavior. All fabrics are of similar thickness, as it was noted that the fabric thickness has a significant effect on the thermal properties of the textile materials. The details of the fabric used in the experiment are listed in Table 3-1.

Table 3-1 Details of the experimental fabrics.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Sample ID</th>
<th>Fabric Composition</th>
<th>Fabric Structure</th>
<th>Weight (g/m(^2))</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wool</td>
<td>100% Merino Wool</td>
<td>Jersey knit</td>
<td>213</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>Cotton</td>
<td>100% Cotton</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>Polyester</td>
<td>100% Polyester</td>
<td>Rib Knit</td>
<td>199</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>Viscose</td>
<td>100% Viscose</td>
<td>Jersey Knit</td>
<td>204</td>
<td>0.67</td>
</tr>
</tbody>
</table>

3.2.2 Methods

*Dynamic Regain Test*

The regain of the fiber is considered to be the driving parameter to explain the exotherm effect of the fibers. The dynamic regains test was carried out to see if there were any significant differences in the rate of water vapor uptake from the environment or in the regain rate between the fiber types. Three different principles have been followed to determine the exotherm effect in
various ways. For the first two principles, the traditional oven dry method was followed for two different experiments with duration 3hrs and 24hrs, respectively.

**Oven Dry Method**

The fabric samples were cut into square shapes weighing approximately 10 g. After weighing, the fabrics were dried in a blow-dryer oven at 105°C for 2 hours. The fabrics were then placed in a plastic bag immediately and sealed after being left in the oven. The bag was then placed in a desiccator to maintain proper humidity. The experiment was carried out in an air-conditioned lab room where a temperature of 20°C±0.5 and a RH of 65%±0.5 is maintained. The fabric samples were kept on a stand placed in a particular type of digital scale with a glass door closed on four sides, which helped to avoid the variation in results due to the airflow from the sides (Figure 3-1). The fabric samples were then allowed to regain moisture from the air for 3 hours, and their weight readings were recorded every 5 minutes. For the other experimental setup, the fabric samples were allowed to regain moisture from the environment for about 24 hrs. If the initial sample weight is $w_i$ and the final weight is $w_f$, the moisture regain ($m_r$) can be calculated from the following equation

$$Moisture \ Regain \ (m_r) = \frac{w_f - w_i}{w_i} \times 100\% \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (1)$$

**2-Phase Humidity Change**

This test was carried out using a small environment chamber and changing the RH from 45% to 85% at two intervals while keeping the temperature constant at 20°C. The environment chamber (*ESPEC, North America*) can control RH from 10% to 95%. After weighing the samples, oven drying has performed at 105°C for 2 hours. The samples were sealed while leaving the oven and kept in a sealed plastic bag. The plastic bag was always kept in a desiccator to maintain a stable surrounding condition. The chamber's RH was initially set to 45%, the
sample was placed on the scale mounted inside the chamber, and weight was recorded at every 5 minutes interval. After 3 hours, the humidity increased to 85% and the data record continued for the following 3 hours. The fabric has undergone two stages in the humidity change; the first transition happened from 0% to 45% RH, then 45% RH to 85% RH.

![Figure 3-1 Dynamic regain rate test experimental setup. (a) The digital scale consists of a glass door closed from four sides which will avoid variation in result due to airflow from sides. (b) Environmental Chamber set up for 2-phase humidity change experiment (c) Digital scale placed inside of the climate chamber.](image)

**ISO16533 set up**

ISO 16533 is a standard testing method to measure the exothermic and endothermic properties of textile materials when changing RH. Two constant containers with 65% and 20% concentrated sulfuric acid solution were used to create the 10% and 90% RH environment. The ISO 16533 setup is shown in Figure 3-2. An MSR sensor (MSR Electronics GmbH, Switzerland) which could measure both temperature and humidity was placed in each of the containers to measure the conditions of the containers. The test specimen was clipped to the MSR sensor to record the temperature change over the transient RH. The test specimen was cut into 5 cm x 5 cm and dried in the oven at 105 °C for two hours, then conditioned in a desiccator until immediately before testing. A sample specimen was folded in half and the sensor probe was placed in the
center of the upper half of the area to be tested. The specimen was folded again to wrap the sensor probe. This sample folding technique was followed as per the standard. Details of the step are shown in Figure 3-3. The fabric was clipped on the sensor and placed in the constant humidity container to condition for a minimum of 3 hours. After more than 3 hours of conditioning, all sensors in two flasks switched on to record the temperature and RH for 30 minutes. Then the plug of the low-humidity chamber with the test specimen was removed and transferred to the high-humidity container. The data record continued for another 1 hour. The temperature change ($\Delta T_{exo}$) can be derived from the equation 1. $T_{peak}$ could be read from the sensor mounted with specimen. $T_{blank}$ could be read from the sensors without specimen in the flask.

$$\Delta T_{exo} = T_{peak} - T_{blank} \ldots \ldots \ldots \ldots (2)$$

Where, $T_{peak}$ is the peak temperature ($^\circ$C), determined using an MSR sensor with the test specimen mounted on the sensor probe in the high humidity container during the test. $T_{blank}$ is the peak temperature ($^\circ$C), determined using an MSR sensor with the test specimen mounted on the sensor probe while changing from a low humidity container to high humidity container. $\Delta T_{exo}$ is the difference in the peak temperature ($^\circ$C), determined between a state of fabric temperature with low humidity and after the transition to a high humidity chamber.
Figure 3-2 ISO 16533 setup for measuring the exotherm effect in the fabric. (a) A glove box of dimension 45 cm ×45 cm ×40 cm placed into a fume hood (b) Constant humidity container with temperature-RH sensor (c) Size comparison of two sensors, temperature sensor (left), temperature and humidity sensor (right).

Figure 3-3 Fabric folding process as per ISO 16533 standard. (a) Sample size (b) Sample specimen is folded to half (c) Sensor probe inserted into the sample specimen, folded again, and clipped.

Three different principles were followed to check the effect of different sensor sizes (within the ISO-16533 standard) and whether the folding principle has any effect on the exothermic property of the fabric. Two external sensors, both temperature and humidity sensors (larger in size but within the dimension of sensors mentioned by ISO 16533), and only the temperature sensor (smaller in size but within the dimension of sensors mentioned by ISO 16533) have been used to check the effect of sensor size by two different experiments; however, the third experiment was used to check if the folding techniques have an impact on the overall
value of the heat gain from the two previous experiments. The details of the experimental procedure are shown in Table 3-2.

Table 3-2 Summary of the three experiments measuring the exotherm effect by ISO 16533.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Size</td>
<td>Large Temperature-RH sensor (Within the ISO Standard range)</td>
<td>Small Temperature Sensor (Within the ISO Standard range)</td>
<td>Small Temperature sensor (Within the ISO Standard range)</td>
</tr>
<tr>
<td>Fold procedure</td>
<td>Same fold as ISO</td>
<td>Same fold as ISO</td>
<td>Both fabrics from Exp 1 and 2 are used and clipped.</td>
</tr>
</tbody>
</table>

**Dynamic Hot Plate Test**

Based on the operation of a sweating-guarded hotplate, Naylor developed a novel approach for measuring the dynamic moisture buffering potential of fabrics by looking at the fabric's exotherm effect during transient humidity change by dynamic hot plate (DHP) shown in Figure 3-4. The hotplate operation mode is the same as the dry hotplate test, while the RH in the chamber becomes dynamic instead of static. The fabric sample (size 60±1 cm× 60±1 cm) is first equilibrated on the hotplate in an environment with low RH (45%). After the heat flux becomes stable, the RH is rapidly increased to 85%. With an increase in RH, the fabrics absorb moisture and generate heat, which reduces the heat flux applied to the plate. The area of the transient peak of the heat flux is a measure of the moisture buffering potential. The transient heat flux peak area was calculated using a simple numerical integration over the peak period. Three repetitions for
each fiber type were taken. The total thermal resistance of the fabric plus the air layer could be calculated using the following equation.

\[ R_{ct} = (T_s - T_a)A/H_c \ldots \ldots \ldots \ldots (3) \]

Where, \( R_{ct} \) is the total resistance to dry heat transfer provided by the fabric system during the steady state and air layer (K*m²/W), \( A \) is the area of the plate test section (m²), \( T_s \) is the surface temperature of the plate (°C), \( T_a \) is air temperature (°C) and \( H_c \) is power input (W).

![Figure 3-4 Dynamic hot plate by Thermetrics.](image)

### 3.3 Test Results and Analysis

#### Dynamic Regain Test

**Oven Dry Method**

Figure 3-5 shows the moisture regain graph (%) versus time (minutes) for all fabric samples. All fabrics exhibited a similar pattern curve, having two phases. In the first phase, from the start of the test to about 20-30 minutes, the moisture was absorbed at a high rate due to the high RH gradient in RH (0 to 65%). After this rapid initial phase, the fabrics continued to slowly absorb water vapor from the environment until the end of the experiment. As observed before, all fabrics did not reach their expected regain value after 3 hours, but the water vapor absorption ...
rate in the wool and viscose samples was greater than in the cotton samples. At 30 minutes after the first start of the rapid uptake phases, the values for wool, viscose, cotton, and polyester were 7.0%, 7.4%, 4.7%, and 0.3%; respectively; these values are approximately 50% of their expected percentage of moisture regain percentage.

The RH gradient between textile samples and the environment started to decrease as time passed. All curves had a "transition point," after which the moisture regain rate only increased slowly (but steadily). The consequence of this curve flattening, due to the fundamental physics of water vapor diffusion and transport, is that the exothermic effect will also decrease as it is directly related to the amount of water vapor uptake rate (curve steepness). Thus, from these primary curves, an estimate of the duration of the exotherm effects can be derived. Polyester, if it shows any exotherm effect, will have a short effect of up to 10 min max. The effect for cotton is likely to last up to 40 minutes maximum as the uptake rate (slope) becomes small after that. The expected effect for wool and viscose could be up to 80-100 minutes (two times as long) and even longer.
Figure 3-5 Moisture regain percentage for different kinds of Textile fabrics over time in minutes over 3 hours; all samples are oven-dried and then tested in the same environmental conditions with 65% humidity and 200°C. The two vertical dotted lines indicate the transition of the fabrics to a lower absorption rate at 20 minutes (cotton) and 40 minutes (wool and viscose).

Figure 3-6 further shows the rapid initial increase in regaining, after which a very long and slow process to reach the final steady state Regain follows, up to 24 hours. With the focus on the regain rate measurement in the first hour, the experiment was conducted at the 1 Hz sampling rate. Figure 3-7 shows the regain values measured after 24 hours of the experiment. With this method, all values appeared consistently slightly (about 1-2%) below the reported values from the literature.
Figure 3-6 Longer-term Regain rate for wool, cotton, and viscose fabrics, measured at larger time intervals up to 5 hours and after 24 hours (the next day). Note the time axis in minutes. The Regain rate of detailed measurements were obtained with 1Hz weight measurements in the first 60 minutes.

Figure 3-7 Moisture regain percentage measured by oven dry method (24 hrs.).

2-Phase Humidity Change

During a 2-phase humidity change experiment, shown in Figure 3-8, all of the curves showed similar patterns based on the absorbency capacity of the fabric. Although it seemed that after 180 minutes (3 hrs.) of the experiment, all of the fiber types had lower regain values than
the literature value. For the initial period of three hours, wool and viscose showed some degree of moisture regaining behavior; however, after switching the humidity to a higher value, the behavior pattern looked more prominent, increasing a value of 3.46% to almost 10% for wool and 2.66% to almost 9% for viscose. As usual, polyester did not show any responses at all. Cotton responded between wool and polyester. The result indicated that a higher humidity gradient accelerated the moisture absorption behavior of the textile fiber and helped it regain equilibrium faster.

Figure 3-8 Moisture regain rate calculated from 2-phase regain test by environmental chamber.

From these experiments, it was evident that viscose and wool absorbed the highest amount of moisture, as expected. Both fabrics are hygroscopic in nature. In the case of wool, the \(-\text{NH}_2\) & \(-\text{COOH}\) groups help to absorb moisture. The morphology of wool is complex and water vapor was absorbed slowly; after 3 hours of experiment, the wool had not reached its final equilibrium value. In the case of viscose and cotton, the \(-\text{COOH}\) groups help absorb moisture. The moisture regain rate of viscose was much higher than that of cotton. This might be due to morphological and structural differences. Viscose has a circular cross section and provides more
surface area than cotton for moisture absorption (Das, B. et al., 2008; Jiang et al., 2020). Moisture regain rate varies significantly with the type of fabric; polyester absorbs the least amount of moisture. The first phase for polyester is the shortest; on the moisture regain rate of other hand, the viscose and wool was the highest.

Thus, the conclusion of these dynamic regain experiments should be that the initial rapid regain uptake rate will be dominant for the realistic exotherm effects as that is directly related to the regain rate. This means that although wool and viscose have a higher steady-state regain and their initial regain rate is higher than that of cotton, the differences may be predicted, in reality, smaller than their end regain values. Instead of a difference of 6 grams of water vapor per 100-gram fabric (e.g., 13 for wool versus 7 for cotton), we may only expect a difference in generated heat from 2 grams of absorbed water vapor per 100-gram fabric (i.e., 6 g versus 4 g). Still, these experiments show that the exotherm effect differs significantly between wool/viscose, cotton, and polyester.

ISO 16533 Test

These three experiments (E1, E2, E3) aimed to determine the optimal protocol for these exothermic tests to detect reliable and significant differences among different types of fiber. The experiments focused on determining the effect of mass (increasing sample volume) and temperature sensor size. A larger sample (double) folded in the same area was expected to have a larger increase in temperature as measured by the sensor folded within the sample. The smaller temperature sensor was expected to have better intimate contact with the sample and thus better register the temperature changes. Figure 3-9 indicates that the three experiments on the same type of fabrics had increasing test results in terms of temperature increase. From E1, viscose fabrics had the highest temperature increase of 5.87°C, while polyester had the lowest or almost
no temperature increase. Cotton increased by 4.80°C when switching the fabric from low to high humidity, while for wool, it was 5.64°C. Also, viscose had the highest temperature increase of 6.17°C and 6.85°C, respectively, for experiments 2 and 3. In comparison, wool had an increase of 5.94°C and 6.79°C, and cotton showed an increase of 5.29°C and 6.31°C, respectively, for E2 and E3. Polyester did not show any responses at all in the three experiments.

Figure 3-9 Summary of the three experiments for ISO 16533, results expressed in mean ± S.D.

Tukey's HSD post hoc test was used for each experiment to see if there was a mean difference in temperature increases between the fiber types using different principles. ANOVA yielded statistically significant differences for each pair of fiber types in each experiment, while showing no statistically significant differences between wool and viscose. This means that, for the ISO 16533 test, during step change of humidity from low to high, the differences in mean temperature increased among each pair of wool, cotton, viscose, and polyester are significant, while the pair of wool-viscose did not show any significant results for the increase in mean temperature (Table 3-3). Even using a small sensor size minimizes the differences between fiber
types. In Table 3-4, it is evident that there are no statistically significant differences between wool, cotton and viscose in terms of their temperature while changing the humidity from low to high. Increasing thickness yielded significant differences between the fiber types; also, in this case, the wool-viscose pair did not show any differences in temperature increase (Table 3-5). Therefore, ISO 16533 can demonstrate the existence of exothermic effect but there is not enough evidence to say that the ISO 16533 test cannot differentiate between fiber types of relatively the same moisture regain percentage, for example, wool (14-19%) and viscose (13%) (Hearle & Morton, 2008).

Table 3-3 Tukey's HSD each pair summary for the sensor size effect in the temperature increase for Experiment 1.

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Difference</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscose &gt; Polyester</td>
<td>5.9</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Wool &gt; Polyester</td>
<td>5.6</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Cotton &gt; Polyester</td>
<td>4.8</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Viscose &gt; Cotton</td>
<td>1.0</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Wool &gt; Cotton</td>
<td>0.83</td>
<td>0.0004</td>
</tr>
<tr>
<td>Viscose &gt; Wool</td>
<td>0.23</td>
<td>0.2705</td>
</tr>
</tbody>
</table>

The '>' sign indicates temperature comparison for two different fiber types.
Table 3-4 Tukey's HSD each pair summary for the sensor size effect in the temperature increase for Experiment 2.

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Difference</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscose &gt; Polyester</td>
<td>6.2</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Wool &gt; Polyester</td>
<td>5.9</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Cotton &gt; Polyester</td>
<td>5.3</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Viscose &gt; Cotton</td>
<td>0.88</td>
<td>0.0193</td>
</tr>
<tr>
<td>Wool &gt; Cotton</td>
<td>0.65</td>
<td>0.0797</td>
</tr>
<tr>
<td>Viscose &gt; Wool</td>
<td>0.23</td>
<td>0.7436</td>
</tr>
</tbody>
</table>

The '>' sign indicates temperature comparison for two different fiber types.

Table 3-5 Tukey's HSD each pair summary for folding procedure effect in the temperature increase for Experiment 3.

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Difference</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscose &gt; Polyester</td>
<td>6.9</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Wool &gt; Polyester</td>
<td>6.8</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Cotton &gt; Polyester</td>
<td>6.3</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Viscose &gt; Cotton</td>
<td>0.54</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Wool &gt; Cotton</td>
<td>0.48</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Viscose &gt; Wool</td>
<td>0.06</td>
<td>0.0975</td>
</tr>
</tbody>
</table>

The '>' sign indicates temperature comparison for two different fiber types.
**Dynamic Hot Plate Test**

In this test, the change of heat flux input of the increase in hotplate as a function of the humidity is of our interest. Fabrics generate heat as humidity increases; therefore, the hot plate’s heat flux input would be reduced to keep the temperature constant. The area of reducing heat flux over time represents the heat that is generated by the fabrics when they absorb moisture from the ambient environment. Since each fabric had different thermal resistance, all heat flux curves were all calibrated to the same baseline. The ambient temperature and RH are shown below in Figure 3-10. The ambient temperature was stable and well controlled, while the ambient RH took some time to increase. The chamber took 23 minutes to increase the RH from 50% to 80% and 40 minutes to reach 85%.

![Ambient relative humidity and temperature](image)

**Figure 3-10** Chamber RH% and temperature during the hot plate test.

The change in heat flux of the fabrics when ambient RH increased from 45% to 85% is shown in Figure 3-11. Each curve of fabric samples showed 10 minutes (600s) heat flux at a stable state and 40.8 minutes (the 2450s) after increase in RH. For all fabrics, a decrease in the
heat flux could be observed, which means that the fabrics generate heat when switching the RH from low to high. The curves had some noise and fluctuation, especially at the end of each trial, which was caused by the slow increase in RH. Wool fabrics had a relatively larger peak than polyester fabrics and cotton fabrics. Viscose had a peak pattern close to wool fabrics. To further analyze the curve, the peak area was calculated for each fiber type.

Figure 3-11 Heat flux change of fabrics when changing from low relative humidity to high relative humidity.

The integration of the heat flux peak over time is the heat generated by the fabrics. Figure 3-12 shows the integration results of the heat flux curves, and detailed heat release data are shown in Table 3-6. The average heat flux value for 10 minutes before switching RH was calculated as the baseline of steady status at 45% RH. The difference value between the baseline and each data point was determined and multiplied by the 10 second value as the data were recorded every 10-second interval. The integration area obtained from the heat flux curve would be the heat release due to the humidity change. It is evident that wool and viscose had higher heat release than cotton and polyester and had significant differences.
Figure 3-12 Integration area under the heat flux change curve.

