Apparent Total Evaporative Resistance Values from Human Trials

Over a Range of Heat Stress Levels

by

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Date of Approval:
March 28, 2011

Keywords: Protective Clothing, Evaporative Cooling, Heat Exchange, Water Vapor Diffusion, Convective Transport

UMI Number: 1490779

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DEDICATION

I dedicate this work to my family. The completion of this manuscript would not have been possible without the strength, love, and support of my beautiful wife, Laura Mae Dooris, my son, Matthew Monroe Dooris, and my parents, Drs. George and Patricia Dooris.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

A_D – Dubois Surface Area
ACGIH – American Conference of Governmental Industrial Hygienists
ANOVA – Analysis of Variance
ASTM – American Society for Testing and Materials

C – Compensable Stage of Heat Stress
C_{res} – Respiratory Convective Heat Flow
CC – Cotton Coveralls
CFI – Correction Factor for Insulation

DH – Dry-Heat Loss

E_{res} – Respiratory Evaporative Heat Flow

f_g – Fractional Grade of the Treadmill

H – Height
H_{net} – Net Heat Gain
HSD – Honestly Significantly Different

I_{clo} - Total Intrinsic Clothing Insulation
i_m – Moisture Permeability Index
$i_{m,a}$ – Apparent Moisture Permeability Index
$i_{m,stat}$ – Static Moisture Permeability Index
I_T – Total Insulation
$I_{T,r}$ – Total Resultant Insulation
$I_{T,stat}$ – Total Static Insulation
ISO – International Organization for Standardization

M – Metabolic Rate
m_b – Body Mass

OSHA – Occupational Safety and Health Administration

P_a – Ambient Water Vapor Pressure
P_{sk} – Skin Water Vapor Pressure
PHS – Predicted Heat Strain

R2 – 20% Relative Humidity
R5 – 50% Relative Humidity
R7 – 70% Relative Humidity
$R_{e,T}$ – Total Evaporative Resistance
$R_{e,T,a}$ – Apparent Total Evaporative Resistance
$R_{e,T,stat}$ – Static Total Evaporative Resistance
RH – Relative Humidity

S – Body Heat Storage Rate
SD – Standard Deviation

T – Transition or Critical Stage of Heat Stress
T_{db} – Ambient Air Temperature
T_{exp} – Expired Air Temperature
T_g – Globe Temperature
T_{pwb} – Psychrometric Wet Bulb
T_{re} – Body Core (Rectal) Temperature
T_{sk} – Skin Temperature
$TLV^{®}$ – Threshold Limit Value

U – Uncompensable Stage of Heat Stress
USF – University of South Florida

v – Air Speed
V_{O2} – Oxygen Consumption
V_T – Ventilation Index
V_W – Walking Speed

w – Walking Speed or Speed of Treadmill
W – Watts (Effective Mechanical Power)
W_{ext} – External Work
WC – Work Clothes

ΔP – Pressure Gradient ($P_{sk} - P_a$)
ΔT – Temperature Gradient ($T_{db} - T_{sk}$)
ΔT_{re} – Rate of Change in Body Core (Rectal) Temperature

ABSTRACT

Failure to maintain thermal equilibrium can cause uncontrollable increases in body core temperature beyond critical upper limits. In selecting clothing, consideration must be given to the heat transfer properties of clothing that may restrict the cooling capacity of the human body under heat stress conditions, most importantly, apparent total evaporative resistance ($R_{e,T,a}$). This study calculated and compared $R_{e,T,a}$ for five clothing ensembles under varying heat stress conditions, including three relative humidity (RH) levels and three stages of heat stress to determine if $R_{e,T,a}$ values varied or remained the same with changes in heat stress conditions. A four-way mixed model analysis of variance demonstrated significant differences for estimated $R_{e,T,a}$ values among ensembles, RH levels, heat stress stages, and interactions among ensembles and RH levels and ensembles and heat stress stages ($p < 0.0001$). No significant interaction among RH levels and heat stress stages was found ($p = 0.67$). A Tukey's Honestly Significant Difference multiple comparison test was used to identify where significant differences occurred ($p < 0.05$). The results of the study indicated that $R_{e,T,a}$ values do change with RH levels and stages of heat stress and that the theoretical framework for explaining heat-exchange in hot environments is not yet well-established. Also confirmed was the dominance of the convection pathway over the diffusion pathway in hot environments.