Table 3-6 Heat release of fabrics from hotplate tests.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Average Heat Release (J/m²)</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>12050</td>
<td>973</td>
</tr>
<tr>
<td>Cotton</td>
<td>5686</td>
<td>1666</td>
</tr>
<tr>
<td>Viscose</td>
<td>10447</td>
<td>364</td>
</tr>
<tr>
<td>Polyester</td>
<td>5541</td>
<td>2408</td>
</tr>
</tbody>
</table>

Comparison of Test Methods, and Relationship with Moisture Regain Rate Test

Both test methods showed the exothermic phenomenon of textile materials when the RH from low to high. ISO 16533 used the temperature increase to interpret the exothermic phenomenon, while the DHP test method used heat flux (which can also be converted to generated heat). The temperature increase could only tell the highest temperature in a certain time but was not able to tell the heat generated in the long term as the temperature increases were very small after 60 minutes. Furthermore, ISO 16533 only measured the surface of a single point
on the specimen, leading to a great variance (Figure 3-5). The DHP method, on the other hand, measured the average heat release on a 60±1cm×60±1cm scale and generated more heat with that much larger sample. However, ISO 16533 had an easy-to-build setup and was easy-made and inexpensive. Furthermore, it was easier to control the RH at low temperatures and implement a rapid change in RH ('step change'). The DHP method had higher equipment requirements. The increase in RH was much slower and not as well controlled at lower temperatures. It is envisioned that an additional, in-depth, mathematical analysis of the DHP data, with the slower humidity increase, may be able to separate the rate of change and convert it to data similar to the ISO16533 method.

The conclusions are that both methods have limitations but potentially have the capacity to show fiber-type differences in exothermic response. Further, more detailed data analysis and mathematical modeling of the diffusion processes that guide the water vapor uptake (regain) with its exothermic effects, and the convective processes that drive the cooling of the fabric, will further allow to reliably determine the differences between fiber types, especially at lower temperatures. Furthermore, the ISO16533 test may allow variations with larger samples and longer exposure times to determine other fiber-type differences, this slow response in temperature is unusual if measured in normal room temperature. as the low-temperature responses are much slower than measured at normal room temperature.

The goal of ISO 16533 and DHP was to connect the known differences between static fiber properties (regain) with the dynamic exothermic properties of fabrics. As it is widely known and accepted from the literature, the regain of wool (water vapor uptake from "bone-dry" to 65% RH) is around 13-15 g/100g dry fiber, whereas the regain for cotton is around 7-8 g/100g dry fiber. These values could be considered static as they represent the steady state in these
fabrics after equilibrating with the environment, which may take many hours, up to 24 hours. Water vapor uptake is an exothermic effect; therefore, a larger water vapor uptake by wool, compared to cotton, should result in a significantly higher increase in heat release.

However, this would assume that the water vapor uptake process is instantaneous, and it can be expected from transport physics phenomena that the process is dynamic in reality (i.e., it will take time to absorb moisture). Thus, dynamic tests should be done to determine practically relevant differences between wool, viscose, cotton, and polyester as they happen with time after a change in humidity, as that is what a wearer would perceive, not just the static endpoints.

3.4 Conclusion

The fabric test methods described in this paper have not led to a clear and convincing test procedure that demonstrates the difference between hygroscopic fibers for practical applications. This seems to be due to the complex time dependencies and dynamics in this multistep adsorption process. Even with a 'perfect' step change in RH of the environment, the water vapor uptake of the fabric samples, due to the regain effect, is not instantaneous, but takes time. The consequence here is that water vapor uptake needs time; after that, temperature build-up and cooling-down are also processes that have specific time constants. More studies will be needed to develop a set of test methods that allow a good prediction of these effects and their relevance to human thermal comfort.
References


CHAPTER 4: A New Approach to Demonstrate the Exothermic Behavior of Textiles by Using a Thermal Manikin: Correction Methods of Manikin Model

Abstract

Textile fibers with high moisture regain can develop exothermic heat when exposed to highly humid environments. However, there are still contradictions between the relative benefits of that behavior since there have not been any reliable test methods to demonstrate these effects on the human body. Previous works in the literature suggest that exothermic behavior exists and demonstrate this through fabric testing. However, fabric testing does not simulate actual environmental conditions and cannot predict the physiological attributes of clothing. In contrast, a manikin can simulate clothing and physiological attributes in a more realistic environment. However, there has not been any evidence of demonstrating this exothermic effect by manikin testing. The current work describes a new approach to demonstrate the exothermic behavior of textiles by using a thermal manikin. A thermal manikin was dressed in four different types of clothing (wool, cotton, viscose, polyester) and moved from a low relative humidity chamber (35%) to a high relative humidity chamber (85%). A transient reduction in heat from different segments of the manikin body was observed as a peak to maintain the manikin skin temperature at 35°C, indicating a significant component of thermal comfort during transient conditions. A key to this new approach is that this research presents a set of correction methods for the manikin model during transient conditions, while considering environmental factors. Although the results suggested a clear difference between hygroscopic and non-hygroscopic fiber types, further studies will be needed to quantify the difference between hygroscopic fibers that allow good prediction of the exothermic effects and their relevance for human thermal comfort.
Keywords
Thermal manikin, exothermic effect, textile fibers, transient conditions.

4.1 Introduction

Comfort in clothing is strongly affected by perceptual aspects. Over the years, there have been many attempts to measure and describe human clothing comfort and related properties in different ways (Das & Alagirusamy, 2010). Haghi mentioned clothing as a second skin, referring to humans as unfinished beings without clothing, which undoubtedly draws attention to how vital clothing is in day-to-day life (Haghi, 2011). Humans, especially in recent days, have a great sense of clothing for different occasions or activities and are very conscious of the comfort and functionality of clothing. So, there is a need to measure clothing comfort and other attributes. Clothing comfort, thermal insulation measurement, dry and evaporative heat resistance, and water vapor transmission rate are vital parameters for evaluating comfort and skin-textile microclimate behavior. Several test methods can demonstrate skin-textile interaction using sweating-guarded hot plates and thermal manikins by addressing these parameters. For example, ASTM 1868 uses a sweating-guarded hot plate to determine thermal and evaporative resistance. ASTM F1291 and F2370 use a thermal and sweating manikin, respectively, to measure thermal insulation and evaporative resistance (American Society for Testing and Materials, 2016; ASTM, 2016; ASTM, 2017). Most test methods deal with measuring the fabric or clothing parameters under steady-state conditions. These test methods are widely practiced throughout the world to determine clothing parameters related to heat transfer in a steady state condition. However, in real-life scenarios, humans are rarely in a steady state. None of the test methods can describe the scenario, considering combined environmental factors such as relative humidity (RH), temperature, and wind speed. Therefore, these parameters should be addressed, and research
should be done to measure clothing parameters during the transient change in environmental conditions to better understand clothing behavior, physiological parameters, and clothing design for specific uses.

This paper aims to show the relationship between the human skin-clothing interaction in a transient environment, especially during the change in RH from low to high, by using a thermal manikin. Hygroscopic natural textile fibers such as cotton and wool have a significant sorption property in transient conditions, especially during a rapid change in ambient humidity (Spencer-Smith, 1976). This property may have been underestimated over the years and is overshadowed by the increasing use of synthetic fibers in the application of functional clothing. The nature of heat loss from hygroscopic fibers during transient conditions may significantly affect human comfort if this clothing can be worn in a suitable atmosphere. Over the years, several researchers in this field have developed new test methods in a transient environment condition. Geoffrey Naylor (Naylor, 2019a) stated the importance of measuring thermo-physiological components under transient environmental conditions. He presented a novel method to quantify the moisture buffering potential using a dynamic hot plate. Other authors describe the necessity for a standard for non-steady measurements. Huang (Huang, 2006) discussed the sweating-guarded hot plate, mentioning its pros, for example, the reproducibility and repeatability of the data, and cons, for example, plates limitation in measuring clothing comfort and related parameters in transient states. The paper also highlighted the need to assess fabric characteristics under transient conditions. Barker (Barker, 2011), in a chapter of the book ‘Improving comfort in clothing’, mentioned the necessity of developing laboratory measurements in non-steady-state tests for heat stress and comfort. To measure the exothermic and endothermic properties of textiles under transient conditions, ISO 16533 has recently become available (ISO, 2014). However, this
method has limitations and cannot predict human sweating and heat loss within clothing. This test method uses a small piece of fabric (5cm ×5cm) folded around a temperature sensor. It cannot simulate and fully explain the benefit of hygroscopic exotherm or endotherm fibers in a real-life scenario. Until now, no test methods can simulate clothing behavior under transient conditions. A sweating thermal manikin simulates human physiological and comfort responses in a steady state, but it may also be used for non-steady-state and transient conditions (Farrington et al., 2004). Thermal manikins in a controlled climate chamber may simulate real-life examples of human comfort in transient conditions. This paper will explain the challenges and opportunities for developing such test methods using a thermal manikin.

**Mechanism of exotherm effect and moisture buffering effect**

The detailed mechanism of the exotherm effect of hygroscopic fibers was well described by Spencer Smith (Spencer-Smith, 1976). The paper mentioned that in transient conditions, the hygroscopic material faces an initial increase in temperature to the value at which the water vapor pressure is in equilibrium with the fabric/fiber regain. When clothing material is brought into a high relative humidity (RH) room, water is absorbed by the clothing, and the absorbed water liberates the latent heat. In simple terms, this raises the temperature of the material and the surrounding air until an equilibrium is reached between the local temperature and the RH of the air and the regain of the material. A study by Cui et al. (Cui et al., 2020) showed that for the heat release of hygroscopic fibers, their moisture-absorbing capacity, the number of hydrophilic groups, and the strength of the binding force between hydrophilic groups are dominant factors. Clothing has very low specific heat (0.3 J/g K). Depending on the extent of moisture regain of the material, the immediate effect of an increase in RH is to increase the temperature of the clothing material. This property of hygroscopic fibers was first noted by Cassie et al. (Cassie et
al., 1939). Later, Li et al. (Li et al., 1992) further investigated this behavior using wear trials. They studied subjective perceptions of clamminess (sensation of humidity and wetness) and thermal sensations and their relationship with a kinetic sorption model under certain activity conditions. On the basis of this study, the authors concluded that the polyester garments were clammier to the wearer than the wool garment. Many studies (Behmann, 1971; Kawabata et al., 1982; Umbach, 1980) have been conducted to make comparisons among hygroscopic and non-hygroscopic fibers in steady-state conditions; however, there was no clear indication of how hygroscopic fibers such as wool, cotton, and viscose would behave under transient environmental conditions.

4.2 Research Design

4.2.1 Method

In this research, a thermal manikin was used to demonstrate the exotherm effect of the fabric while the manikin was switched from low relative humidity to a high relative humidity chamber.

4.2.2 Equipment and Facilities

Sweating Thermal Manikin

The NCSU sweating thermal manikin system is a “Newton”-type instrument designed to evaluate the heat and moisture management properties of clothing systems. The size of a Newton Manikin is 50th percentile of a western male. This instrument simulates the production of heat and sweat, making it possible to assess the influence of clothing on the thermal comfort process in a given environment. Simultaneous heat and moisture transport through the clothing system and variations in these properties over different body parts can be quantified. The manikin consists of several features designed to work together to evaluate comfort in clothing and heat
stress. The surface of the manikin is divided into 34 separate sections, each of which has its own sweating, heating, and temperature measuring system. Apart from a small portion of the face, the entire surface of the manikin can sweat continuously, but sweating was not used in this study. The thermal zones of a manikin are shown in Figure 4-1. The blue segments were covered with a long sleeve top sample and used to record the data (torso zone); the other zones were covered with the same clothing in each experiment. The mean surface temperature (skin) of the manikin was maintained at 35°C.

![Figure 4-1](image)

**Figure 4-1** Different segments of a Newton thermal manikin.

**RH and temperature sensor**

Two temperature and RH dataloggers (MSR, Switzerland) were placed on the manikin, between the shirt and the manikin surface (about 1-2mm distance from the manikin skin) in front and back. These were intended to measure the dynamic microclimate and ambient environment of the manikin.

**Sampling and Test Specimens**

The details of each of the samples are shown in Table 4-1. Two repetitions of each of the samples were used for the data analysis. The full-sleeve garments were made according to the size of the manikin to obtain a close fit. The fitting on the manikin of four garments for the test is shown in Figure 4-2. To minimize the bellow effect at the waist, the bottom of the shirt was
tucked into the sports shorts. The sample was conditioned for 24 hours in a standard testing atmosphere. The thickness and weight of the fabrics were kept as close as possible for each of the samples. The sample thickness was measured according to ASTM D 1777 test option 1. A total of 6 specimens (15cm × 15 cm) were measured with a thickness gauge at an applied pressure of 0.6 psi (4.1 KPa) and a mean value. Weight was measured according to the ASTM D3776 small swatch option. In total, three specimens (15cm × 15 cm) were weighed in analytical balance, weight was calculated in mass per unit area (g/m²), and an average of the data was taken.

Table 4-1 Details of the sample.

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Thickness (mm)</th>
<th>Weight (g/sq. m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Wool Jersey Knit</td>
<td>0.69</td>
<td>213</td>
</tr>
<tr>
<td>100% Cotton Jersey Knit</td>
<td>0.65</td>
<td>188</td>
</tr>
<tr>
<td>100% Viscose Jersey Knit</td>
<td>0.67</td>
<td>204</td>
</tr>
<tr>
<td>100% Polyester Rib Knit</td>
<td>0.69</td>
<td>199</td>
</tr>
</tbody>
</table>

Figure 4-2 Thermal manikin dressed in test garments.
4.2.3 Test Procedures

This test had two environmental conditions to accommodate the rapid change in relative humidity from low to high. The low-humidity room was a side lab room outside the climate chamber. Two dehumidifiers were used to reduce the RH in this room down to 35%. The side room temperature with the humidifier working was around 25°C (no temperature control system in this room) and recorded continuously. The climate chamber was used to control the high relative humidity and to equalize the temperature of the side room. Four humidifiers were used to increase the chamber’s RH to 80% (as high as possible). In each room, the spot where the manikin was placed was labeled so that the manikin measurement was performed every time at that exact location, controlling convection. The thermal manikin control system is designed to control the mean surface temperature to drift no more than ±0.2°C during the test. The details of the testing conditions are shown in Table 4-2.

Table 4-2 Test Conditions of the Chambers.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lab Room</th>
<th>Climate Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (°C)</td>
<td>25±0.5°C</td>
<td>25±0.5°C</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>35±5%</td>
<td>80±0.5%</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>0.4-0.5</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td></td>
<td>(normal condition)</td>
<td>(normal condition)</td>
</tr>
</tbody>
</table>

The test garments were weighed and dressed in the standing manikin prior to the test. Sports shorts were used to fixate the bottom part of the shirt to minimize the bellow effect and better fit the garment to the manikin skin. The dressed manikin was brought to the laboratory room with low relative humidity at the labeled spot, and the system was allowed to reach steady state (i.e., the mean surface temperature of the manikin and the power input remained constant at
±3%). Thirty minutes were generally sufficient to reach equilibrium. After that, the manikin was moved to the climate chamber as quickly as possible at the labeled spot, and the system was again allowed to reach a steady state. One hour was sufficient to reach equilibrium after the transition. Finally, the garment mass was weighed after the test. Hand gloves were always used when handling the manikin and garments.

4.3 Result and Discussion

Heat Flux Data with Time

Figure 4-3 shows an overview of all the torso segments (covered with a long sleeve shirt) during the test. The graph shows the transition after 1800 seconds. There were significant differences between the responses of the different segments; some segment curves went down for a while and then recovered or sometimes ended at a higher value. The curves of some other segments almost immediately reached that higher value.

Moreover, some deviations in the starting heat flux before the transition were observed in the waist and lower back regions. One possible reason for these deviations could still be the size of the air gap between the manikin and the fabric, even though the shirts were designed to be tight fitting. As shown in Table 4-2, the temperatures in both chambers were not exactly the same, and therefore the overall heat loss was different. However, even when the differences in environmental temperature were corrected for, the differences in steady-state heat flux still existed. This deviation is most likely due to differences in airflow in both chambers, which affects overall insulation of the clothing and its attached air layers. These airflow differences are difficult to control. Even with the temperature correction, there still was a difference for most segments between the steady-state heat loss in the side room chamber and the climatic chamber.
Handling the manikin while moving it into the chamber may also have affected the air layers, fit, and the insulation.

**Figure 4-3 Raw Heat Flux Data Before correction.**

**Methods Used for the Correction of Data**

One method for correction is using the steady-state data just before the RH transition and the steady-state data at the end of the experiment. Assuming that the only thing that has changed is the wind and maybe some fit and air layers due to handling the manikin, the heat loss data immediately after the transition should have reached that new steady state immediately. Thus, correcting the data just before and just after the transition to their steady-state values should clearly show the vapor absorption effect on the heat loss and compensate (correct) for these environmental differences. For the correction, the average values of heat flux around 1200-1800 seconds, i.e., before the transition, and around 4000-5000 seconds, i.e., around the finishing time of the experiment, have been taken, and a heat flux factor was generated by dividing two heat
flux values at the transition point. After that, multiplication was done with that factor for each heat flux value after 1800 seconds. This correction was made considering the constant dry insulation value before and after the humidity transition. If the temperature and wind speed had been the same during the experiment, there should not have been a significant change in the heat flux values. Figure 4-4 represents a graph after the data correction just before and after the transition; the data still show the periodic changes in heat flux, likely due to periodic changes in the chamber environment (temperature, relative humidity, and wind speed), due to its HVAC control systems.

![Graphs of heat flux over time for different materials](image)

Figure 4-4 Representing corrected data considering a steady-state transition.

Another method of correcting the data is to use relative segment data regarding a bare segment. In this case, the head segment data was used as a reference, as the fabric did not cover it. The heat flux is then calculated for the segments in the torso zone relative to the head for all
the samples. The advantage of this method seems to be that it strongly reduces the effects of changes in the chamber environment. The corrected data are shown in Figure 4-5. These methods generated two mean value curves representing wool, viscose, cotton, and polyester samples. One mean curve is for the method used to correct the heat flux before and after the transition, and the other one is for correcting the heat flux with reference to a bare segment of the manikin body.

Figure 4-6 represents the mean heat flux value for all samples by taking average values of all the manikin body segments in the torso zone considering the above two methods. These two calculations are used to compare and validate the correction methods. A transient peak was observed in both graphs during changing environments. Unless the garment was polyester, the shape of the transient peak for all the hygroscopic fibers was significant. The shape and amplitude of the transient peak depended on the moisture-fiber interaction during this transient change in humidity. It is noticeable that the heat flux curve on the right side represents less variation in the steady-state and after the transition (after 1800 seconds). In addition, that curve also made a good platform to calculate the area under the curve as a measure of the moisture buffering potential during the transition.
Figure 4-5 Representing corrected data considering head segment data of the manikin.

**Quantifying Moisture Buffering Effect**

Since the manikin was moved from a low-humidity room to a high-humidity climate chamber after the first 1800 seconds of the test and the skin temperature of manikin was maintained at 35°C, it was expected that the response the manikin to heat flux for different types of garments would be different. During the rapid change of the RH of the environment, the heat flux by the manikin reflected a transient peak to maintain a constant body temperature. Both graphs in Figure 4-6 demonstrated transient peaks during this step change in the RH. Hygroscopic fibers such as wool, cotton, and viscose showed a more substantial buffering effect than polyester. This phenomenon supported the theory explained by Spencer Smith (Spencer-
Smith, 1976) and, as found by Naylor (Naylor, 2019b), on the sweating-guarded hot plate. During transient conditions, specifically changing the RH from low to high, hygroscopic clothing absorbs moisture, reducing heat loss from the wearer’s body.

This reduction in heat loss can positively affect the comfort of the wearer in a certain environment. For example, the windy cliff-top environment can induce a chill during rock climbing, which might be mitigated by reducing the heat flux by hygroscopic fibers. This heat loss during environmental change can be quantified by measuring the area associated with that peak during that period. Quantitative peak area values represent the buffering potential associated with heat loss and can be calculated by simple numerical integration as a function of time. We used Origin pro-2020 b. The area measured as a function of time represents energy over a specific period during the transition from a low RH environment to a high RH environment. Table 4-3 represents the adjusted heat flux areas. The results highlight the difference in moisture buffering potential among fiber types. Although there was a clear distinction between the hygroscopic and non-hygroscopic fiber types, the differences among the hygroscopic fibers were not so prominent but still promising. According to Naylor, this heat release from fabrics during a step increase in RH should be proportional to absorbed water vapor (Naylor, 2019).
Figure 4-6 Mean heat flux value for all the samples, (a) steady-state correction, (b) relative heat flux regarding head.

Table 4-3 Calculated Heat Flux Area (J/m²) During a Transient Change in Humidity from the Corrected Graphs in Figure 4-6.

<table>
<thead>
<tr>
<th>Fibers</th>
<th>Method-1</th>
<th>Method-2</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>4228</td>
<td>488</td>
<td>4554</td>
</tr>
<tr>
<td>Wool</td>
<td>6973</td>
<td>9511</td>
<td>8242</td>
</tr>
<tr>
<td>Viscose</td>
<td>5067</td>
<td>7113</td>
<td>6090</td>
</tr>
<tr>
<td>Polyester</td>
<td>265</td>
<td>283</td>
<td>274</td>
</tr>
</tbody>
</table>

*Response of Skin-Microclimate Humidity to Ambient Humidity*

The microclimate in the air layer between the garment and the skin can significantly moderate the influence of the environment. Clothing materials respond to these environmental changes and can also enhance, delay, or modify with different modes of heat transfer to and from the body. Figure 4-7 represents microclimate and environmental RH, respectively. The observed increase in environmental humidity after 1800 seconds validates the experimental protocol. Therefore, a sharp increase in microclimate humidity was also observed during the same period of time. These responses to microclimate humidity were not differentiable between the types of
hygroscopic fibers, and the differences are small. The heat loss associated with this small RH transition also seemed small. These responses may be further be expanded to the sweating manikin experiment to impart a larger humidity gradient, which could provide a better understanding of the exothermic and endothermic behavior of textile fabrics.

Figure 4-7 (a) Skin-microclimate RH responses during transient change (b) Ambient RH responses.

4.4 Conclusion

In this experiment, the behavior of the hygroscopic and non-hygroscopic fibers was studied in a transient environment using a thermal manikin. The thermal manikin was dressed in knit garments and moved from the low RH chamber to the high RH chamber. The exothermic effect of the hygroscopic fibers was noticed by a transient peak while the environment changed. This peak area indicates moisture buffering potential and is a significant component of thermal comfort in transient conditions. This phenomenon was previously demonstrated by the exotherm test (ISO16533) and the dynamic hot plate (“Naylor”) test. The thermal manikin appeared to be an appropriate tool to measure heat loss and comfort perception in a real-life scenario. Further experimental planning was done on a sweating manikin to provide a more significant humidity
gradient to better understand exothermic and endothermic benefits of fabric in transient conditions.
References


*Chemiefasern/Textilindustrie*, 628-636.
CHAPTER 5: Exothermic and Endothermic Effects of Fibers on a Sweating Thermal Manikin under Windy and Non-Windy Conditions

Abstract

Clothing significantly impacts comfort and physiology when participating in various sports such as hiking, cycling, and other outdoor activities. Fibers in clothing can affect the comfort aspects of the wearer. The main purpose of the study is to see how the exothermic and endothermic behavior of fibers affects the wearer in a realistic environment. The experiments were carried out on a sweating thermal manikin in a controlled climate chamber with a temperature of around 15 °C and 50% relative humidity. For realistic testing, it was done in two and a half hours in three phases imitating rest-activity-dry with both windy and non-windy conditions. The temperature of the skin microclimate, the temperature of the fabric, and the mean skin temperature were measured. The release of heat from wool fibers (approximately 2°C after moisture absorption) had the greatest impact on the ability to maintain a stable micro-climate (about 50% less drying rate). The wind expedited the drying of the fabric, causing a considerable post-exercise chill that was minimized in wool fibers. Wool fibers helped to maintain a warmer mean skin temperature, which is 20% higher than polyester and viscose, and about 10% higher than cotton in moderately cold conditions. The ability of wool fiber to retain heat could help prevent post-exercise cooling by maintaining a balanced skin microclimate.

Keywords

Sweating manikin, transient conditions, textile fiber, exothermic behavior.

5.1 Introduction

Comfort is considered an essential aspect of the development of functional clothing. Various attempts have been made to assess and describe the clothing comfort of human (Das &
Alagirusamy, 2010). Haghi referred to clothing as a second skin in his book "Heat and Mass Transfer in Textiles," highlighting how important it is in everyday life (Haghi, 2011) (Li, Yi, 2001; Li, Yun, 2005). In recent years, humans have developed an interest in clothing for different activities, such as running, hiking, and rock climbing, and are aware of its comfort and functionality. Therefore, it is necessary to measure clothing comfort and other attributes, especially for the activewear manufacturer. Several researchers and organizations have tested clothing-physiology interactions by evaluating thermal insulation, dry and evaporative heat resistance, and water vapor transmission rate, which are considered as critical parameters for comfort (Li, 2001; Li, 2005). Clothing producers use these steady-state measurements to design their garments. However, humans do not exist under steady-state conditions (Cui et al., 2020); therefore, the benefits of steady-state parameters of sportswear may be lost when worn in a dynamic environment. Because of this, dynamic testing methodologies should be developed to reveal the specific advantages of garments under realistic transient conditions.

The vapor absorption causes an exothermic reaction of the fabric, a property that only manifests in dynamic states of body metabolism or environmental circumstances. In transient settings, the hygroscopic fibers display a change in temperature to regain equilibrium water vapor pressure. Spencer Smith mentioned in a high-water-vapor-pressure room; hygroscopic clothing absorbs water vapor, which releases latent heat. This raises the temperature of the material and the surrounding air until equilibrium is reached (Spencer-Smith, J. L., 1976). The heat release of textile fibers is affected by moisture absorption capacity, the number of hydrophilic groups, and the binding force between hydrophilic groups of hygroscopic fibers (Cui et al., 2020). Non-hygroscopic synthetic fiber manufacturers highlight this characteristic,
sometimes confused with 'breathability' (a comfort term) (Spencer-Smith, J., 1966). This fundamental characteristic of naturally hygroscopic fibers has been disregarded for many years.

Figure 5-1 The relationship between change in mean body temperature and sweat rate for thermoregulation. (Modified from (Zhong et al., 2021)).

This behavior is governed by moisture vapor, for example, insensible sweat. Figure 5-1 shows a relationship between sweat rate and the change in mean body temperature. Insensible sweat is the main loss of bodily sweat under the onset threshold (office work, sleeping, yoga, etc.). Liquid or sensible sweat dominates beyond the onset threshold (running or high-intensity activity). The sensible sweat rate has a maximum even if body temperature continues to rise (Zhong et al., 2021). Sweating may cause the garment to absorb some of the body's moisture; this may be in a liquid state (hydrophilic) and a vapor state (hygroscopic). Cooling will occur if liquid sweat evaporates from the skin or clothing, but little research is available on the warming effect of water vapor absorption. As many outdoor activities are alternating high and low activities, the entire sequence of activity and rest should be studied for effects of cooling via evaporation and heating via hygroscopic effects to determine in what phase hygroscopic, and non-hygroscopic fibers may be most beneficial. To this day, there is debate regarding how non-
steady textile fibers/clothing react and how this impacts human thermal balance and comfort. Lotens (Lotens & Havenith, 1995) stated that hygroscopic fibers might not provide benefits through their moisture absorption and desorption processes. In contrast, Cassie, and Spencer-Smith (King et al., 1940) (Spencer-Smith, J. L., 1978) provided experimental and numerical evidence for the exothermic benefits of hygroscopic fibers. The main reason behind this could be that the test materials included a wide range of tests that all seemed to address steady-state conditions, such as sweating-guarded hot plates, manikin tests, and steady-state human subject trials with few participants. There has not been a comprehensive series of tests to understand the complete theory and mechanism of moisture management and its benefits in dynamic settings.

Thermal and sweating manikins in a controlled climate chamber may simulate real-life examples of human comfort in transient conditions (Farrington et al., 2004). This study examined how transient climatic conditions affect the thermal management of a specific type of sportswear and the human body heat balance. This study focuses on sweating manikin experiments in a transient setting by replicating outdoor activities with five distinct garment types.

The thermal manikin experiment during a step change in the humidity described in the previous chapter did not properly address the exothermic benefits of the textile fiber. As shown, changing the ambient humidity to 85% causes a change in the skin-microclimate humidity of around 55%~60%. Although the fabrics demonstrated heat loss in the form of peaks during the humidity transition, they could not differentiate between the hygroscopic fiber types. So, this sweating manikin approach could be effective in providing a better humidity gradient to demonstrate the moisture buffering potential of hygroscopic fibers.
5.2 Research Design

5.2.1 Method

In this research, a sweating manikin was used to demonstrate the exotherm effect of fabrics while changing the body metabolic rate at three different phases (preparation, activity, and rest) in a controlled climate chamber with a controlled wind speed. The three phases were the preparation, activity, and rest (drying) phases. The met rate set for the phases was based on relevant data from the literature for rest and moderately high levels of exercise.

5.2.2 Clothing Ensembles

Australian Wool Innovation (AWI, Sydney, Australia) provided the test garments (full-sleeve t-shirts, size: medium, three replicas) with five different fiber types. To reduce the below effect, which generally causes by the bottom part of the shirt when not tucked in, the sweating manikin was outfitted in those garments tucked into a sport short (Figure 5-2). The fiber type selection for testing was based on the moisture regain value and covered both synthetic and natural fibers. A detailed description of the sample is presented in Table 5-1.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Sample ID</th>
<th>Fabric Composition</th>
<th>Fabric Structure</th>
<th>Weight (g/m2) ASTM D3776</th>
<th>Thickness (mm) ASTM D177</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WBT</td>
<td>100% Merino Wool</td>
<td>Jersey knit</td>
<td>213</td>
<td>0.69</td>
<td>Wool-Hydrophobic</td>
</tr>
<tr>
<td>2</td>
<td>WLT</td>
<td>100% Merino Wool</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.69</td>
<td>Wool-Hydrophilic</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>100% Cotton</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.65</td>
<td>Cotton-Hydrophilic</td>
</tr>
</tbody>
</table>
Table 5-1 (continued).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>0.69</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>PLT</td>
<td>100% Polyester</td>
<td>Rib Knit</td>
<td>199</td>
<td>0.69</td>
<td>Polyester-Hydrophilic</td>
</tr>
<tr>
<td>5</td>
<td>VB</td>
<td>100% Viscose</td>
<td>Jersey Knit</td>
<td>204</td>
<td>0.67</td>
<td>Viscose-Hydrophobic</td>
</tr>
</tbody>
</table>

Figure 5-2 Manikin dressed in test garments

5.2.3 Equipment and Facilities

A series of instruments were employed to determine the effects of changing conditions and different fiber types on temperature, humidity, and heat flux.

*Sweating Manikin:* Newton thermal manikin by Thermetrics (Thermetrics LLC, Seattle, WA, U.S.A.) was used in this research. It has 34 body sections. The size of a Newton Manikin is 50th percentile of a western male. Manikin simulates heat and sweat production, making it possible to assess the influence of clothing on the thermal comfort process in a given environment. Figure 5-2 shows a manikin dressed in test clothing.

*The Climate Chamber & Wind Tunnel:* The research facility houses a controlled climate chamber. The chamber is used to replicate the realistic temperature, humidity, and wind speed. The 16.5 ft x 13 ft x 8.75 ft chamber contains a four-fan wind tunnel that can maintain a temperature of -30°C to 40°C and relative humidity between 10% and 90%.
**Microclimate and Fabric Sensors:** Four Modular Signal Recorders (MSR®/MSR 145, Seuzach, Switzerland) were employed to monitor the skin microclimate and the clothing surface temperature. The average of the two sensors’ data was used to express the results. Figure 5-3 shows the position of sensors on the manikin skin. Two sensors were placed on the front side of the manikin body, and the other two sensors were placed on the back side of the manikin torso zone.

**FLIR Thermal Camera:** FLIR (Model A325) (Teledyne, CA, USA) was used to analyze temperature readings of different activity phases. The camera was remotely controlled via PC with static or real-time analysis.

5.2.4 Test Procedures

In three phases, the two-and-a-half-hour experiment was conducted in a fully controlled climate chamber at 15 °C and 50% RH. The sweating manikin was allowed to acclimatize (preparation) for the first 30 minutes with a metabolic (met) rate of 1.5 MET (87 W/m²), and then the met rate was increased to 5 MET (290 W/m²) for 60 minutes in order to simulate strenuous activity and have the manikin sweat moderately; lastly, the manikin was allowed to dry for 60 minutes under both windy and non-windy conditions in separate experiments while the met rate was decreased to 1 MET (58 W/m²) (resting). ThermDAC Control Software (Thermetrics LLC, Seattle, WA, USA) controlled the met rate setpoints on the manikin body. The test protocols are summarized in Figure 5-4 and Figure 5-5. Table 5-2 highlights the test conditions of the chamber during testing.
Table 5-2 Climatic conditions of the test chamber.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Climate Chamber Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (°C)</td>
<td>15±0.5°C</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>50±5%</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>1 m/s</td>
</tr>
</tbody>
</table>

Figure 5-3 Skin microclimate sensor and fabric sensor placement on the manikin skin (a) front side (b) backside.

Figure 5-4 Summary of the test protocol for the non-wind condition.

Figure 5-5 Summary of the test protocol for wind condition.
5.2.5  **Measurements of physiological, skin, and fabric parameters**

For this research, the sweating manikin was used in a ‘constant heat flux mode’, with the heat flux set constant in each phase at the levels described above. The manikin control system then recorded the resulting mean skin temperature of the manikin for each body segment on the torso zone. Additionally, the MSR skin-microclimate and fabric sensors recorded data for the skin-microclimate temperature and the fabric temperature at an interval of 5 seconds interval. The FLIR camera image captured images every 10 minutes to qualitatively analyze the thermal management in sports clothing.

5.2.6  **Quantifying Moisture Buffering Effect**

Normalized curves were obtained by subtracting the steady-state temperatures at the end of the initial preparation phase as the baseline temperature. Quantitative peak area values associated with the observed transient fabric temperature curves were extracted from the normalized curves by simple numerical integration. The normalization was done to remove small temperature differences between the fabrics at the beginning of the exercise. The area under the temperature curve, measured as a function of time, represents the temperature increases over a specific period and is proportional to the heating energy that is added to or released from the system. Origin 2022b (Northampton, MA, U.S.A.) was used to calculate the area under the curve.

5.3  **Result and Discussion**

*Skin Microclimate Response Over Time*

The microclimate temperature is important for skin comfort, as it is an intermediate between the local conditions of the skin and the fabric (Lee, 2014). Mean skin micro-climate temperature results can be seen in Figure 5-6 for wind and non-wind conditions. The step-change
in the met rate (from 1.5 to 5) at 1800 seconds led to a corresponding increase in the micro-
climate temperature for all the fiber types, followed by a corresponding decrease at 5400 seconds
when the body metabolism changed to the lower met rate (from 5 Met to 1 Met). Both figures
show normalized temperature curves, which express the temperature increase related to the value
of the temperature just before the transition to the activity phase.

As expected, a significant microclimate temperature increase was observed as the activity
phase progressed, resulting in higher absolute temperature differences between the phases for all
fiber types, which was more prominent in the windy condition. Hydrophobic wool showed a
higher temperature increase than all the other types of fiber. At 5400 seconds, the normalized
increase in microclimate temperature increase reached 2.77 °C for hydrophobic wool, which was
0.5 °C higher than cotton, and hydrophilic wool, and 0.61°C, 0.8°C higher than polyester and
viscose, respectively, during the windy conditions. In contrast, with no wind conditions, the
difference in temperature between the fibers was not prominent unless the PLT.

Figure 5-6 Skin microclimate temperature responses (a) non-wind (b) wind conditions.
The area under the skin microclimate temperature curve was calculated at a definite time frame of 2000-7000 seconds, the quantitative peak area extracted from the temperature data, representing the body temperature increase and exothermic effect of the garment over a specific period which is shown in Figure 5-7. The reason behind selecting this time frame was to evaluate the effects of the step change on body metabolism. Hydrophobic wool showed a greater area under the curve in the wind and non-wind conditions compared to other fiber types. This area represents the increase in temperature during the activity and rest phase. The area for WBT was 12%, 23%, 74%, and 28% higher than WLT, CLT, PLT, and VB in windy conditions. Although the line graph (a) in Figure 5-6 did not show any apparent differences, it was found from the area under the curve that WBT had a 40%, 6%, 60%, and 14% larger area than WLT, CLT, PLT, and VB respectively under non-windy conditions. Although hygroscopic, VB showed the least amount of heat release in both of the cases.

In addition, the results in Figure 5-6 and Figure 5-7 demonstrated that the microclimate of the hydrophobic wool became progressively warmer in all the phases. It was also evident that the rate of decrease in microclimate temperature during the drying phase for hydrophobic wool was lower than for other fiber types. The greater moisture regain of wool fiber may be the main
reason for the response. Another possible reason could be that hygroscopic natural fibers tend to swell when they absorb moisture from the skin, which slightly reduces the air spaces between the yarns and lengthens the amount of time it takes for the fabric to dry out. Because of the specific surface chemistry of wool fiber, having hydrophobic nature on the surface for the cuticle cells and hydrophilic nature in the interior composed of cortical cells (Popescu & Wortmann, 2010), wool fiber can trap moisture and heat, which eventually helps in slow release of heat in the cold condition. It helps the wearer to buffer the sudden in the environment.

**Fabric Temperature Response over time**

The outside fabric temperature responses are shown in Figure 5-8 with the test garments worn next to the skin on the manikin body. It was expected that the fabric would absorb moisture from the manikin skin when it sweated and released moisture during the activity and drying phases. If the humidity remains on the fabric, the moisture may condense and cause an increase in the vapor content of the fabric. However, it is also essential to notice how quickly the fabrics dried out and how it potentially impacted the wearer's comfort level through the changing of mean skin temperature. In the figure, it can be seen that the change from rest to activity caused the fabric to absorb moisture and release heat, showing a temperature increase in the fabric. In non-wind conditions, WLT showed a higher temperature increase, almost 81%, than the PLT at the end of the activity phase, which became more prominent at the end of the drying phase. PLT reached its saturation point earlier (at least 1000 seconds) than the other fiber types before the start of the drying phase, even though the manikin was sweating. In other words, for PLT, the fabric temperature began to drop during the exercise phase, which would cause the wearer to feel cooler. On the other hand, in windy conditions, WBT showed the highest temperature increase, which was 50% higher than PLT, 20% higher than VB, and 12% higher than CL and WLT. Also,
during the drying phase, WBT showed slower cooling, which would protect the wearer from sudden temperature changes. PLT started cooling (reducing temperatures) before the activity phase ended, and the temperature decrease rate was quite sharp. It can be concluded that, despite having a high drying rate, PLT did not show any exothermic effect during activity and showed cooling, which may have induced discomfort during post-exercise chill.

![Fabric temperature responses](image1.png)

**Figure 5-8 Fabric temperature responses (a) non-wind (b) wind conditions.**

![Area under the curve calculation](image2.png)

**Figure 5-9 Area under the curve calculation from fabric temperature (a) non-wind (b) wind conditions.**

Figure 5-9 showed greater variability among the fiber types in the area under the curve when the temperature increases during the activity and rest periods. For non-wind conditions, CL had the highest area under the curve, whereas for windy conditions, WBT had the highest. As
wind can be expected in realistic environmental scenarios, WBT may have the highest advantage in buffering the post-exercise chill. In the non-wind condition, WBT had an area of 16%, and 80% higher than VB, and PLT, respectively, and 5% less than CL and WLT, while, in the windy conditions, WBT had an area of 23%, 12%, 29%, and 73% higher than CL, WLT, VB, and PLT respectively. This exothermic response to fabric temperatures was aided by the higher moisture regain of wool fiber, indicating that the fibers were able to generate more heat by absorbing moisture from the skin.

**Manikin mean Skin Temperature Response Over Time**

The study of heat transfer through clothes often uses mean skin temperature as a key measure of human thermal status (Livingstone et al., 1988). Figure 5-10 (a) shows the normalized mean skin temperature evolution of the manikin over time during different phases under windy conditions. As seen in the figure, with the increase in the metabolic rate, the mean skin temperature increased, as expected. After the activity phase, all clothing showed a similar trend of decreasing temperature while WBT had the lowest decreases. At 5400 s, WBT had a temperature 0.4°C, 0.6°C, 0.8°C and 1°C higher temperature than CL, WLT, VB, and PLT, respectively. However, during the drying phase, when the body's metabolic rate was considered to be at rest, the temperature started to decrease. Still, WBT maintained a higher temperature than all the other fiber types. At the end of the test, WBT had a temperature of at least 1°C higher than those of the other fiber types. In addition, the area under the curve calculation shown in Figure 5-10(b) validates the finding of the results shown in Figure 5-10(a). WBT had the highest area under the curve throughout the test duration. WBT had an integrated area that was 20%, 27%, 15%, and 12% higher than VB, PLT, WLT, and CL.
Figure 5-10 Mean skin temperature (manikin) responses in wind conditions (a) temperature responses over time (b) area under the curve calculation.