CHAPTER 1: INTRODUCTION

Problem Statement

Many workplaces provide different types of clothing ensembles to offer protection to employees from assorted chemical, physical, and biological agents. A serious concern faced by employers when selecting appropriate clothing is whether it will induce some level of heat stress. Heat stress is a significant occupational problem in the U.S. as 5-10 million workers are exposed to heat stress conditions each year (Occupational Safety and Health Administration [OSHA], 2010). It is estimated that in 2006 approximately 44 U.S. workers died and 3,100 more lost work hours from heat-related disorders (Office of Compliance, 2009). Through the implementation and enforcement of effective control measures and work practices, risk associated with heat-related disorders can be managed. OSHA has not promulgated any specific regulations to govern the protection of employees from heat stress; however, the agency expects employers to protect workers from heat stress in accordance with the General Duty Clause, Section 5(a)(1) of the OSH Act (OSHA, 1999). Originally adopted in 1972, the American Conference of Governmental Industrial Hygienists (ACGIH®) publishes a threshold limit value (TLV®) for heat stress to limit body core temperatures of workers to 38°C. Body core temperatures above 38°C should be avoided to prevent the onset of heat

strain although brief, intermittent work periods are acceptable with sufficient recovery periods (ACGIH, 2010; Bernard, 1999).

Heat balance analysis as outlined by Havenith (1999) and further discussed by Havenith et al. (2008) and Bernard (1999) is a method used to conceptualize the processes involved in thermoregulation. When a person is capable of eliminating body heat at a rate greater than the rate it is being generated the body is said to be in a state of compensable heat stress. Failure to maintain thermal equilibrium results in an uncontrollable rise in body core temperature beyond a critical upper limit, a homeostatic threshold, which has become recognized as uncompensable heat stress (Bernard et al. 2010). When uncompensable heat stress is achieved, the human body cannot eliminate heat at the same rate it is being generated. The critical upper limit was originally described by Lind (1963) as the upper limit of the prescriptive zone but has since become known as the critical condition (Bernard et al. 2010, 2009, 2005; Caravello et al. 2008; Kenney et al. 1993; Frye & Kamon, 1981; Belding & Kamon, 1973). Other physiological indicators of heat stress include increased heart rates and profuse sweating (Ashley et al. 2008; Barker, Kini, & Bernard, 1999).

Job risk factors for inducing heat stress consist of environmental conditions, work demand, and clothing requirements (Bernard & Ashley, 2009; Barker et al. 1999). Environmental conditions include air temperature, ambient air vapor pressure (humidity), radiant heat, and air movement. Heat stress conditions can be induced by elevating the ambient air temperature or the ambient water vapor pressure in hot environments (Kenney et al. 1993). The human body absorbs heat from the environment when air temperatures exceed 40°C (104°F) and loses heat when temperatures fall below 32°C

(90°F). The consequence of reducing air temperature is decreased water vapor pressure levels supported by air. Air loses its capacity to retain water with decreases in temperature which results in higher evaporative cooling rates (heat loss) at lower air humidity levels. The rate of evaporative heat loss is influenced by the amount of water vapor pressure present in the air *versus* the skin. In most environmental conditions, higher concentrations of water vapor on the skin than in the air promote effective evaporative cooling. In very rare situations and only in extreme climatic conditions will the moisture concentration gradient become equalized or even reversed, prohibiting evaporative heat loss (DiNardi, 2003; Plog & Quinlan, 2002; Havenith, 1999; OSHA, 1999).

Radiant heat is generated from hot surfaces that are not adequately shielded, insulated, or where the emissivity of the source has not been sufficiently reduced. The body absorbs radiant heat readily at temperatures exceeding 43°C (109°F). Air movement stimulates greater air contact with human skin promoting evaporative cooling and body core temperature reduction. However, several temperature thresholds must be considered when assessing the effect of air movement on heat stress. At temperatures below 35°C (95°F) effective heat loss is possible with increased air movement, while opposing results are observed with temperatures above 40°C (104°F). Minimal body heat loss occurs between 35°C and 40°C (95°F and 104°F). Another relevant factor that must be considered is air speed. The best results are obtained between 0 and 2 m/s while no gain in evaporative cooling is detected at air speeds exceeding 3 m/s (ACGIH, 2010; DiNardi, 2003; Plog & Quinlan, 2002; Bernard, 1999; Havenith, 1999; OSHA, 1999).