**Thermal Image Analysis**

An infrared camera system was used to investigate the thermal properties of the fibers during the testing of five different fiber types. The images for WBT, along with the scale shown in Figure 5-11 and Figure 5-12.

Figure 5-11 Thermal properties of hydrophobic wool clothing during testing at non-wind conditions; the image was taken (a) beginning of the test, (b) at the end of the activity phase, (c) at the end of the drying phase.

Figure 5-12 Thermal properties of WBT (hydrophobic wool) clothing during testing in windy conditions; the image was taken (a) beginning of the test, (b) at the end of the activity phase, (c) at the end of the drying phase.
Both images show that, after the activity period, the fabric temperature increased from 24°C to 29°C and dropped to 24.3°C at the end of the drying period under non-wind conditions. In windy conditions, the temperature increased from 24.6°C to 31.8°C and dropped to 23.7°C toward the end of the drying phase. All the other thermal images from Figure 5-13 to Figure 5-18 have been shown for the other fiber types following the same trend of increase-decrease of temperature during the activity-drying period. The microclimate temperatures, fabric temperatures, and mean skin temperatures agree with these findings.

Figure 5-13 Thermal properties of WLT (hydrophilic wool) clothing during testing in non-windy conditions; the image was taken (a) beginning of the test, (b) at the end of the activity phase, (c) at the end of the drying phase.

Figure 5-14 Thermal properties of WLT (hydrophilic wool) clothing during testing in windy conditions; the image was taken (a) beginning of the test, (b) at the end of the activity phase, (c) at the end of the drying phase.

Figure 5-15 Thermal properties of VB (Viscose) clothing during testing in non-windy conditions; the image was taken (a) beginning of the test, (b) at the end of the activity phase, (c) at the end of the drying phase.
5.4 Conclusion

In this experiment, the behavior of the hygroscopic and non-hygroscopic sports clothing was studied in a transient environment using a sweating manikin. The test method discussed in this research is novel to demonstrate the exothermic behavior of the hygroscopic fibers in a realistic transient setting. The hydrophobic wool fiber showed better thermal management across the skin-microclimate, fabric, and mean skin temperature by delayed exothermic responses in all phases. Furthermore, the data showed that the type of fiber in an activewear influenced not only...
the control of heat during exercise, but also the preservation of heat during the rest phase,
possibly reducing after-chill in cool resting conditions after exercise.
References


6 Chapter 6: Clothing Impact on Post-Exercise Comfort: Human Trials to Determine Skin-Clothing Physiology in Transient Environment

Abstract

Sportswear manufactured from hygroscopic fibers can absorb moisture during activity or intermittent exercise and may change the thermal management of clothing. This change in the thermal behavior of the fabric can lead to buffer the chill during the post-exercise period. During activity in a moderately cold environment, for example, rock-climbing, mountain biking, or other outdoor activities, clothing made of wool fiber helps wearers to slow down evaporative and conductive cooling, which can provide a significant amount of thermal and perceived comfort compared to other fiber types such as cotton, viscose, and polyester. Twelve young males (age:26±3 years) performed cycling (25 min, 65 rpm, 100 watts) in a controlled climate chamber (temperature:15±1°C, relative humidity (RH):50±5%) followed by a drying phase in a windy environment (speed:1.7 m/s). Through multiple trials, each subject has undergone this testing protocol with a full-sleeve t-shirt made of four fiber types (wool, cotton, viscose, and polyester). Specifically, in a windy, moderately cold environment, wool was observed to hold a greater local torso skin temperature (p<0.05) than the other fiber types, which was reported to buffer the post-exercise chill by the participants. Throughout the exercise and cool-down periods, participants were asked a range of comfort-related questions at varying intervals. The perceived thermal sensation was found (p<0.05) significant for wool clothing, whereas wool maintained a higher micro-climate skin temperature than the other fiber types. Moreover, participants rated wool significantly (p<0.05) as more comfortable than all the fiber types during the post-exercise phase.
Keywords
Post-exercise comfort, Thermal Sensation, Skin-Clothing Interaction, Sportswear, Transient Condition

6.1 Introduction
As a bridge between the human body and its surroundings, textiles have drawn considerable attention for their ability to manage the comfort of the microenvironment next to the skin and play a critical part in the body's humidity and temperature balance (Wang et al., 2022). In his book “Heat and Mass Transfer in Textiles,” Haghi mentioned clothing as a second skin, referring to humans as unfinished beings without clothing, which undoubtedly draws attention to how vital clothing is in day-to-day life (Haghi, 2011). In recent years, humans have a keen sense of clothes for different occasions or activities such as outdoor runs, hiking, rock climbing, and others, and are cognizant of comfort and functionality. Many researchers and organizations have tested clothing-physiology interactions by evaluating thermal insulation, dry and evaporative heat resistance, and water vapor transmission rate, which can be considered the crucial parameters for comfort attributes (Li, Yi, 2001; Li, Yun, 2005). Clothing manufacturers use steady-state measurements to design their garments based on these parameter measurements. Despite this, humans have never existed in a static state (Cui et al., 2020); hence the benefits of clothing may be lost when worn in a dynamic environment. Because of this, new dynamic testing methodologies should be developed to reveal the specific garment advantages in transient conditions.

In transient settings, hygroscopic textile fibers will absorb or desorb water vapor from the environment, and this may result in temperature changes as water vapor absorption is an exotherm effect. When moving into a room with a high-water vapor pressure, clothing will
absorb water, which releases latent heat. This absorption raises the temperature of the substance and the surrounding air until equilibrium is reached (Spencer-Smith, J. L., 1976). In a recent paper, Gao et al. (Gao, S. et al., 2022) explained that textile fibers' exothermic behavior is due to high sorption capacity, with interim hydrogen bonding forms between water molecules and polar hydrophilic fiber groups. However, breaking the forces to free the water molecules, generally referred to as drying, requires heat and can be called desorption (endothermic heat). Under steady-state conditions, natural fibers like wool's keratin and cotton's cellulose have little water vapor transfer resistance, whereas polyester, polyacrylonitrile, and polyamide have high (Spencer-Smith, J., 1966) although fabric properties, e.g., weight, thickness, porosity, and other parameters contributed to this. This fundamental characteristic of naturally hygroscopic fibers has been disregarded for many years and was first noted by Cassie et al. (Cassie et al., 1939). Later, Li et al. (Li, Yi et al., 1992) investigated this behavior using human wear trials. They studied subjective perceptions of clamminess and thermal sensations and their relationship with a developed kinetic sorption model under certain activity conditions. The study concluded that polyester garments were clammier to the wearer than wool garments. Many studies (Behmann, 1971; Kawabata et al., 1982; Umbach, 1980) have been found to compare hygroscopic and non-hygroscopic fibers; however, there was little indication of how hygroscopic fibers such as wool, cotton, and viscose would behave in the transient environmental conditions.

Engaging in physical activity while also being in a relatively cold environment can induce a significant drop in skin and body core temperature, leading to decreased performance and an increased risk of cold stress. Clothing significantly reduces the effects of cold stress and enables wearers to carry out their activities naturally and comfortably. Considering the fact that sportswear is meant to be worn while doing outdoor activities such as mountain biking or
running in chilly weather (when people usually avoid heavy clothing), it must be capable of successfully mitigating thermal stress and providing thermophysiological comfort as much as possible. An appropriate physiological and perceptual balance can only be maintained when clothing can effectively manage thermal and moisture interaction (Wang et al., 2022). So, it is crucial to characterize the performance metrics relevant to human perception and physiological comfort and then translate the performance into meaningful terms for sensorial comfort for next to skin clothing. Not such study yet done to investigate the subjective and objective parameters of clothing when worn as a single layer while being in a moderately cold environment. The present investigation is focused on investigating the above-mentioned parameters for next to skin clothing.

Any property that can be seen on benchtop material testing might be negligible in the testing of the garment. Testing at the benchtop level is typically carried out in a controlled environment with regulated experimental parameters. In contrast, testing at the garment level (such as on manikins or humans) is more prone to variability. Also, it is crucial to assess how fabric properties could affect the end user of the clothing. For example, benchtop results of different fibrous battings after 8 and 24 hours at -20°C for polyester and viscose fibers resulted in almost zero water content next to the skin for polyester fibers compared to about 18% for viscose, suggesting less “post-chill” discomfort for non-hygroscopic fibers (Fan & Cheng, 2005). However, Lotens et al. (Lotens & Havenith, 1995) experimentally with human subject trials and numerically proved that the assumptions regarding benefits of hygroscopic and non-hygroscopic fibers are not always effective in realistic situations. It is pertinent to remember that although the results appear significant in the benchtop and laboratory settings, they may be negated in a practical sense by layering effects, air gaps between layers, duration at which clothing is often
worn. Moreover, the state of the test condition is always a vital factor. In steady-state conditions, non-hygroscopic fibers may show more excellent water vapor resistance compared to hygroscopic fibers than in transient conditions (Spencer-Smith, 1966). Only a handful of literature is available, and it suggests the necessity of testing in non-steady conditions to demonstrate the fabric benefits in real-life conditions and translate the benefits in terms of human physiology (Barker, 2011; Huang, 2006; Naylor, 2019).

To evaluate the performance of sportswear for winter sports (hiking, climbing, mountain biking, and other activities), it is necessary to facilitate the actual scenario while taking into consideration various factors. These factors include environmental conditions such as temperature and relative humidity (RH), wind conditions, clothing materials and properties, fitting of the garments, clothing size, the activity length and level, the recovery or drying phase after the activity, and lots of other factors. Although a large number of studies have been conducted to evaluate the efficacy of various types and materials of clothing in hot environments during the activity and post-activity period with temperatures (20°C-40°C) and RH (15%-70%) (Davis & Bishop, 2013) there are very few studies that focus on the impact that clothing has in environments that are only moderately cold environment (10°C-15°C). Also, there have been some research studies that have mainly looked at the efficacy of clothing and comfort aspects in the post-activity or recovery period, which lasted for 10-60 minutes (Brazaitis et al., 2010a; Dai et al., 2008a; Gavin et al., 2001a; Kaplan & Okur, 2012a; Laing et al., 2008a; Stapleton et al., 2011a; Tokura, 1987). However, those studies were not able to differentiate between the fiber types.

This research aims to determine and compare the physiological and thermal performance of different natural and synthetic fiber types used in sportswear for cool climates and their
hygroscopic nature (wool, cotton, viscose, polyester). The concept here is to investigate the exothermic and endothermic behavior of the clothing when subjects are exposed to exercise in a moderately cold environment followed by a drying/recovery phase in a windy condition. In other words, the research point of interest is how moisture management in the clothing can benefit the wearer's physiological, sensorial and perceived comfort during the post-exercise period.

6.2 Experimental

6.2.1 Test Garments

The test garments (full sleeve t-shirts) were received from Australian Wool Innovation in two sizes, short and medium. Subjects donned the test garments without underwear beneath them with their own sports track pants or shorts. Test samples were labeled to identify their sizes and fiber types. The details of the sample are given in the following.
Table 6-1 Fabric Parameters of test garments.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Sample ID</th>
<th>Fabric Composition</th>
<th>Fabric Structure</th>
<th>Weight (g/m²)</th>
<th>Thickness (mm)</th>
<th>Air permeability (cm³/s/cm²)</th>
<th>Surface Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WBT</td>
<td>100% Merino Wool</td>
<td>Jersey Knit</td>
<td>213</td>
<td>0.69</td>
<td>99</td>
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<tr>
<td>2</td>
<td>WLT</td>
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<td>188</td>
<td>0.69</td>
<td>93</td>
<td>Hydrophilic</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>100% Cotton</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.65</td>
<td>79</td>
<td>Hydrophilic</td>
</tr>
<tr>
<td>4</td>
<td>PLT</td>
<td>100% Polyester</td>
<td>Rib Knit</td>
<td>199</td>
<td>0.69</td>
<td>393</td>
<td>Hydrophilic</td>
</tr>
<tr>
<td>5</td>
<td>VB</td>
<td>100% Viscose</td>
<td>Jersey Knit</td>
<td>204</td>
<td>0.67</td>
<td>204</td>
<td>Hydrophobic</td>
</tr>
</tbody>
</table>

6.2.2 Test Subjects

Twelve male participants were recruited from our lab’s participant pool, aged between 20 and 32. All subjects were free of skin disease, heat illness, cardiovascular disease, and respiratory illness, which was confirmed by a questionnaire. Also, they were requested to avoid any alcoholic beverage before 24 h of the test. All the subjects had previous experiences with biking with a continuity of at least 30 minutes. The participants had age (26±3) years; height (181±6) cm, weight (80±8) kg, and body mass index of (1.71±0.15) kg. cm⁻². Each subject was supposed to have five sessions by wearing each garment type. In order to avoid potential bias
resulting from the physical exertion of the subjects, each subject was allowed at least 24 hours gap in between each trial. Before conducting any testing, each subject was given the informed consent and photo consent papers, which they signed to indicate that they understood the study and enrolled as participants. The test protocol was approved by the Institutional Review Board of North Carolina State University. The approved protocol number is eIRB-24783. Each subject attended five sessions with five different garment types.

6.2.3 Experimental Environment

All testing was conducted in an environmentally controlled chamber, where the ambient temperature and RH were maintained at 15°C±0.5 °C and 50%±2 RH, respectively. The indoor air speed was 1.7 (m/s). A sweat cage preventive of high wind speed was set in that chamber with a bike in it to perform the activity phase of the experiment. The sweat cage maintained a low airflow (~0.4 m/s) to avoid wind exposure while biking.

6.2.4 Instrumentation and Data Acquisition Equipment

A slew of instruments was employed to record and monitor data to guarantee that all aspects of the experiment ran smoothly. Subjects with the test clothing, sports shorts, and other equipment (skin temperature and humidity sensors, fabric temperature, and RH sensors) were weighed separately on a weighing scale (Adam Equipment Company, USA). Four MSR (Modular Signal Recorder MSR®/ MSR 145, Seuzach, Switzerland, accuracy ±0.1°C for temperature and ±2% for RH) were employed by tape (3M) to monitor the skin microclimate and the cloth surface temperature and humidity. The average of the sensors' data was used to express the results. After donning in the subjects entered into a sweat cage (custom built plexiglass construction) placed into the climate chamber and performed cycling on a bicycle ergometer (True CS800).
6.2.5 Pre-Test garment and cycle fitting

Prior to the start of the testing, each subject was fitted tightly with an appropriately sized test garment, the fit and comfort verified by both the subject and the research team. Moreover, the individual was also set to a comfortable posture on the bike ergometer by adjusting the seat height, handlebars, and pedal straps. The position was recorded for each subject and maintained the same throughout the trial. Figure 6-1 depicts the garment-fit test evaluation procedure for the trials.

![Figure 6-1 Fit test evaluation of the participants, (a) not a good fit (b) Example of garment fit approved by the research team (front side) (c)Backside of the approved fit garment.](image)

6.2.6 Test Procedures

Acclimatization/Rest Phase

Upon arrival in the laboratory, each subject changed into test clothing (full sleeve t-shirts), sports shorts (own), and socks (own) while in the privacy of the dressing room. Participants then entered a room with controlled environmental conditions of ~20°C (68-75.2°F) temperature and ~50 % RH. The subjects sat and rested for 20 minutes. During this stabilization period, the subject became acquainted with the test procedures, questionnaires, and subjective scales, and the physiological measurement sensors were attached. A photo image and an infrared image of the instrumented subject were taken after donning the test garment. At the end of the acclimatization period, the instrumented weight of each subject was taken, and they were asked
subjective questions. A tabulated step-by-step test procedure of the complete test protocol is depicted in Figure 6-2.

**Activity Phase**

The subjects entered the sweat cage and was then mounted on the cycle ergometer in the testing (climatic) chamber. The chamber was set at ~15°C and ~50% RH with a wind speed of 1.7 m/s; however, the sweat cage prevented exposure to the high wind speed, while maintaining the chamber’s temperature and humidity with a low airflow (~0.4 m/s). The subject performed a designated activity for 25 minutes with a bike load resistance set at ~100 watts while maintaining a minimum rpm of 65 to achieve a moderate workload. The bicycle ergometer setting was expected to enable participants to get barely or slightly wet at the end of the activity period. After 25 minutes, a photo image, an infrared image, and the instrumented subject weight were taken. The infrared image helped to validate the body temperature and wetness qualitatively (Appendix B). During the activity period, subjective questions were asked at every 8 minutes interval. A poster board with subjective questions was set in front of the subject to allow the subject to answer the questions while performing the activity.

**Drying Phase**

After the designated activity period, the subjects exited the sweat cage and sat on a chair in that climate chamber. The cooling condition in the chamber allowed the subject to dry the accumulated sweat for up to 25 minutes while sitting on a chair. Also, in the drying stage, at 5 minutes intervals, the participant was asked to provide subjective ratings.
6.2.7 Physiological and Clothing Measurements

Microclimate-skin temperature ($T_{skin}$), and RH ($R_{skin}$) were recorded by MSR temperature, and RH sensors were attached by sensitive skin tape at both left and right side of the upper chest region and the left and right side of the upper back portion of the subjects. In other words, four-sensor probes were attached to the subject’s skin on both the front and back sides of the torso zone. The sensors recorded $T_{skin}$ and $R_{skin}$ at every 5 seconds interval.

For shirt temperature ($T_{fab}$), and RH ($R_{fab}$), also the same procedure has been followed. Four MSR sensors were attached to the fabric by sticky tape (3M, U.S.A). The sensors were placed on the left and right side of the upper chest region and the left and right side of the upper back portion of the subjects. Also, in this case, the sensors recorded the temperature and humidity at every 5 seconds interval.

Mean $T_{skin}$, $R_{skin}$, $T_{fab}$, $R_{fab}$ were calculated from the following equations.

$$T_{skin} = \frac{T_{skin\ (upper\ chest\ left)} + T_{skin\ (upper\ chest\ right)} + T_{skin\ (upper\ back\ left)} + T_{skin\ (upper\ back\ right)}}{4}$$

$$R_{skin} = \frac{R_{skin\ (upper\ chest\ left)} + R_{skin\ (upper\ chest\ right)} + R_{skin\ (upper\ back\ left)} + R_{skin\ (upper\ back\ right)}}{4}$$

$$T_{fab} = \frac{T_{fab\ (upper\ chest\ left)} + T_{fab\ (upper\ chest\ right)} + T_{fab\ (upper\ back\ left)} + T_{fab\ (upper\ back\ right)}}{4}$$

$$R_{fab} = \frac{R_{fab\ (upper\ chest\ left)} + R_{fab\ (upper\ chest\ right)} + R_{fab\ (upper\ back\ left)} + R_{fab\ (upper\ back\ right)}}{4}$$

6.2.8 Subjective Measures

Throughout the test, each individual was asked three separate questions. Following acclimatization, which typically lasted about 20 minutes, the first set of questions was asked. During the 25-minute exercise phase, the subjects were asked questions at every 8 minutes interval. As a final step, the subjects were asked questions every five minutes during the drying time, which lasted 25 minutes.
The participants were polled regarding their perceived comfort level, thermal sensation, and wetness sensation. The researcher asked the questions, and responses were recorded almost immediately on a sheet of paper. In order to eliminate any possibility of bias, the recruited individuals were not informed of the different types of garments, nor were they told anything about the characteristics of the garments. The scale of perceived comfort (ISO 10551:1995) ranged from '0=comfortable' to '4=extremely uncomfortable'. The thermal sensation scale (ISO 10551:1995), ranged from '-4= very cold' to '+4= very hot'. The wetness sensation scale [adapted from (Raccuglia et al., 2018)] has a rating of '0= extremely dry' to '6= extremely wet'. The details of the subjective scale are presented in Appendix. Different scales are utilized to understand better how the subjects perceive the difference.