Metabolic work demand contributes significantly to body heat gain but can be controlled by automating processes, reducing workloads, and pacing job tasks. High metabolic rates sustained over a period of time can generate body heat at levels which cannot be dissipated effectively, resulting in physiological strain. Higher levels of metabolic rates are observed with dynamic work when compared to static work as muscles are required to flex and extend in response to work demands. Standard metabolic rate tables have been established to assist employers in estimating work demands imposed on workers for different types of job tasks (International Organization for Standardization [ISO], 2004b). However, metabolic rates will not be uniform among a group of employees because individual differences in height, weight, and oxygen consumption influence metabolic rate levels. Heat loss can occur by five different pathways including conduction, convection, radiation, evaporation, and respiration. Evaporation is the primary pathway governing thermal equilibrium in hot environments. The body eliminates sizeable amounts of heat through the evaporation of sweat on the surface of the skin or, in some cases, clothing layers. Conduction is only important for work performed in water. Convection provides a reliable means for dissipating heat from warmer skin to cooler ambient air as long as air temperatures remain near or below skin temperatures. Internally generated body heat may also be transferred to nearby cooler objects by means of radiation. Exerting even lower effect on heat exchange is respiration which unloads heat by way of convection and evaporation in the pulmonary system (DiNardi, 2003; Plog & Quinlan, 2002; Bernard, 1999; Havenith, 1999; Holmer et al. 1999; OSHA, 1999).

The final job risk factor, clothing, is the focus of the remainder of this thesis. Protective clothing can be extremely useful in protecting workers from a number of occupational hazards including chemicals, cold stress, radioactive contamination, burns, among other deleterious exposures. Unfortunately, clothing can also lead to heat stress and heat-related disorders. The beneficial and potentially hazardous characteristic of clothing is its ability to act as a barrier. Some of the desired qualities of clothing barriers, depending on intended use, include the ability to prevent the intrusion of chemicals or other unwanted substances, reflect radiant heat, or provide thermoregulation in cold environments. However, the same barrier which protects the worker can also cause physiological stress. Clothing serves as an impedance barrier to the exchange of heat and water vapor between the skin and the environment which can result in lower rates of evaporative cooling. Restriction of heat exchange pathways may not disturb thermoregulation in cool environments with low-moderate metabolic rates or warm environments with low metabolic rates. However, moderate-high metabolic rates in cold environments or moderate metabolic rates in warm environments could induce heat strain. Evident in this discussion is the importance of time as a fourth job risk factor for heat stress. Moderate work rates in a warm environment may not induce heat stress over 30 minutes but it may if work continued for 60 minutes keeping all other job risk factors constant (ACGIH, 2010; Bernard & Ashley, 2009; Havenith, 1999).

Havenith (1999) described the most important factors of clothing relative to heat stress to be the construction, configuration, and number of layers worn by a worker. Loose fitting, light-weight clothing such as a cotton work uniform permits ambient air to enter the ensemble and make rapid contact with human skin. In doing so, the air,

depending on temperature and humidity, supports evaporative-heat exchange by transporting vaporized sweat and heat from the body to the environment. New air from the workplace environment takes the place of the exiting air to continue the process. The net result is evaporative cooling or loss of body heat. Single layer vapor-barrier clothing, multi-layered clothing, or clothing which is tight fitting can impede the ability for ambient air to enter and make contact with human skin. The worker perspires but limited or no evaporative cooling occurs because air is not adequately circulated in and out of the clothing. A very good example of vapor-barrier clothing can be observed among wetland scientists who must wear chest waders to enter very wet areas during the summer months in Florida. The coveralls effectively keep water from entering the coveralls but the ensemble is impermeable to both water and air. For this reason, limited air is permitted to circulate inside the coveralls, except from the "pumping effect" produced from body movement, preventing sufficient removal of metabolic heat generated from walking and performing other demanding work (Havenith & Nilsson, 2004; Havenith, 1999).