6.2.9 Statistical Analysis

The results presented were mean and standard deviation (SD) values for physiological and subjective responses. A two-way analysis of variance (ANOVA) with repeated measures was employed (Time × Clothing Types) for analyzing physiological parameters. $T_{\text{skin}}$, $R_{\text{skin}}$, $T_{\text{fab}}$, and $R_{\text{fab}}$ were examined at the time of 20, 28, 36, 45, 50, 55, 60, 65, 70 minutes. When the analysis revealed a significant difference, post hoc analysis (Tukey Pair Test) was performed to compare the five different clothing types.

For the ratings of subjective responses, the results were also compared using (Time × Clothing Types) two-way ANOVA with repeated measures for both shirt and time. A pairwise comparison between shirts was made at each time point if a significant interaction was found during the analysis. The significance level for statistical tests was set up at $p \leq 0.05$. It is important to note that several post hoc analyses were carried out to determine the significance level and its trend concerning the different mean groups. Since each testing concept was unique, conducting
this extensive post-hoc analysis made it possible to determine how significant the mean difference between the groups was. Origin Pro Version 2022b was utilized for each statistical test performed (Origin Lab Corporation, MA, U.S.A.).

6.3 Results & Discussion

6.3.1 Results

Physiological and Clothing Responses

Concerning 70 minutes experiments, data were analyzed with n = 12 for all the clothing types. Table 6-2 shows the mean difference between clothing types throughout the experimental period for physiological parameters.

Table 6-2 Tukey paired comparison among fiber types for the overall experimentation time (0-70 minutes) in the case of physiological responses.

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Skin Temperature (°C)</th>
<th>Skin RH (%)</th>
<th>Shirt Temperature (°C)</th>
<th>Shirt RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLT&gt;CL</td>
<td>-0.1</td>
<td>-7*</td>
<td>-0.9*</td>
<td>-4.3*</td>
</tr>
<tr>
<td>PLT&gt;VB</td>
<td>0.3</td>
<td>-6*</td>
<td>-0.9*</td>
<td>-2.4*</td>
</tr>
<tr>
<td>PLT&gt;WBT</td>
<td>-0.5*</td>
<td>-10*</td>
<td>-0.9*</td>
<td>-7.7*</td>
</tr>
<tr>
<td>PLT&gt;WLT</td>
<td>-0.2</td>
<td>-4*</td>
<td>-0.3</td>
<td>-5.5*</td>
</tr>
<tr>
<td>CL&gt;VB</td>
<td>0.4*</td>
<td>1.4</td>
<td>-0.1</td>
<td>1.9</td>
</tr>
<tr>
<td>CL&gt;WBT</td>
<td>-0.5*</td>
<td>-2.7</td>
<td>0</td>
<td>-3.4*</td>
</tr>
<tr>
<td>CL&gt;WLT</td>
<td>-0.2</td>
<td>2.8</td>
<td>0.6*</td>
<td>-1.2</td>
</tr>
<tr>
<td>VB&gt;WBT</td>
<td>-0.9*</td>
<td>-4</td>
<td>0.1</td>
<td>-5.3*</td>
</tr>
<tr>
<td>VB&gt;WLT</td>
<td>-0.5*</td>
<td>1.4</td>
<td>0.7*</td>
<td>-3.1*</td>
</tr>
<tr>
<td>WBT&gt;WLT</td>
<td>0.3*</td>
<td>5.5*</td>
<td>0.6*</td>
<td>2.17*</td>
</tr>
</tbody>
</table>
Table 6-2 (continued)

| '<' sign indicates greater than the objective measures or better than in the case of subjective measures. |
| *Indicating significance and the direction of effect. |

Figure 6-3 and Figure 6-4 showed the $T_{\text{skin}}$ and $R_{\text{skin}}$ in three conditions throughout the testing. As shown in the figure, the temperature curve trend is almost the same for all the fiber types. The temperature did not increase but there was a decreasing trend throughout the testing period. WBT maintained a moderately higher temperature than the other fiber types and ended at higher (at least 1°C), whereas viscose demonstrated a lower temperature at the end. The figure illustrates a specific temperature drop (at least 2°C) at the end of the activity period. The experiment was designed to see if any of the garments could help to reduce the post-exercise chill; in other words, an effective garment will help to maintain a higher $T_{\text{skin}}$ to reduce the after-exercise chill in a windy environment. Two-way repeated ANOVA analysis suggested that significant differences were observed for time ($p (0.00) <0.05$), clothing types ($p (0.00) <0.05$), and within-subjects; however, for the interaction of (time × clothing types) ($p (0.17)>0.05$) significant differences were not observed within subjects (Appendix C). The post hoc analysis showed that WBT was significantly different from other fiber types (Table 6-2). However, no significant differences were found for the (PLT, CL), (PLT, WLT), and (CL, WLT) pairs. Table 6-3 indicates significantly different paired comparisons according to the Tukey pair test at each time point for $T_{\text{skin}}$. It can be seen that there are no significant mean differences in skin temperature from 50-70 minutes which is in the post-exercise period. However, differences were observed for 28, 36, and 45 minutes. At the end of the exercise period at 45 minutes, WBT was found to be significantly different from PLT and VB, whereas no differences have been observed.
in WLT, CL, VB, and PLT. Measures of $T_{\text{skin}}$ showed how the temperature varies across the activity and drying phase while putting on different clothing types.

Figure 6-3 Skin micro-climate temperature between shirts over time during different phases. All values are presented as means ± SD. Significant differences have been noticed between clothing types.

Table 6-3 Tukey Paired Differences in skin-microclimate temperature.

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>VB</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>PLT</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

* Means followed by at least one common letter are not significantly different at a 95% confidence interval.
With regards to the $R_{\text{skin}}$, it increased gradually with the proceeding of the exercise. At the end of the activity period, it was seen that for all of the garment types the $R_{\text{skin}}$, reached at least 83% for the PLT and a maximum of 90% for WBT. During the drying phase, they decrease and end up at a percentage level of the initial period. Both time and clothing had significant effects on the $R_{\text{skin}}$. Li (Li, Yi, 2001b) found that the rise in metabolic rate at the beginning of exercise was linked to the rise in mean body temperature, which was correlated with the change in skin-microclimate humidity. The trend in the $R_{\text{skin}}$ curves supported that, during the activity period, the body heats up and releases moisture to cool down, whereas during the drying phase, $R_{\text{skin}}$, starts to fall as the body temperature decreases. A sharp decrease in the RH of almost 50% was observed for all fiber types when the subjects were allowed to dry in a chilly environment. WBT tended to follow a higher $R_{\text{skin}}$, during the drying period, which means it tends to dry at a slower rate compared to other fiber types. Two-way repeated ANOVA suggested significant differences in the test within subjects (Appendix C). For time (p (0.00) <0.05), clothing types (p (0.001) <0.05), and (time × clothing types) (p (0.01) <0.05) have found to have significant mean differences within subjects. Moreover, for the test between subjects also (p (0.00) <0.05), significant differences have been observed. Pairwise comparison in Table 6-2 showed that for the $R_{\text{skin}}$, PLT was significantly different from the other fiber types. Also, (VB, WBT) and (WLT WBT) was found to be different. However, no significant differences were observed between (CL, VB), (CL, WBT), (CL, WLT), and (VB, WLT) fiber types. Tukey paired comparison shown in Table 6-4 showed the mean differences for $R_{\text{skin}}$ at each time point. Significant differences were observed during and after the exercise, specifically for 36 minutes and 55 minutes. At 36 minutes, $R_{\text{skin}}$ for WBT is found significantly different from PLT, whereas no
differences were observed with WLT, CL, and VB. At 55 minutes, which is during the post-
exercise period, WBT was also found to be significantly different from PLT and WLT.

![Graph](image)

Figure 6-4 Skin Micro-climate RH% between shirts over time during different phases. All values 
are presented as means ± SD.

Table 6-4 Tukey Paired Differences in skin-microclimate RH (%).

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>VB</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A, B, C</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>PLT</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

* Means followed by at least one common letter are not significantly different at a 95% 
  confidence interval.
The responses of $T_{fab}$, $R_{fab}$, in the torso zone are shown in Figure 6-5 and Figure 6-6, respectively. All the shirt temperatures responded to the phase changes during the study. At 45 minutes after the activity phase was finished, the shirts exhibited about a $3^\circ$C drop in temperature. Statistically significant differences were found (Appendix C) in the interaction of the (time \times clothing types) for all of the clothing types as both within-subjects effects (p (0.00) <.005) and in between subjects’ effects (p (0.00) <.005). The pairwise post-hoc comparison showed that WBT significantly differs from PLT and WLT, whereas no significant difference was observed between CL and VB, as shown in Table 6-2. PLT was found to be different from all other fiber types but WLT. Also, the (CL and VB) pairs showed no significant differences.

Table 6-5 illustrates the paired comparison at every individual time period according to the Tukey pair test for $T_{fab}$. Significant differences have been observed between WBT and PLT in the activity period, whereas no differences observed among the fibers in the post-exercise period.
Figure 6-5 Shirt temperature over time during different phases. All values are presented as means ± SD.

Table 6-5 Tukey paired Difference in Shirt Temperature (°C).

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>VB</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>PLT</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

* Means followed by at least one common letter are not significantly different at a 95% confidence interval.
However, for the $R_{fab}$, the responses were found to increase up to the end of the activity phase. WBT showed the highest increase of almost 45% in the RH considering its initial RH at the rest period, whereas PLT showed the lowest increase, around 38%. Significant differences have been found during the two-way repeated ANOVA analysis (Appendix C). From the comparison for each time point, Table 6-6 shows that the differences between the fiber types were statistically significant during the drying period at 50 and 55 minutes. At the end of the exercise period, no significant difference was observed among the fiber types.

![Relative Humidity (%) of Shirt](image)

Figure 6-6 Shirt RH% over time during different phases. All values are presented as means ± SD.

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B, C</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>
Table 6-6 (continued).

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Thermal Sensation</th>
<th>Wetness Sensation</th>
<th>Perceived Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLT&gt;CL</td>
<td>-0.8*</td>
<td>-0.2</td>
<td>0.2*</td>
</tr>
<tr>
<td>PLT&gt;VB</td>
<td>-0.6*</td>
<td>-0.4*</td>
<td>0.1</td>
</tr>
<tr>
<td>PLT&gt;WBT</td>
<td>-1.3*</td>
<td>-0.3*</td>
<td>0.4*</td>
</tr>
<tr>
<td>PLT&gt;WLT</td>
<td>-0.8*</td>
<td>-0.2</td>
<td>0.2*</td>
</tr>
<tr>
<td>CL&gt;VB</td>
<td>0.1</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>CL&gt;WBT</td>
<td>-0.6*</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>CL&gt;WLT</td>
<td>-0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VB&gt;WBT</td>
<td>-0.7*</td>
<td>0.1</td>
<td>0.3*</td>
</tr>
<tr>
<td>VB&gt;WLT</td>
<td>-0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>WBT&gt;WLT</td>
<td>0.5*</td>
<td>0.2</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

‘>’ sign indicates greater than the objective measures or better than in the case of subjective measures.

*Indicating significance and the direction of effect.

Subjective Responses

Statistical data for all subjective responses are presented in Table 6-7, showed the mean difference between clothing types throughout the experimental period.

Table 6-7 Tukey paired comparison among fiber types for an overall experimentation period in the case of subjective responses (0-70 minutes).

<table>
<thead>
<tr>
<th>Fiber Comparison</th>
<th>Thermal Sensation</th>
<th>Wetness Sensation</th>
<th>Perceived Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLT&gt;CL</td>
<td>-0.8*</td>
<td>-0.2</td>
<td>0.2*</td>
</tr>
<tr>
<td>PLT&gt;VB</td>
<td>-0.6*</td>
<td>-0.4*</td>
<td>0.1</td>
</tr>
<tr>
<td>PLT&gt;WBT</td>
<td>-1.3*</td>
<td>-0.3*</td>
<td>0.4*</td>
</tr>
<tr>
<td>PLT&gt;WLT</td>
<td>-0.8*</td>
<td>-0.2</td>
<td>0.2*</td>
</tr>
<tr>
<td>CL&gt;VB</td>
<td>0.1</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>CL&gt;WBT</td>
<td>-0.6*</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>CL&gt;WLT</td>
<td>-0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VB&gt;WBT</td>
<td>-0.7*</td>
<td>0.1</td>
<td>0.3*</td>
</tr>
<tr>
<td>VB&gt;WLT</td>
<td>-0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>WBT&gt;WLT</td>
<td>0.5*</td>
<td>0.2</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

*Means followed by at least one common letter are not significantly different at a 95% confidence interval.
Thermal Sensation

The evolution of the thermal sensation of the torso zone is displayed in Figure 6-7. The figure shows that the torso zone felt warmer as the exercise continued for 25 minutes. These sensations were mainly derived from sensory mechanisms in the skin, and they interact strongly with moisture sensations (Wingo & McMurray, 2007). The subjects responded with the lowest ranking (slightly warm) for PLT to the highest ranking (warm) for WBT in the activity period. Whereas, as participants entered the drying phase, thermal sensation decreased and was found to reach -3 (very cool) for PLT. At the end of the test, participants gave a 0 (neutral) rating for WBT, which means they felt warmer than all the other garment types. Significant differences were found with the two-way repeated ANOVA analysis when testing was done on the subjects (Appendix C). Time (p (0.00) <0.05), clothing types (p (0.00) <0.05), and interaction of clothing and time (p (0.00) <0.05) demonstrated significant differences in the mean comparison. The post-hoc analysis shown in Table 6-7 revealed that WBT and PLT significantly differed from all other fiber types. However, no significant difference was observed between (CL, VB), (CL, WLT), and (VB, WLT) pairs. Table 6-8 shows the mean comparison of thermal sensation at various time points for five clothing types. The results were surprising. Thermal sensation differed significantly in the post-exercise phase, even though no differences were found during the activity period.
Figure 6-7 Thermal sensation rating over time in different phases. All values are presented as means ± SD.

Table 6-8 Tukey Paired in Thermal Sensation.

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>A, B</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>A, B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>VB</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>PLT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

* Means followed by at least one common letter are not significantly different at a 95% confidence interval.
Wetness Sensation

The wetness sensation can represent humidity in the environment and moisture accumulation in the clothing. Moisture in clothing is a major source of discomfort when wearing a garment (Li, 2001). The ratings of wetness sensations are displayed in Figure 6-8. As shown in the figure, the torso zone felt barely wet to slightly wet with the exercise proceeding. In other words, the subjects were not observed obvious liquid sweat throughout the activity period due to moderate exercise intensity. The test protocol was designed in such a way that it helped participants to heat up and sweat slightly to understand the effect of exothermic reactions for the given garment types. During the drying phase, with the wind effect, the garments tended to reach a dry position for all of the garment types, but for the VB, which showed some degree of wetness at the end of the test. Two-way repeated ANOVA analysis showed significant differences within the subjects for time (p (0.00) < 0.05), clothing (p (0.03) < 0.05), and also for (time × clothing) (p (0.003) < 0.05) (Appendix C). Pairwise comparison in Table 6-7 showed a significant difference between PLT with WBT, CL, and VB, whereas no significant differences were found between PLT and WLT. Also, no significant differences in wetness sensation were found between CL, WBT, VB, and WLT. Table 6-9 displayed the mean comparison for skin wetness sensation for all the clothing types at different time intervals. Although fibers showed some degree of differences at the beginning of the drying phases, no significant differences were found at the end of the test.
Figure 6-8 Wetness sensation rating over time in different phases. All values are presented as means ± SD. Significant differences have been noticed between clothing types.

Table 6-9 Tukey Paired Difference in Wetness Sensation.

<table>
<thead>
<tr>
<th>Clothing Types</th>
<th>20 minutes</th>
<th>28 minutes</th>
<th>36 minutes</th>
<th>45 minutes</th>
<th>50 minutes</th>
<th>55 minutes</th>
<th>60 minutes</th>
<th>65 minutes</th>
<th>70 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>WLT</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>CL</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>VB</td>
<td>A</td>
<td>A</td>
<td>A, B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>PLT</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

* Means followed by at least one common letter are not significantly different at a 95% confidence interval.

**Perceived Comfort**

The term "perceived comfort" in terms of thermal perspective refers to how well an individual can regulate their body temperature while wearing a specific type of clothing. This
can be affected by multiple factors, including the environment, the wearer's activity level, and the garment type (Li, 2001). Figure 6-9 displays the evolution of perceived comfort sensation for all garment types. As the activity phase proceeds, all the garments showed some discomfort at the end of the activity period. However, from the starting of the drying phase till the end, WBT ended with the highest perceived comfort of all other fiber types. Participants rated PLT more uncomfortable than all the other garment types. Two-way repeated ANOVA analysis showed that time (p (0.00) <0.05), clothing types (p (0.00) <0.05) and interaction (time × clothing types) (p (0.00) <0.05) all had significant effects within subject’s test (Appendix C). A pairwise comparison (Table 6-7) showed that the perception for WBT was significantly different from VB and PLT. However, no significant effect was found between WBT, WLT, and CL. Table 6-10 shows the mean-wise comparison for perceived comfort. There were no noticeable changes in comfort until about halfway through the drying phase. At the end of the phase, participants evaluated WBT as substantially more comfortable than PLT and VB. WLT, CL, and WBT were shown to have no difference during the post-exercise period.
Figure 6-9 Perceived comfort sensation rating over time in different phases. All values are presented as means ± SD.

Table 6-10 Tukey Paired Difference in Perceived Comfort.

<table>
<thead>
<tr>
<th>Perceived Comfort Mean Difference (Tukey Paired Comparison).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothing Types</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>WBT</td>
</tr>
<tr>
<td>WLT</td>
</tr>
<tr>
<td>CL</td>
</tr>
</tbody>
</table>
Table 6-10 (continued)

<table>
<thead>
<tr>
<th>VB</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>A</th>
<th>A, B</th>
<th>A, B</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLT</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

*Means do not share a letter are significantly different at a 95% confidence interval.

6.4 Discussion

The research study aimed to investigate the exothermic and endothermic behavior of hygroscopic textiles during a transitory state of physiological and environmental variables. This attribute was accomplished by having participants wear four fiber types of long sleeve sports shirts. The ability of the shirts to provide thermoregulatory benefits and wearer comfort during post-exercise chill was compared when the subjects were exposed to a moderately cold environment after a specific exercise protocol was maintained and followed by a drying phase in the same climatic chamber. During the testing, the subjects were asked several questionnaires regarding thermal, stickiness, wetness, pleasantness, and perceived comfort sensation. Moreover, their skin temperature, skin humidity, shirt temperature, and shirt humidity were recorded by sensors.

Impact of Climatic Conditions on Testing

In the study, the climate chamber was set to 15°C and 50% RH with a wind speed of around 1.7 m/s. However, the activity phase was performed in the same chamber with a plastic cage to minimize the wind effect during the activity. This protocol was designed because high wind chill would reduce human body heat and perspiration during the activity. If the body does not heat up, the exothermic and endothermic advantage of hygroscopic fiber will not be prominent in the post-exercise period, which was previously proven by Spencer-Smith (Spencer-Smith, 1966). In such a plastic cage with minimum wind and a windy environment during the
drying phase, the heat from the body to the environment can be dissipated by both dry and wet heat exchange. Thermal sensation and skin moisture increase with moderate physical activity, and heat might still accumulate in the body due to enhanced metabolism (Zhao et al., 2015). Moreover, $R_{\text{skin}}$ was found to be increased significantly for all the fiber types, and conductive heat loss was expedited when the heat was absorbed by clothing (Barwood et al., 2009; Gao, C. et al., 2011). In addition, the high-velocity airflow in the chamber throughout the drying phase helped promote evaporative heat loss and speed up the process of sweat evaporation (González-Alonso et al., 1999).

**Physiological Parameters**

Measuring $T_{\text{skin}}$, found significantly different for different fiber types in the activity and drying phases. To a lesser extent, but still, substantial differences have been detected at different time points for the $R_{\text{skin}}$, $T_{\text{fab}}$, and $R_{\text{fab}}$. To put it another way, there was a tendency for the fiber types to act differently during the various phases. These findings were different from several other studies, showing no differences in thermophysiological variables between natural and synthetic fiber-made sportswear during exercise (Brazaitis et al., 2010b; Gavin et al., 2001b; Ha et al., 1999; Heus & Kistemaker, 1998a; Kaplan & Okur, 2012b; Laing et al., 2008b; Noonan & Stachenfeld, 2012; Sperlich et al., 2013; Stapleton et al., 2011b; Wickwire et al., 2007; Wingo & McMurray, 2007). This experiment employed a plastic cage with a controlled air velocity. It is essential to keep in mind that activities carried out in a natural setting would result in a substantially increased volume of air movement. Because of the airflow, there will be a larger loss of heat due to convection and evaporation, which may further reduce the increases in $T_{\text{skin}}$, $R_{\text{skin}}$, and $R_{\text{fab}}$ (Gavin, 2003).
**Moisture Absorption and Performance**

Wearing WBT did not affect performance, even though the RH% was the highest of all fiber types. This phenomenon is also true for $T_{skin}$. The participants did not report that wearing WBT hindered their performance during the activity phase, as all twelve participants could be able to finish the 25 minutes of continuous riding without a single break for each clothing type. Therefore, it was unlikely that there were changes in the performance of the individuals regardless of whether they wore hygroscopic or non-hygroscopic synthetic or natural fiber. Several researchers (Noonan & Stachenfeld, 2012; Park et al., 2006; Sperlich, 2013) have evaluated the impacts of clothing fiber types on sportswear's performance; however, only one (Park et al., 2006) indicated that natural fibers perform significantly better than synthetic fibers.

**Subjective Responses**

The study's most noteworthy findings were the broad range of subjective responses observed between the shirts tested. No evidence suggests that synthetic fibers PLT (low moisture regain) and VB (high moisture regain) are more comfortable than natural fibers CL, WLT, and WBT. Thermal sensation, perceived comfort, and pleasantness were shown to be significantly different in the case of synthetic and natural fibers, whereas, in the earlier studies, researchers were unable to achieve any distinctions between these two (Brazaitis et al., 2010; Gavin et al., 2001; Ha et al., 1999; Kwon et al., 1998; Laing et al., 2008; Stapleton et al., 2011; Wickwire et al., 2007). In contrast, WBT outranked PLT, VB, CL, and WLT in evaluations for thermal sensation, thermal comfort, and subjective pleasantness. The objective data showed very few differences throughout the trials, whereas subjective data were much more significant. It should be noted that the subjects were unaware of the fiber types of shirts.
A more humid micro-climate environment reduces the amount of evaporative heat loss (Havenith, George, 2002), which may result in feelings of enhanced warmth (Ha et al., 1999). However, in the present study, the sweat dripping did not occur, and from the wetness sensation rating, it can be seen that there were significant differences found after the 45 minutes and lasted for only 5 minutes, and most of the ratings lay in between (barely wet) and (slightly wet). This significant difference could not impact much on the perceived comfort. The enhanced evaporative cooling during the drying phase greatly influenced the $T_{\text{skin}}$ and $R_{\text{skin}}$. Both $T_{\text{skin}}$ and $R_{\text{skin}}$ significantly decreased due to both conductive and evaporative cooling and moisture vapor. In the drying phase $T_{\text{skin}}$ and $R_{\text{skin}}$ for PLT, decreased significantly, which induced a greater discomfort at the end. In contrast, the $T_{\text{skin}}$ and $R_{\text{skin}}$ for WBT decreased at a much slower rate, which helped the participants to buffer the post-exercise chill and feel more comfortable than all other fiber types.

The wetness of clothing is one of the most significant elements contributing to discomfort during wear (Li, 2001; Li, Yun, 2005b). Although PLT revealed the lowest wetness among the five tested shirts, it exhibited the most uncomfortable feeling in the post-exercise period due to wind conditions. In contrast, due to the high moisture regain of WBT, it exhibited a certain degree of wetness in the torso zone that developed endothermal heat to buffer the post-exercise chill.

**Thermal Comfort During the Post-Exercise Phase**

As mentioned earlier, one of the best findings of this research based on the test method and test protocol is that the study found statistically significant differences among the fiber types for subjective responses. In contrast to prior research that failed to distinguish between different types of fiber, the responses were distinct and noticeable in terms of subjective responses (Davis
& Bishop, 2013). Gavin et al. tested polyester and cotton with eight male subjects with a test protocol of running, walking, and rest phases in moderate warm conditions (30°C, 35% RH) in a very windy environment. They demonstrated that during or after the exercise, fabric characteristics of the clothing did not have any significant impact on physiological, thermoregulatory, or comfort responses (Gavin et al., 2001c). These researchers may not have appropriately utilized the wind speed because high-speed wind influences drying out the moisture during the exercise. Ultimately, no difference between the hygroscopic and non-hygroscopic fiber types was observed. With similar wind speed and exercise protocol, Laing et al. tested in both hot (32°C, 20% RH) and cold (8°C, 40% RH) conditions with wool, wool-polyester blend, and polyester. Nevertheless, they could not find conclusive results for thermophysiological variables and comfort sensations (Laing et al., 2008c). Also, studies from (Brazaitis et al., 2010c; Dai et al., 2008b; Heus & Kistemaker, 1998b; Kaplan & Okur, 2012c) tested objective and subjective responses and concluded that no notable differences were observed for natural or synthetic fabrics. The present work, however, shows that WBT's delayed endothermic nature was responsible for the gradual heat release in the drying stage. This means that although no significant differences were observed in the physiological parameters between the fiber types due to exothermic heat generation, the effects were prominent in the case of thermal sensation, which seemed to buffer the post-exercise chill.

Participants preferred WBT to Cl, VB, WLT, and PLT because it was perceived as more comfortable during the chilly post-exercise condition. The high moisture regains of wool fiber helped trap moisture into inter-fiber gaps. This subsequently contributed to the slow endothermic reaction and improved comfort in the post-exercise phase.
Effect of Air-permeability and Hydrophilicity and Hydrophobicity Behavior

All of the five fabrics are the same thickness; however, their air permeability varied substantially (Table 6-1); also, all the shirts were fitted tightly on the torso of the subjects, so that air permeability effects should have been limited due to the very narrow ventilation area underneath the fabric. According to studies by Prahsarn et al. (Prahsarn et al., 2005) and Bedek et al. (Bedek et al., 2011), textiles having a higher air permeability dry faster than those with lesser air permeability. Even though both PLT and VB have high air permeability, it was found that VB had the highest degree of dampness at the end of the test, which was significantly different from PLT. In this experiment, participants wore clothing that fitted them very snugly. Therefore, there was minimal space for air to circulate around the skin's microclimate. Even though PLT (393 cm$^3$/s/cm$^2$) and VB (204 cm$^3$/s/cm$^2$)) had much higher air permeability than CL (79 cm$^3$/s/cm$^2$), WLT (93 cm$^3$/s/cm$^2$), and WBT (99 cm$^3$/s/cm$^2$), it was seen that the $T_{\text{skin}}$, $R_{\text{skin}}$, $T_{\text{fab}}$, $R_{\text{fab}}$ and subjective ratings pairwise post hoc comparison could not differentiate CL, VB, and WLT at some time points in the drying phase. On the other hand, despite the fact that the value of WBT was approximately the same as that of CL and WLT, WBT was notably distinct from CL, WLT, VB, and PLT in almost every instance. The same reasoning applies to the PLT, meaning that a higher permeability did not result in an increased comfort rating. On the other hand, hygroscopic natural fibers tend to swell when they absorb moisture from the skin, which slightly reduces the air spaces between the yarns and lengthens the amount of time it takes for the fabric to dry out (Lee, 2014). Therefore, at 45 minutes, fibers absorb moisture and have fewer inter-yarn-free spaces to allow wind to pass through. As the fabrics dry out, the remaining moisture in the fabric evaporates, and at the end of the test, the air permeability has less effect on the subjective responses.
6.5 Limitations

Finally, the study solely included male participants. Male volunteers were chosen as the primary test subjects to verify that the garment would fit well in the torso area. A further possibility is that females have a lower cold tolerance than males; nevertheless, researchers have concluded that the differences in regulating body temperature are minor (Havenith, G., 1997). According to $T_{skin}$, the cold stress experienced throughout the experiment was not particularly strong. The mean skin temperature reached for VB was 26.8°C, the lowest temperature that could have been experienced, and was simple for the male participants to complete. Despite this, a future strategy that involves research on quantifying and evaluating the exothermic advantages for both male and female individuals should be taken into consideration by undertaking broader and more severe environmental conditions.

6.6 Conclusion

This study aimed to investigate the thermophysiological effects and subjective evolution of exothermic reactions by hygroscopic and non-hygroscopic fibers in clothing in a dynamic setting. However, the feedback from participants during the post-exercise period revealed a significant impact of fiber behavior on thermal comfort, especially with wool fiber, compared with cotton, viscose, and polyester. The dynamic state was achieved by cycling in a moderately cold environment. Following the cycling activity, the subjects were given the opportunity to dry off in a windy atmosphere so that the effect of exothermic advantages could be assessed. The study demonstrates that the hydrophobic wool garment was effective in maintaining an excellent thermophysiological balance by its delayed endothermic heat release properties and is significantly different from cotton, viscose, and polyester. The hydrophobic wool shirt also garnered more favorable responses from participants. This study was one of the first to analyze
the effects of exothermic behavior on thermophysiological variables and comfort. Further research on female subjects should be undertaken to improve and validate the investigation.
References

Barker, R. (2011). In Song G. (Ed.), *Evaluating the heat stress and comfort of firefighter and emergency responder protective clothing*. Copyright status: This work, authored by Dr Roger L. Barker, was funded in whole or in part by National Institute of Occupational Safety and Health of the Centre for Disease Control and Prevention under U.S. Government contract number 254-2004-M-05954, and is, therefore, subject to the following license: The Government is granted for itself and others acting on its behalf a paid-up, nonexclusive, irrevocable worldwide license in this work to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. All other rights are reserved by the copyright owner. Woodhead Publishing. https://doi.org/10.1533/9780857090645.3.305.


CHAPTER 7: Measuring the Heat of Wetting of Clothing Fabrics by Isothermal Calorimetry

Abstract

One of the fundamentals for studying the interaction between moisture and textiles is the heat of wetting. Much previous research explained the measurement of heat of wetting in the fiber form. The value reported for the heat of wetting in fiber form may not fully represent the benefits of a higher sorption value in the clothing form. The purpose of this research was to investigate the sorption behavior of textile materials while in fabric form by determining their exothermic behavior during interaction with water. The heat of wetting of textile fabrics was measured using a TAM Air isothermal microcalorimeter. This research presents a new approach to measuring the heat of wetting of fabrics.

Keywords: sorption properties, the heat of wetting, calorimetry, fabrics

7.1 Introduction

The potential of natural fibers for use in functional clothing has attracted academic interest in studying their physical properties beyond their traditional uses in textiles. Due to their hygroscopicity, they have not only the potential to act as a passive insulation material but also to buffer rapid changes in humidity in the environment. Understanding the sorption behavior of natural fibers in the presence of various ambient humidity conditions is essential for their use in functional clothing (Hill et al., 2009). In Chapter 5 and Chapter 6, we showed that hygroscopic fibers develop exothermic heat while absorbing moisture, which can buffer the post-exercise chill. That exothermic heat is because of the interaction of water with textile materials during moisture absorption. Individual fibers have their own way of reacting with water molecules which can contribute to different sorption heat mainly because of their chemical structure.
Although the heat of sorption of different textile fibers is well established, the sorption behavior of materials in clothing form needs to be investigated. Hygroscopic natural fibers, e.g., cotton, and wool, exhibit exotherm effects while absorbing moisture from the human skin or the environment. Due to the high heat of wetting, some textile fibers, like wool, are often used for winter clothing. One of the most important factors is that the heat of wetting of fibers is one of the determinants of clothing comfort when it is used for a specific environmental condition (Mizutani et al., 1999; Varga, Schaedel et al., 2007).

Thermodynamically, the heat released during vapor or liquid water absorption can be described as the differential heat of sorption and the integral heat of sorption (also known as the heat of wetting). The differential heat of sorption is defined as the heat released during the absorption of one gram of water by an infinite mass of textile material. In comparison, the heat released during the complete wetting of fabric at a given regain and whose dry mass in one gram is known as the heat of wetting. The units of measure for both are joules per gram (Kondo, 1985). It should come as no surprise that the heat of wetting is greatest for the most absorbent fibers and is minimal in non-hygroscopic fibers. The amount of heat generated is directly proportional to the amount of moisture the fiber can absorb (Hearle & Morton, 2008).

As a vital fabric and comfort parameter, it should be well defined how to determine the heat evolved during moisture absorption. Several methods can be found for the thermal analysis of textile material, including conventional differential scanning calorimetry (DSC), temperature-modulated DSC (TMDSC), and simultaneous DSC–TGA. DSC measures heat absorption, TMDSC measures heat capacity, and simultaneous DSC–TGA measures heat evolved in Joules per gram (Varga, Schädel et al., 2007). Furthermore, many researchers have tried to measure the heat of wetting for various kinds of textile fibers (Guthrie, 1949; Hearle & Morton, 2008; Kondo,
1985; Rees, 1948; Shorter, 1924; Toy et al., 1946). Most of the earlier studies have been concerned with the sorption isotherm using calorimetry techniques, which can measure the heat of absorption of textile fibers; however, no studies have been reported on the heat of wetting for clothing fabrics. Because measuring it in a clothing form will allow considering a wide range of factors such as air permeability, the air gap between skin and microclimate, fabric structure, and others that can influence the moisture sorption behavior. Therefore, studying the heat of wetting of textile fabrics should provide more context on textile materials and the physiology of clothing comfort. The primary objective of this work was to investigate the heat of wetting of fabrics by reaction calorimetry technique using iso-thermal air calorimetry. Textile materials usually evolve less heat compared to other materials, and the novelty of the instrument is that it can measure evolved heat effectively on the nanowatt scale.

7.2 Materials and Methods

Five different materials with the same thickness were employed to measure the heat of wetting by TAM air isothermal calorimetry. Two different approaches were used to check if sampling methods affect the measurement value. The experiments were carried out at 23°C and under isothermal conditions. By dividing the heat evolved (J) by the sample weight (g), the heat of wetting (J/g) is calculated.

7.2.1 Materials

Table 7-1 shows the summarized results of the tests on the basic physical properties of wool, cotton, viscose, and polyester. ASTM D1777 was used to determine the thickness. Six specimens (15 cm × 15 cm) were measured at a pressure of 0.6 psi (pounds per square inch) with a thickness gauge. The small swatch option of ASTM D3776 was also used to determine the weight of the fabric. A total of three samples (15 cm × 15 cm) were weighed in an analytical
balance, and their weight was calculated in mass per unit area (g/m\(^2\)). Air permeability was measured according to ASTM D737 using a Frazier Air Permeability tester.

Table 7-1 Physical properties of fabric samples.

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Sample ID</th>
<th>Fabric Composition</th>
<th>Surface Characteristics</th>
<th>Fabric Structure</th>
<th>Weight (g/m(^2))</th>
<th>Thickness (mm)</th>
<th>Air Permeability (cm(^3)/s/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WBT</td>
<td>100% Merino Wool</td>
<td>As it comes</td>
<td>Jersey Knit</td>
<td>213</td>
<td>0.69</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>WLT</td>
<td>100% Merino Wool</td>
<td>Hydrophilic (finished with softener)</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.69</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>100% Cotton</td>
<td>As it comes</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.65</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>PLT</td>
<td>100% Polyester</td>
<td>As it comes</td>
<td>Rib Knit</td>
<td>199</td>
<td>0.69</td>
<td>393</td>
</tr>
<tr>
<td>6</td>
<td>VB</td>
<td>100% Viscose</td>
<td>Hydrophobic (finished with softener)</td>
<td>Jersey Knit</td>
<td>204</td>
<td>0.67</td>
<td>204</td>
</tr>
</tbody>
</table>
7.2.2 Sample Preparation

After weighing the samples of 0.5 g (5 cm × 5 cm), oven drying was performed at 105°C for 2 hours. The samples were sealed while leaving the oven and kept in a plastic bag. The plastic bag was always kept in a desiccator to maintain a stable surrounding condition. In this experiment, two different methods of sample preparation were followed. Keeping the sample at the dimensions mentioned above was one approach. The second approach involved slicing the sample into smaller pieces to expose more surface area of the fabric.

7.2.3 Determination of Heat of Wetting by TAM Air Isothermal Calorimeter

The heat of wetting of six different samples was measured using a TAM Air isothermal calorimeter from TA instruments (New Castle, DE, USA). TAM air is an 8-channel calorimeter that works according to the heat flow principle and is designed as a twin or differential instrument (Figure 7-1). An inert material with the same thermal properties as the sample is used on the reference side to cancel out thermal fluctuation and strengthen the signal. Thermoelectric modules are typically placed between a sample ampoule holder and the heat sink to measure heat flow. Each ampoule holder consists of an injected system and manual stirring that can inject 4 ml of liquid for optimization. The thermoelectric module produces a voltage proportional to the heat flow due to a temperature differential. Once the samples had been in the calorimeter for 45 minutes, the heat flow measurements could begin to ensure that the samples had reached thermodynamic equilibrium with the calorimetric temperature, as time counting starts when the samples are placed in the calorimeter. The procedure followed manufacturer guidelines to reduce the impact of the temperature difference between the sample and the calorimeter on the precision of the heat flow measurements (Pushp et al., 2022) (TAM AIR Isothermal Calorimetry, 2022).
Two methods (Figure 7-1) were used to measure the heat of wetting of the samples, as previously mentioned. The samples were folded and inserted into the ampoule in the first method. Water was injected into the fabric sample after 45 minutes in 0.5 ml, 1 ml, 2 ml, and 4 ml from four different channels. The quantity was chosen to test the effects of various amounts of water on the sorption characteristics of textile fiber. Each of the samples was tested once for a specific amount of water.

The second method involved dissecting the samples (WBT and VB) before loading them into ampoules and carrying out the same steps as the first. Each sample was tested twice, and the heat of wetting was expressed as an average.

![Figure 7-1](image-url) (a) TAM Air isothermal calorimeter by TA instruments (b) Fabric samples are folded and loaded into the ampoules with 0.5 ml, 1 ml, 2 ml, and 4 ml with syringe adjustments. (c) Fabric samples are cut into pieces and loaded into the ampoules with the syringe adjustments.

### 7.3 Results and Discussion

The results of measuring the heat of wetting with the TAM Air isothermal calorimeter were illustrated in Figure 7-2 for different amounts of water when folded samples were used. The measured value of the maximum heat of wetting is also shown in Figure 7-3. Besides the polyester, heat evolution was noticed for the other fiber types. WBT showed the highest increase in heat when 0.5 ml of water was used. Additionally, it showed a decreasing tendency to heat
release as the amount of water increased; however, it was not consistent. On the other hand, in hydrophilic wool, WLT showed a lower heat release than WBT. However, viscose showed moderate heat release while the data seemed inconsistent while adding different amounts of water during experimentation. Cotton showed a lower amount of heat release despite being hygroscopic; for 4 ml of water, it did not seem to release heat. Furthermore, from the graphs shown in Figure 7-2, it can be shown that the sorption behavior is a two-stage process for the moisture-absorbing fibers. WLT and CLT reacted to exothermic heat release almost immediately. In contrast, WBT and VB showed a more extended period for exothermic heat release (almost 200 minutes) until equilibrium was reached. Despite the inconsistency in the exothermic trend shown in the graphs, it can be said that WBT and VB showed more significant sorption heat while absorbing water.
Figure 7-2 Heat of wetting measured in J/g for WBT, WLT, VB, CLT, and PLT at (a) 0.5 ml (b) 1 ml (c) 2 ml (d) 4 ml water.
The summary shown in Figure 7-3 explains that WBT has the highest heat release among the fiber types. This value of the heat of wetting of different fabrics is lower than the literature value of fibers reported by Varga et al. (Varga et al., 2007). The paper mentioned values for
cotton, viscose, and polyester fibers are 45 J/g, 90 J/g, and 10 J/g, respectively. However, they did not measure the value of wool fibers. The TAM Air isothermal calorimetry measures sorption heat in the solution calorimetry principle. In solution calorimetry, the heat evolved is measured when unbound water is attached to the primary and secondary bond water in the fiber molecules. When water bonds directly with hydroxyl groups during absorption, the sorption heat is at its maximum. Heat dissipation is diminished when water molecules are arranged in multiple layers. Also, in this case, all the fabrics were dried at 105°C; this high temperature causes the closure of the hydroxyl pores, which undoubtedly reduces the heat release, which can be observed in the case of CLT (Fernandes Diniz et al., 2004). The hydrophobic nature of PLT did not allow it to absorb moisture and did not show sorption heat.