Over the past several decades, studies have been performed to expose the principal factors governing the thermal properties of assorted clothing ensembles regularly used in occupational settings (Bernard et al. 2010; Caravello et al. 2008; Havenith et al. 2008; Barker et al. 1999; Holmer et al. 1999; Kenney et al. 1993). The most commonly used values to describe the thermal properties of clothing and what is recommended by the ISO are: total insulation (I_T), water vapor permeability, expressed using a moisture permeability index (i_m), and total evaporative resistance ($R_{e,T}$). Each value will be described in detail in Chapter 2 but a brief description of $R_{e,T}$ is warranted considering its importance in characterizing the risk of heat stress among clothing

ensembles. $R_{e,T}$ values are expressed in m^2kPaW^{-1} and static ($R_{e,T,stat}$) or resultant ($R_{e,T,a}$) values can be calculated (Barker et al. 1999; Kenney et al. 1993). Static values reflect periods of clothing wear absent air or body movement while resultant values are adjusted for conditions where workers are in motion and air movement exists. The term "apparent" is often used to describe resultant values because they are measured in laboratory settings and may not represent accurately the complicated mechanisms of heat transfer experienced in the workplace (Caravello et al. 2008). As will be seen in Chapter 2, $R_{e,T,a}$ values are largely contingent on the differences in water vapor pressure between the skin and air. Different clothing barriers will prohibit or limit the transfer of air and moisture between the skin and the environment, thus artificially altering water vapor pressure differences inside the ensemble. The end result is a reduction in evaporative cooling. $R_{e,T,a}$ estimates the water vapor resistance observed from the skin to the environment under prescribed climatic conditions and work demand. What also makes $R_{e,T,a}$ so useful and telling of heat stress conditions is the estimated resistance takes into consideration all layers of clothing, as well as enclosed and boundary air layers (ISO 2007).

The problem examined in this thesis is the relationship between $R_{e,T,a}$ values and variable moisture levels in the environment. Presently unknown is whether $R_{e,T,a}$ varies or remains the same with changes in ambient air temperature (T_{db}) or ambient water vapor pressure (P_a) in hot environments. The purpose for this study is to calculate $R_{e,T,a}$ for five clothing ensembles under varying heat stress conditions and analyze results using a mixed model analysis of variance (ANOVA) in combination with Tukey's Honestly Significant Difference (HSD) multiple comparison tests to determine if statistical

differences between $R_{e,T,a}$ values exist. All $R_{e,T,a}$ calculations were conducted using environmental and physiological data over a range of heat stress conditions at, near, or beyond critical conditions. The data were collected previously by Caravello et al. (2008) and Bernard et al. (2005) using a progressive heat stress protocol. Empirically quantifying the relationship between $R_{e,T,a}$ using variables derived from different environmental conditions which promote stress on the thermoregulation process will advance heat stress research and help safety professionals in the field advise employers regarding appropriate clothing for use in work settings.

Research Question

The following research question is addressed in this thesis:

"Will estimates of $R_{e,T,a}$ for five different clothing ensembles remain the same independent of compensable, critical, and uncompensable heat stress levels?"

Significance of Research

This research is critically important to industry, first responders, and the military where heat stress hazards exist in the workplace. The first step towards the selection and implementation of controls to mitigate risks associated with exposure to chemical, physical, or biological agents is a thorough risk assessment. Knowledge of the job risk factors linked to heat stress is necessary for the design and execution of any effective company heat stress control program. Addressing one hazard may unintentionally create another, more substantial hazard. For example, procuring protective clothing without

consideration for its thermal properties may prevent scratches, splinters, contact dermatitis, or burns but it may result in rapid heat stress for wearers depending on environmental conditions and workload. It is essential for company safety program managers to have some level of understanding of the construction and configuration characteristics of protective clothing. Although a great deal is known relative to the roles of different clothing factors in thermal regulation, much is yet to be learned. This thesis seeks to uncover the relationship(s) between $R_{e,T,a}$ values and different environmental conditions, and expand current knowledge of thermal properties of protective work clothing.

Overview of Thesis

Chapter 2 of this thesis contains a literature review regarding the estimates of clothing heat and vapor resistance, testing methods for computing estimates, progressive heat stress protocol, and heat exchange processes in hot environments. Following the literature review, Chapter 3 describes the methods used in the collection, extraction, and analysis of data for this thesis. In Chapter 4, the data are tabulated and graphically displayed. Chapter 5 presents statistically significant trends and compares thesis results with other published findings. Potential heat exchange pathways occurring during human trials are evaluated and discussed, and conclusions are reported and suggestions for future research offered.