![Figure 7-3 Summary of the maximum heat of wetting measured (J/g) during the different amounts of water absorption by wool, cotton, viscose, and polyester fibers when folded samples were used.](image-url)
The heat release when grinding samples were used is shown in Figure 7-4. A summary of the measured heat release for different amounts of absorbed water is also shown in Figure 7-5. WBT showed the highest amount of wetting heat than viscose in all cases, unless for 0.5 ml of water. The reason might be that the WBT samples did not wet uniformly and did not show the exothermic heat as expected. The higher value of heat released for wool may be due to its more amorphous region (70-75%) than the viscose (60-65%), which enables the WBT structure to have more binding water (Mizutani et al., 1999). Moreover, Wool's unique interior and exterior structure may contribute to its greater sorption heat. The wool surface has overlapping scales called cuticle cells with a waxy coating, which helps protect the fiber from exterior damage and makes the fiber hydrophobic at the surface. The interior of wool is composed of the cortical cell surrounded by the cell membrane complex, which can absorb water moisture (Popescu & Wortmann, 2010). Generally, wool repels water liquid at the surface but can absorb or desorb water vapor and appears hygroscopic. Because of the greater sorption heat of wool fiber, it may serve as a temperature regulator in apparel to protect and keep the warmth in the human body. Its three-dimensional hierarchical structure causes water to react exothermically with the polar groups of polypeptide chains during moisture absorption, breaking down its hydrogen bonds and releasing heat, which is trapped between the air pockets (Cook, 1984).

In this experiment, the fabric samples were prepared at almost the same thickness; however, the samples were not uniform in terms of structure, weight, and air permeability. Although the fiber structure has an influence, the above properties might influence the lower heat of wetting value of the fibers as well. Also, the sample density was low, and it caused the floating of samples above the water's surface. The current setup that was used did not allow fabric materials to be in close contact with the calorimeter surface, which may have lowered the
obtained values for sorption heat. However, this may still be a relevant example of mimicking the human clothing environment. An air gap exists between the skin and fabric in regular clothing. So, the literature value of the heat of wetting might not work in the actual scenarios.

The calorimetry method utilized to calculate the heat of wetting was not optimal. Instead of soft materials like textile fibers, the TAM air isothermal calorimeter is typically employed to evaluate the heat of wetting for cement materials. Nevertheless, it offered some useful information to get things started, and more research might be done on sampling and precisely quantifying the heat emitted during water vapor absorption. We cut the samples into pieces with scissors for sampling; notably, the size of the samples was not homogeneous. On the other hand, we found that uniform sampling had the biggest effect on calorimetry trials. Therefore, a template or a fabric grinding machine can be recommended for better sampling. Moreover, an additional device might be designed to be used with the injection system to hold materials in touch with the ampoules' surface.
Figure 7-4 Heat of wetting measured in J/g for WBT and VB when samples cut into pieces (a) WBT (b) VB.
Conclusion

This work attempted to measure the heat of wetting of wool, viscose, cotton, and polyester fabrics using TAM Air isothermal calorimetry. This technique enables measuring the heat of wetting while considering the skin-clothing interaction. Although wool and viscose showed greater heat of wetting, the values were lower than the fiber values reported in the literature. The feasibility of TAM Air isothermal calorimetry for measuring the heat of wetting may be a topic of further research considering the fabric structure, weight, and porosity of the fabric.
References


CHAPTER 8: A Novel Test Method to Measure the Exothermic and Endothermic Behavior of Fabric in Dynamic Condition

Abstract

This paper describes use of a novel dynamic hot plate to analyze the exothermic and endothermic behavior of textile fabrics. Based on fabric testing, manikin testing, and human trials discussed in the earlier chapters, this test method on a dynamic hot plate can address the limitations of ISO 16533 and Naylor's dynamic hot plate test. The fabrics were conditioned and placed on the hot plate following the standard procedure for the dry mode test, but sweating was enabled after a certain time to mimic the activity. In addition, the wind was induced to investigate the drying behavior of the fabric. Moreover, the test method also identifies the fabric behavior if the wind is reduced. These steps (rest-activity-dry) in the dynamic hot plate allow the temperature, and humidity gradient, which was not addressed by the previous test methods, to recognize the importance of transient microclimate conditions on perceived comfort in active wear.

Keywords: dynamic hot plate, exothermic and endothermic behavior, moisture management, activewear

8.1 Introduction

It is well-known that hygroscopic textile fibers can generate exothermic heat while absorbing moisture from the skin or environment. During the exercise period, those fibers can develop this exothermic effect, which can buffer the discomfort during the process of cooling down or releasing moisture through evaporation. Chapter 5 and 6 briefly described the measurement of exothermic and endothermic characteristics of textile materials and its physiological impact through sweating manikin testing and human trials. However, manikin and
human studies are complex to execute and interpret, and therefore, are not suitable as a standardized methodology. As discussed in previous chapters, testing comfort properties of fabrics in transient conditions is a complex phenomenon and yet no such test methods have been proposed that can properly address fabric behavior and physiological attributes in a one-step continuous test method.

As part of their marketing strategies, activewear companies frequently use testing procedures and environments that yield the best results for their products, as was amply demonstrated by (McCullough et al., 2003). In most cases, test procedures were unable to address the fabric's behavior and the comfort level associated with it because they were designed for steady-state conditions. Nevertheless, the dynamic process of moisture adsorption and liberation is crucial when designing activewear and moisture testing apparatus, as clothing is typically served in a dynamic condition. In this research, we investigated the exothermic and endothermic properties of textile fabrics, using samples of the same thickness but designed for activewear to explore dynamic moisture transport behavior and physiological impacts.

8.2 Materials and Methods

8.2.1 Materials

The basic physical properties of five different textile materials have been tested, and the results have been summarized in Table 8-1. The measurement methods of basic physical properties of the materials were discussed in Chapter 4.
<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Sample ID</th>
<th>Fabric Composition</th>
<th>Surface Characteristics</th>
<th>Fabric Structure</th>
<th>Weight (g/m²)</th>
<th>Thickness (mm)</th>
<th>Air Permeability (cm³/s/cm²)</th>
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</thead>
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<td>1</td>
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<td>As it comes</td>
<td>Jersey Knit</td>
<td>213</td>
<td>0.69</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>WLT</td>
<td>100% Merino Wool</td>
<td>Hydrophilic (finished with softener)</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.69</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>100% Cotton</td>
<td>As it comes</td>
<td>Jersey Knit</td>
<td>188</td>
<td>0.65</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>PLT</td>
<td>100% Polyester</td>
<td>As it comes</td>
<td>Rib Knit</td>
<td>199</td>
<td>0.69</td>
<td>393</td>
</tr>
<tr>
<td>5</td>
<td>VB</td>
<td>100% Viscose</td>
<td>Hydrophobic (finished with softener)</td>
<td>Jersey Knit</td>
<td>204</td>
<td>0.67</td>
<td>204</td>
</tr>
</tbody>
</table>

### 8.2.2 Test Instrument

The dynamic sweating hot plate used in the testing is shown in Figure 8-1. The instrument was set in a standard testing atmosphere (temperature 21°C and relative humidity 65%). It consists of a guarded hot plate with four sweat pores, a diffusion cell, and a data
acquisition system. The diffusion cell can simulate a sweat pulse produced by a sweating human. The plate was maintained at 35°C and used as a heat source. A blower was also attached to the instrument and maintained an air velocity of 1 m/s.

Figure 8-1 (a) The dynamic sweating hot plate consists of a testing plate, water reservoir, a blower, and data acquisition system (b) Water reservoir for sweat initiation (c) MSR temperature and humidity sensor placed on the plate to determine temperature and humidity of the skin - microclimate.

The experimental setup mimics how water vapor evaporates from the skin after a sweat pulse is released. Fabric with one side exposed to the regulated atmosphere and the other facing the plate was used to create a realistic environment. Maintaining temperature and vapor pressure gradients between the point where moisture vapor emerges from the simulated skin at 35°C, 100% relative humidity (RH) and the ambient environment controlled at 21°C and 65% RH drives the movement of moisture vapor (Prahsarn et al., 2005). MSR (Modular Signal Recorder MSR®/ MSR 145, Seuzach, Switzerland, accuracy ±0.1°C for temperature and ±2% for RH) were used with tape (3M) to monitor the skin microclimate and the cloth surface temperature and humidity.
8.2.3 Test Method

The test period lasted 90 minutes (5400 s) and consisted of three phases: relaxation, activity, and drying. After the plate had reached its steady state temperature of 35°C, a 12 cm x 12 cm fabric sample was placed on it to begin the test. After 20 minutes, a sweat rate of about 650 ml/hr/m2 was initiated to simulate a moderate metabolic rate in the body. There was no variation in the activation time of the simulated sweat pulse for the study. After 20 minutes, the blower was turned on and the sweat pulse was turned off. The blower kept its 1 m/s speed constant. The blower was turned off after 35 minutes, and the test continued for an additional 15 minutes to completely dry the fabric. Throughout the experiment, heat flux (W/m²), microclimate temperature and humidity, and fabric surface temperature were measured. Three repetitions of each sample were used, and results expressed as their mean value.

8.3 Results and Discussion

8.3.1 Characterizing the Heat loss Behavior of Fabrics

The guarded hot plate, which generates the heat flux, operates on a similar principle with a sweating guarded hot plate, albeit in a non-isothermal test. The ambient side was kept at 21°C and 65% RH, while the sweating skin side was kept at 35°C and 100% RH. The temperature and humidity gradients provided the dynamics for the test. Figure 8-2 shows the results of real-time measurements of the heat flux data from the hot plate. All types of fiber maintained a constant heat flux value up to 1200 s. When sweating was induced, the disparities in heat flux became apparent. At the end of the activity period, PLT had the highest heat loss (388 W/m²) while WBT had the lowest (212 W/m²). In addition, after 2400 s, the wind increased the heat flux value for all types of fiber. Initially, when the wind was induced, the value of PLT increased by almost
50% (800 W/m²). The wind lasted approximately up to 4500 s, and the heat flux value revealed interesting fiber behavior. WBT and VB were more stable over the course of the windy conditions, while the PLT’s value dropped to about 300 W/m² at around 3500 s. CL and WLT followed the same pattern, though their curves were flatter than those of PLT. When the wind stopped at 4500 s, the heat flux value of the fabrics decreased further. One of the reasons of decreasing the heat flux value before the ventilation was switched lower could be faster drying out of fabric surface that facilitates more wind to pass through hence lowering the heat flux value.

![Figure 8-2 Heat loss at the skin surface during the three stages phase change](image)

8.3.2 Microclimate Temperature and Humidity

The temperature and humidity changes in the microclimate during the transient condition were plotted in the Figure 8-3 and Figure 8-4. Once sweating began, at 1200 s, the PLT, WLT,
and VB temperatures gradually decreased (by at least 3 °C). Until the introduction of the wind, WBT and VB kept the same temperature because they did not absorb the liquid moisture and did not show any variation in the temperature. Enhanced heat loss from the fabric surface causes a cooling of the local microclimate. WBT demonstrated the lowest temperature drop (0.5°C) compared to the other fiber types at 2400 s, when the wind started, while CLT showed the largest temperature drop (around 5°C) compared to the other fiber types. It was also observed that when the wind ceased, the microclimate temperature was increased again to its original value.

The value of microclimate humidity depicted in Figure 8-3 may support the aforementioned observations. In a dynamic sweating plate system, the microclimate's humidity changes over time, unlike in a static plate system (Prahsarn et al., 2005). When sweating was activated, the humidity increased from its initial value, and when wind was induced, it gradually decreased. PLT, CL, and VB demonstrated complete drying at the end of the testing period, but WBT and VB were found to still have some moisture on the fabric.
8.3.3 Fabric Surface Temperature

Changes in fabric temperature are caused by the equilibrium of the humid fabric with its environment through the release of moisture (Li et al., 2008). Fabric surface temperatures were previously studied by Li and Holcombe (Li, Y. & Holcombe, 1992) during the moisture adsorption process; here, we illustrated those temperature changes during the adsorption and desorption process. Figure 8-5 showed, through a series of curves for different types of fiber, how the surface temperature of fabrics changes as they absorb and release moisture in the presence of wind. It was observed that the temperatures remained stable from the beginning of the curves to the first transition point at 2400 s, despite the fact that the fabric absorbed moisture during that time. Because evaporating water is an endothermic process, the temperature dropped dramatically when the wind was induced and the water on the fabric's surface evaporated. The temperature decrease was greatest for PLT (down to 24.5°C from 30°C) and least for WBT.
(down to 27°C from 30°C). Finally, when the wind stopped, its surface temperature continued to rise.

Figure 8-5 Surface temperature of the fabric in the process of moisture adsorption and desorption.

8.3.4 Relationship Between Heat Flux Value, Microclimate Temperature and Humidity, and Fabric Surface Temperature

Although they had identical thicknesses, the test fabrics differed in weight, air permeability, fiber composition, yarn type, and finish, which could affect their evaporative cooling and the water adsorption, wicking, and drying capabilities associated with them. 100% Polyester knit (PLT) and 100% wool knit (WLT) treated with a water-wicking finish were representative of contemporary high performance activewear knits that demonstrate great wicking and quick drying performance (Manshahia & Das, 2014) (Chapter 5). On the other hand, cotton knit (CLT) and wool knit (WBT) represented commonly used moisture-absorbent t-shirt material with slower wicking and drying properties compared to treated wicking fabrics. The
CLT, WBT knit had no wicking finish. Furthermore, a hydrophobic finish was applied to 100% viscose knit (VB) to compare its characteristics with regular wool garments (WBT), since the outer surface of natural wool acts as a hydrophobic surface (Popescu & Wortmann, 2010).

The PLT fabric displayed a greater heat loss during the sweating period primarily; it can be considered that PLT has the highest cooling potential in this comparison. In addition, it also showed a drying time faster than that of other fiber types. These observations suggested that polyester fabrics were superior in terms of temperature cooling and moisture management. However, the impact of the magnitude of these attributes depends on several other factors, namely activity levels, environmental conditions, and the subject’s ability to discern those attributes. As evident in Figure 8-3, the microclimate temperature dropped by at least 4.5°C for the PLT during the sweating phase, while the wind further worsened the scenario. This drop in temperature could seriously affect the thermal sensation of the wearer, as a relatively minor change of 1°C is noticeable when a person moves from a warmer to a colder area (Holcombe, 2009). Additionally, this discomfort in thermal sensation was validated by human trials described in Chapter 6. The microclimate humidity shown in Figure 8-4 also revealed that WBT maintained a much drier microclimate than the other fiber types. WBT showed a delayed response to buildup humidity in the microclimate compared to the other types of fiber, whereas PLT showed a quicker response to buildup humidity. It took only 400 s to reach a maximum microclimate humidity of 72% for the PLT, whilst for the WBT; it took around 1200 s to reach a maximum humidity of 60% during the sweating phase. This gradual increase in humidity should provide comfort during the dynamic change in the environment.

Although there was no change in fabric temperature before the wind was added, WBT had a tendency to keep the fabric surface warmer in the wind between 2400 and 4500 s. WBT's
ability to retain heat could improve wearer warmth even while the garment loses heat through evaporation. It may considerably buffer post-exercise chill, which was observed during the human trial and discussed previously in Chapter 6. Limitations in sensor placement on the fabric's surface could account for the inability to display temperature variations during the sweat phase. Due to the proximity of the fabric surface to the plate, it was possible to acquire temperature data from both the fabric and the plate.

8.4 Conclusion

The newly developed exothermic and endothermic test method provided the optimum platform for observing the dynamic interaction between microclimate conditions and evaporative cooling provided by textile materials. The protocol simulated a realistic scenario through sweating (during exercise) and non-sweating (during drying) phases, as well as windy and non-windy environments (introduced subsequently). Although the polyester had a higher heat flux value, suggesting that it was more effective at dissipating heat, the high cooling rate could result in discomfort. The microclimate managed by natural wool, on the other hand, was more consistent in terms of temperature and humidity, which should result in improved thermal comfort and stability for the wearer.
References


CHAPTER 9: Conclusions: Discussion of Findings, Suggestions, and Proposed Future Research

The main interest of the textile & clothing industry is to have a fabric test method that reliably measures the exothermic effects and allows for a clear explanation of these results to the customers and end-users (consumers). The studies that were conducted as part of this research project focused on understanding and questioning the current test methodologies to characterize the exothermic and endothermic behavior of fabrics in transient environment conditions and provide the industry with tangible explanations for their impact on physiological sensations and comfort. The overarching conclusions that can be made by combining all results of these fabric tests (ISO 16533, Naylor’s dynamic hot plate test), manikin testing (thermal manikin testing with a step change in humidity, sweating manikin testing with a step change in body metabolic rate), and human trials (in a controlled climate chamber with an activity-rest protocol) are the following:

- Methods that only use changes in relative humidity in the environment exhibit exotherm effects, but these effects on human physiology are small because of the temperature gradient from the skin to the environment.
- Methods that used ‘sweat’ as liquid produced on the hot plate or skin showed better potential for physiologically relevant exotherm effects as it induces a larger humidity change at the fabric.
- The methods that use sweat will have some interference from the wicking and absorption properties of the fabric, as that will enhance cooling in the tests that were run.
- The manikin and human studies are complex to execute and interpret, and therefore, are not suitable as a standardized methodology.
- The fabric test method that combines these concepts is the dynamic hot plate test protocol. This seems the most appropriate fabric test to demonstrate where and when exotherm effects significantly impact human thermal comfort. This dynamic hotplate test is proposed as a novel test method.

In Chapter 8, this proposed novel test method was discussed to assess the exothermic and endothermic behavior of the fabric during a continuous one-step protocol mimicking activewear by simulating sweating and drying.

9.1 Discussion of Findings

9.1.1 Comparison of Test Methods

The standard (static) regain test measures only the final absorption of water vapor to the fabric. The dynamic regain test reflects the water vapor absorption processes in fabrics during humidity (RH) changes. The initial rapid regain uptake rate can be used to measure realistic exothermic effects, as that is directly related to the regain rate and can show measurable differences among the fiber types. However, there seem to be only small differences between the initial uptake rates of wool, cotton, and viscose. The prolonged effects to fully achieve the steady state regain value has a very limited (not measurable) effect on the exotherm responses. Therefore, the addition of long-term dynamic regains tests does not seem practical.

The ISO 16533 method is a standard for determining the exothermic and endothermic behavior of textiles and is relatively simple in its setup and procedure. However, there are still some challenges in repeatability, depending on the size of the container and the effects of changes in humidity. Furthermore, the current method suggests only measuring temperature
changes (peak temperature), which is shown to be a very poor estimate of exothermic (and endothermic) effects. Although this method could provide a direct measure of energy release, it cannot quite describe the potential for heating and cooling of the wearer and predict the results of dynamic change if sweating is involved.

The Naylor test generates data that is even more directly linked to human thermal comfort and sensations. However, the method is more complex and expensive, and changing the relative humidity in the chamber rapidly and consistently can incorporate a variation in the test result. If the chamber can generate a rapid RH response, the control characteristics of the plate may not be able to maintain a constant plate temperature of 35°C, affecting the overall results and estimates of exothermic effects. Climatic chambers and hot plates with faster control mechanisms for air RH and plate temperature would be possible but are not standard available and may be expensive. Furthermore, the presence of a temperature gradient affects the actual local RH of the fabric, leading to a much smaller RH change and, therefore, too much smaller measured effects than expected from the large environmental RH change. In Chapter 3, the fabric test methodologies were investigated, and scientific comparisons of the above-mentioned test methods were discussed.

The manikin test is yet a step more complex and expensive and is currently not recommended for standardized testing for the industry for this specific purpose – apart from its standard use to measure clothing insulation and evaporative resistance. Furthermore, not many test laboratories worldwide would be able to perform manikin testing in a controlled environment in the manner our study has executed. It is difficult to control the environment, and the methodology requires a relatively complex data analysis. In short, it is a step closer to reality but an even more challenging experiment that indicates what the human responses might be, but
that would be too complicated as a standardized test. Chapter 4 and Chapter 5 discussed, respectively, the use of thermal and sweating manikin in a transient condition. Although the test results provided new insight into how to use manikin to determine the fabric and physiological attributes under dynamic conditions, they also showed how complex the data analysis was. This data did show, however, a very good correlation with the subsequent human subject studies in Chapter 6.

On the other hand, the proposed novel test method for fabric discussed in Chapter 8 mostly resolved the limitations of the previous ISO 16533 test and Naylor’s hot plate test methods. More importantly, this method was developed considering the human subject’s response (Chapter 6) to predict the physiological responses more accurately and elaborately. This approach can compare the ability of several athletic wear materials to disperse moisture vapor from a saturated skin/clothing environment to the ambient atmosphere by measuring heat loss, microclimate temperature, humidity, and drying time.

9.1.2 The Behavior of Hygroscopic and Non-hygroscopic fiber in a Transient Condition

This research evaluated the fabric surface temperature, the microclimate temperature, and the humidity in an extensive series of tests, including human trials. The test results discussed in the previous chapters depicted a brief idea about the behavior of hygroscopic and non-hygroscopic fiber types in a transient condition—the results showed distinct differences between wool (hygroscopic) and polyester (non-hygroscopic), and we found the behavior of cotton generally in between the two. Because the moisture regain value is close to that of hydrophilic wool, the viscose response was mostly found to be nearly the same; however, its physiological impact on the wearer seemed to be smaller than wool.
Despite the high heat of sorption, wool had a lower overall evaporative cooling rate from the surface (“sweat”) in both the manikin and dynamic hot plate tests (discussed in Chapter 7). This significantly lower evaporative cooling may be interpreted as a higher heat of wetting. The enhanced heat of wetting is likely due to the hydrophilic groups in the wool fibers having a strong attraction to water. High sorption heat in the inter-yarn gaps raised the fabric’s surface temperature. Because of this exothermic increase in surface temperature, evaporative cooling from the heated surface was reduced. This fascinating trait of wool fiber may shield the wearer from the effects of a sudden shift in the surrounding environment (discussed in Chapter 6).

Polyester demonstrated substantial heat loss while sweating, suggesting it may facilitate higher evaporative cooling to the wearer; however, it also showed a much higher cooling right after the active sweat (“exercise”) period, inducing thermal discomfort.

Nonetheless, several pieces of literature and sportswear companies take advantage of this cooling feature to create ‘dri-fit’ workout clothes. However, when we consider the whole scenario of heat loss during various phases and the microclimate temperature and humidity, the results become evident. Human studies confirmed that the high heat loss of polyester could cause thermal discomfort by lowering the microclimate temperature. The findings from cotton, on the other hand, fell somewhere in the middle between wool and polyester. As natural wool also has a hydrophobic surface, the viscose surface was treated to make it more comparable to the latter. Compared to wool, viscose has a similar heat of sorption, but its surface chemistry is considerably different, and its thermal comfort qualities are more similar to those of polyester. Also, hydrophilic wool exhibited liquid absorption and showed a behavior quite similar to cotton and was not distinguishable from cotton in most tests. It would be misleading to consider the test
findings only during the exercise phase, and the cool-down phase should be analyzed as well, as was shown in Chapters 6 and 8.

9.1.3 Manikin Model Data Corrections for Transient Conditions

The manikin models covered in Chapter 4 might be an excellent addition to the manikin data acquisition system. However, because manikin data exhibit greater fluctuation during the transition, no model had been devised to take manikin heat flux data into account for transient environmental changes. However, using the generated manikin data, we determined a “heat-flux factor” using two different approaches. One estimates heat flux relative to a naked segment, while the other considers data rectification after the transition. Both of these approaches have the potential to produce a more precise model for the transient testing environment since they appear to lessen the variation in the various components of the manikin body. When manikin tests need to be conducted in two separate chambers that do not have the exact same temperature and wind conditions, these correction methods may be very feasible to extract the exotherm effects.

9.1.4 Defining ‘Dynamic Breathability’

In terms of ‘breathability,’ it would be highly preferable to use the term as it is meant to be in the dictionary: “related to the flow of air.” This definition includes a combination of air permeability and water vapor transmission, which would indeed be most appropriate for true ‘breathability.’ However, in commercial textiles, this definition is often narrowed to merely water vapor transmission (measured with a moisture vapor transmission rate – MVTR or via evaporative resistance), which is an incomplete use of the term seemingly driven by membrane manufacturers. To explain: one cannot breathe through materials that only allow water vapor to pass and no air. With that, this classic definition of “breathability” might be expanded, as the consequence of the breathability might also be considered. For human body heat loss, air must be
transported away from the body, as in general, the environmental air is cooler and dryer, and with the moving air, heat is taken away from the skin (dry cooling), and sweat is evaporated from the skin (evaporative cooling), the latter being the dominant cooling in warm conditions. Thus, an expanded definition of “breathability” could include the effects of the fabric on the heat loss (heating and cooling) aspects of fabrics. However, as mentioned above, with the current industry confusion around the term, it may be hard to explain yet another view on “breathability” that includes different aspects.

Chapter 2 discussed how water vapor and liquid moisture could interact with textiles and transport via different mechanisms. Considering these theories, any process that affects the transport of air and water vapor through the fabric, potentially interfering with human heat loss, is relevant to the breathability (in the broad sense) aspects of the fabric. Liquid transport within the fabric (wicking) is not associated with heat loss; wetting and water absorption may affect heat loss but may have a larger impact on wetness sensation than heat loss. When fabrics would exist that facilitate wicking in such a way that they would enhance the total amount of evaporated sweat, such fabrics might be claimed as ‘cooling fabrics,’ but generally, thus would not be considered as enhanced breathability as those would be not associated with air and water vapor transport through the fabric, but with evaporation from the fabric surface.

The standardized tests for air and water vapor permeability have been described in Chapter 2, which assess fabric properties in a steady state condition, i.e., static and stable conditions are applied, and the measurements are taken in the absence of any changes (ideally). This provides the classical values for breathability – the transfer of air and water vapor through the fabric. Although the standard sweating-guarded hot plate measures heat loss, it measures the amount of water evaporated from the plate under steady-state conditions. None of these methods
exhibited fabric properties under changing conditions. If the definition of ‘breathability’ is indeed broadened to include heat loss aspects, it would be more appropriate to include dynamic aspects. However, it seems more practical to consider a different terminology for these effects, considering the multiple definitions of “breathability” that exist already.

The term ‘dynamic breathability’ thus could be an acceptable term to cover all the aspects. It sounds more appropriate because it covers the term ‘dynamic,’ which potentially means ‘environmental transition’ or ‘physiological transition.’ For example, the dynamic component of wool is expected to affect human heat loss positively, and this research project aimed to define the best methods to assess that. Nevertheless, technically, if, for example, the wool hygroscopically absorbs water vapor due to changing to a cool, humid environment, it would release heat but actually, reduce the water vapor transfer to the environment. The net effect would be a temporary (transient) heating, a positive but causes an actual decrease in dynamic (transient) water vapor transfer, and thus a decrease in breathability (true for the outer fabric surface, but no decrease from the skin surface) – in this case, a potential positive!

9.2 Proposed Future Research

This research has evaluated a wide variety of exotherm effects of wool, but some research questions remain as they were not within the scope of the current research project:

- Future research on developing more sophisticated dynamic plates that can facilitate more quickly changing conditions both in the environment and for the plate. Naylor has shown that the sweat-guarded hot plate can measure such dynamic (transient) effects, but it is not what the equipment was developed for.
- Regarding fabric structure, only a single jersey structure has been used in this research. This research can be expanded into different derivatives of knit fabrics,
such as interlock and rib knits, because those structures may vary in fabric weight, density, air permeability, and porosity which may influence the exothermic characteristics of the fabrics.

✓ In addition, a more detailed statistical analysis of how different fabric parameters can affect the exothermic and endothermic behavior of the fabric can be investigated. Here, we statistically showed how fiber types (with the same thickness) could affect the physiological and subjective variables during human trials. However, the effect of weight, air permeability, and fabric density should be statistically justified to better design the fabric for activewear purposes.

✓ In this research, we found limitations of physiological sensors (e.g., MSR) in determining the microclimate and fabric temperature and humidity of the fabric. The sensors are localized and very small. For example, while determining the humidity of the microclimate in the sweating manikin experiments, in some cases, the sensors were found to determine humidity locally if those were placed in alignment with the sweat pores of the manikin body. In several instances, its wiring design prevented it from placing the sensors appropriately on the manikin or human body. A more sophisticated way to measure physiological parameters could be explored. The sensors could be wireless, and technology should be used to cover data at least twice its physical area, not just the area itself.

✓ The calorimetry technique used to determine the heat of wetting of the fabrics was not ideal. The TAM air isothermal calorimeter is generally used to measure the heat of wetting for cement materials, not soft materials such as textile fibers. However, it provided some good data to start with, and further investigation could
be done on sampling and accurately measuring the heat released during water vapor absorption. For sampling, we used scissors when grinding the samples into pieces; notably, those samples were not uniform in size. Contrarily, a template or a fabric grinding machine can be suggested for better sampling, as we observed that uniform sampling had the most significant impact on calorimetry trials. Furthermore, an additional device could be designed with the inject system that can hold the materials with the surface contact of the ampoules.

- A new statistical way of analyzing the repeatability of the dynamic testing method should be defined and developed. In other words, a method should be developed to express the percentage of coefficient of variation (CV%) of different phases (resting, activity, drying). During testing with the hot plate or manikin, data acquisition software usually provides data every 5 seconds (can be changed). For instance, we obtained about 1080 data points from a sample of manikin tests lasting 90 minutes (5400 seconds) to measure the heat flux. Therefore, there should be variations in the data across the phases. How can we effectively display the standard deviation and CV% across phases if the same sample is repeated multiple times? Some authors in the literature do not distinguish between the stages but instead determine an overall average for the process, which may not be the ideal for this instance. However, the development of a standard test method should appropriately address issue, as the phase change will incorporate some variability in the dynamic process.

- The human trials solely included male participants. A future strategy that involves research on quantifying and evaluating the exothermic advantages for both male
and female individuals should be taken into consideration by undertaking broader
and more severe environmental conditions.

✓ To evaluate fabric tactile performance in the dry, humid and wet state, using
methods such as the Kawabata Evaluation System (KES), additional (wet) fabric
friction tests can be explored to further assess overall wear comfort aspects of
fabrics and effects of fiber type.
### Appendix A: Comfort Rating Form

<table>
<thead>
<tr>
<th>Subject Code:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Garment Code:</td>
<td></td>
</tr>
<tr>
<td>Date &amp; Time:</td>
<td></td>
</tr>
</tbody>
</table>

**Fit Session***

***Garment should be tucked in***

<table>
<thead>
<tr>
<th>Checklist</th>
<th>Put a tick if done</th>
<th>Subject Physiological Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Garments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shorts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socks</td>
<td></td>
<td>Weight (lb)</td>
</tr>
<tr>
<td>Fit check</td>
<td></td>
<td>Heart Rate</td>
</tr>
<tr>
<td>MSR Sensor Placement</td>
<td></td>
<td>Height</td>
</tr>
</tbody>
</table>

**Chamber Conditions**

<table>
<thead>
<tr>
<th>Temperature</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity (%)</td>
<td></td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td></td>
</tr>
</tbody>
</table>

**Step--1**

<table>
<thead>
<tr>
<th>Acclimatization/Rest Period (20 minutes)</th>
<th>Checklist</th>
<th>Put a tick if done</th>
</tr>
</thead>
</table>

- Familiarize with test protocols and subjective questionnaires and scales
- Image (Camera)
- Image (IR)
- Instrumented weight

**Time Started:**

Report any observations:
<table>
<thead>
<tr>
<th>Subjective Response</th>
<th>Q-1 (Perceived Comfort)</th>
<th>Q-2 (Thermal Sensation)</th>
<th>Q-3 (Wetness Sensation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>At the end of rest period (after 18 mins.)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step--2</th>
<th>Activity (25 minutes)</th>
<th>Checklist</th>
<th>Put a tick if done</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycling</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image (Camera)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image (IR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrumented weight</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subjective Response</th>
<th>Q-1 (Perceived Comfort)</th>
<th>Q-2 (Temp Sensation)</th>
<th>Q-3 (Wetness Sensation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step--3</th>
<th>Drying Period (25 minutes)</th>
<th>Checklist</th>
<th>Put a tick if done</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sitting</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image (Camera)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Image (IR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrumented weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subjective Response</td>
<td>Q-1 (Perceived Comfort)</td>
<td>Q-2 (Temp Sensation)</td>
<td>Q-3 (Wetness Sensation)</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------------</td>
<td>----------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>5 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After Test Activity</th>
<th>Checklist</th>
<th>Put a tick if done</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dismounting Sensors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sanitization Sensors, bike, surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Garments for Washing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Any other</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix B: Test Subjects and Chamber conditions for Human Subject Trials

#### Table B-1 Subject Demographic and Anthropometric Data.

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Age (years)</th>
<th>Weight (lb.)</th>
<th>Height (inch)</th>
<th>Assigned Garment Size</th>
<th>*Body Mass Index</th>
<th>**Max Heart Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT_001</td>
<td>26</td>
<td>210</td>
<td>75</td>
<td>Medium</td>
<td>26.3</td>
<td>196</td>
</tr>
<tr>
<td>HT_002</td>
<td>26</td>
<td>194</td>
<td>75</td>
<td>Medium</td>
<td>24.3</td>
<td>196</td>
</tr>
<tr>
<td>HT_003</td>
<td>23</td>
<td>171</td>
<td>72</td>
<td>Small</td>
<td>23.1</td>
<td>198</td>
</tr>
<tr>
<td>HT_004</td>
<td>30</td>
<td>177</td>
<td>72</td>
<td>Medium</td>
<td>24</td>
<td>193</td>
</tr>
<tr>
<td>HT_005</td>
<td>23</td>
<td>176</td>
<td>70</td>
<td>Small</td>
<td>25.2</td>
<td>198</td>
</tr>
<tr>
<td>HT_006</td>
<td>29</td>
<td>190</td>
<td>69</td>
<td>Medium</td>
<td>28.1</td>
<td>193</td>
</tr>
<tr>
<td>HT_007</td>
<td>26</td>
<td>197</td>
<td>74</td>
<td>Medium</td>
<td>25.3</td>
<td>196</td>
</tr>
<tr>
<td>HT_008</td>
<td>32</td>
<td>157</td>
<td>72</td>
<td>Small</td>
<td>21.3</td>
<td>191</td>
</tr>
<tr>
<td>HT_009</td>
<td>28</td>
<td>148</td>
<td>67</td>
<td>Small</td>
<td>23.2</td>
<td>194</td>
</tr>
<tr>
<td>HT_010</td>
<td>23</td>
<td>153</td>
<td>71</td>
<td>Small</td>
<td>21.3</td>
<td>196</td>
</tr>
<tr>
<td>HT_011</td>
<td>20</td>
<td>179</td>
<td>68</td>
<td>Medium</td>
<td>27.2</td>
<td>201</td>
</tr>
<tr>
<td>HT_012</td>
<td>23</td>
<td>164</td>
<td>71</td>
<td>Small</td>
<td>22.9</td>
<td>198</td>
</tr>
<tr>
<td>Mean</td>
<td>26</td>
<td>176</td>
<td>71</td>
<td></td>
<td>24.4</td>
<td>196</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3</td>
<td>19</td>
<td>3</td>
<td>2.2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*Body Mass Index (BMI)= [weight (lb.)/ height (inch)^2] ×703

** Maximum Heart Rate (MHR) = 218- [0.85×Age (yrs.)]

---

Figure B-1(a) Plastic sweat cage (b) Screen-system to enter into the sweat cage (c) Bicycle ergometer placed in the plastic sweat cage (d) Checked wind speed in the cage.
Figure B-2 Position of MSR sensors to record temperature and humidity on the fabric (a) front side (b) back side.

Figure B-3 Subjects performing test protocols (a) Activity phase (b) Dry phase.

Figure B-4 Thermal images for PLT during human trials for HT-001 (a) rest phase (b) activity phase (c) drying phase.
Figure B-5 Thermal images for CL during human trials for HT-001 (a) rest phase (b) activity phase (c) drying phase.

Figure B-6 Thermal images for VB during human trials for HT-001 (a) rest phase (b) activity phase (c) drying phase.

Figure B-7 Thermal images for WBT during human trials for HT-001 (a) rest phase (b) activity phase (c) drying phase.

Figure B-8 Thermal images for WLT during human trials for HT-001 (a) rest phase (b) activity phase (c) drying phase.
### Appendix C: Detailed Table for Statistical Analysis

Table C-1 ANOVA summary table for physiological & Shirt variables.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skin-Microclimate Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>206.2</td>
<td>354.9</td>
<td>1.6E-63*</td>
</tr>
<tr>
<td>Clothing Types</td>
<td>4</td>
<td>10.6</td>
<td>2.7</td>
<td>0.04*</td>
</tr>
<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>0.3</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Test of between Subjects</td>
<td>1</td>
<td>4.4E+5</td>
<td>2.9E+04</td>
<td>3.2E-20*</td>
</tr>
<tr>
<td><strong>Skin-Microclimate RH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>2.1E+04</td>
<td>86.2</td>
<td>2.7E-38*</td>
</tr>
<tr>
<td>Clothing Types</td>
<td>4</td>
<td>1530.6</td>
<td>5.6</td>
<td>0.001*</td>
</tr>
<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>94.4</td>
<td>1.7</td>
<td>0.01*</td>
</tr>
<tr>
<td>Test of between Subjects</td>
<td>1</td>
<td>1.57E+06</td>
<td>887.8</td>
<td>7.2E-12*</td>
</tr>
<tr>
<td><strong>Shirt Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>570.6</td>
<td>716.2</td>
<td>1.3E-76*</td>
</tr>
<tr>
<td>Clothing Types</td>
<td>4</td>
<td>20.6</td>
<td>4.3</td>
<td>0.005*</td>
</tr>
<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>0.8</td>
<td>2</td>
<td>9.8E-4*</td>
</tr>
<tr>
<td>Test of between Subjects</td>
<td>1</td>
<td>2.4E+05</td>
<td>4.7E+04</td>
<td>2.5E-21*</td>
</tr>
<tr>
<td><strong>Shirt RH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>4768.9</td>
<td>115.4</td>
<td>2.7E-43*</td>
</tr>
<tr>
<td>Clothing Types</td>
<td>4</td>
<td>941.9</td>
<td>6.2</td>
<td>4.5E-4*</td>
</tr>
<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>54.3</td>
<td>4.6</td>
<td>2.3E-13*</td>
</tr>
<tr>
<td>Test of between Subjects</td>
<td>1</td>
<td>1.6E+06</td>
<td>4192.7</td>
<td>1.5E-15*</td>
</tr>
</tbody>
</table>

**Note.** — MS=Mean squares, DF= Degree of Freedom, *p<0.05.
Table C-2 ANOVA summary table for Subjective Responses.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
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<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Sensation</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>113.2</td>
<td>84.4</td>
<td>6.1E-38*</td>
</tr>
<tr>
<td>Clothing Types</td>
<td>4</td>
<td>23.8</td>
<td>21.6</td>
<td>6.4E-10*</td>
</tr>
<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>1.6</td>
<td>4.1</td>
<td>1.2E-11*</td>
</tr>
<tr>
<td>Test of between Subjects</td>
<td>1</td>
<td>3.8</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Wetness Sensation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (minutes)</td>
<td>8</td>
<td>26.4</td>
<td>33.4</td>
<td>1.5E-23*</td>
</tr>
<tr>
<td>Clothing Types</td>
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<td>2.8</td>
<td>0.04*</td>
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<tr>
<td>Time (minutes)× Clothing Types</td>
<td>32</td>
<td>0.3</td>
<td>1.9</td>
<td>0.003*</td>
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<td>429.6</td>
<td>3.6E-10*</td>
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<tr>
<td>Time (minutes)</td>
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<td>6.2</td>
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*Note. —MS=Mean squares, DF= Degree of Freedom, *p<0.05.*