CHAPTER 2: LITERATURE REVIEW

Estimates of Clothing Heat and Vapor Resistance

Protective clothing is becoming more important in the workplace as employers become more aware of regulatory requirements and potential health hazards present in work settings. Many different types of hazardous jobs exist which require clothing impermeable to water or vapor, or both. In some cases, multiple layers of clothing are necessary. Protective clothing meeting these requirements will likely increase the thickness or insulation of clothing while simultaneously reducing the evaporation of sweat from the skin (Kenney et al. 1993). To protect workers, employers must carefully choose the most suitable clothing ensemble given the environmental conditions of the worksite, work demand, and thermal properties of clothing (Barker et al. 1999). Special consideration must be afforded to heat transfer properties of clothing such as total insulation (I_T), water vapor permeability expressed using a moisture permeability index (i_m), and total evaporative resistance ($R_{e,T}$), all which have been shown to influence the cooling capacity of the human body under heat stress conditions (Caravello et al. 2008; Barker et al. 1999; McLellan & Frim, 1994; Kenney et al. 1993).

Clothing Insulation

I_T is a calculated value representing the ability of an ensemble to allow dry-heat exchange between the skin and the environment. I_T, incorporating both fabric and

enclosed air pockets, is expressed in $m^2 \,^{o}C \; W^{-1}$ and both static ($I_{T,stat}$) and resultant ($I_{T,r}$) values can be estimated. The American Society for Testing and Materials (ASTM) publishes criteria for determining $I_{T,stat}$ values for different clothing ensembles (ASTM, 2002) while the International Organization for Standardization (ISO) lists $I_{T,stat}$ values for a number of commonly used ensembles (ISO, 2007). A method for estimating $I_{T,r}$ recommended by the ISO is discussed later in this section. Clothing insulation is also commonly expressed as total intrinsic clothing insulation (I_{clo}) or clo as used in some publications (ISO, 2004a). Higher I_T values are characteristic of lower dry-heat exchange levels by convection and radiation (Barker et al. 1999). Research indicates that the presence of air pockets has a greater influence on heat stress than clothing fabric composition and is affected by the introduction of air into the garment from wind and fans or from body movements and changes in posture (Havenith & Nilsson, 2004; Havenith, 1999; Havenith et al. 1990). Nilsson, Anttonen, and Holmer (2000) observed that I_T may be reduced by as much as 20-30% by walking. The insulative capacity of clothing material also diminishes as it becomes inundated with perspiration (Brode et al. 2008; Caravello et al. 2008; Havenith et al. 2008; Holmer & Nilsson, 1995; Kenney et al. 1993). It is notable that significant changes in I_T result in only minimal adjustments to $R_{e,T}$ estimated values (Barker et al. 1999; Bernard & Matheen, 1999).

Water Vapor Permeability

The ability of water vapor to travel through clothing fabric between the skin and the environment is estimated by the dimensionless value, i_m. The moisture permeability index is calculated using the equation, $i_m = I_T / 16.7 \, R_{e,T}$, where 16.7 refers to the Lewis

Number expressed as $16.7^{\circ}C\ kPa^{-1}$ (ISO, 2007; Woodcock, 1962). Both static ($i_{m,stat}$) and apparent ($i_{m,a}$) values may be calculated depending on the nature of I_T and $R_{e,T}$ estimates used in the equation. Apparent i_m values are greater than those estimated statically due to the "pumping effect" described by Havenith & Nilsson (2004) and Havenith (1999). Using five different types of single-layered cotton woven fabrics and a constant ambient air temperature (T_{db}) of $23^{\circ}C$, Hes & Araujo (2010) found that tight fitting, wet layered clothing increase water vapor permeability while loose-fitting, dry layered clothing exhibited the lowest values. It can be demonstrated from the equation that lower $R_{e,T}$ values for a given clothing ensemble will lead to higher i_m values and rates of evaporative cooling (Anna, 2003). The inverse relationship observed between $R_{e,T}$ and i_m reveals the significance of clothing permeability and the movement of water vapor between the skin and the environment to heat exchange in hot environments.

Evaporative Resistance

Evaporation of sweat on the skin surface is the primary cooling mechanism employed by the body to maintain body core temperature in hot environments making $R_{e,T}$ of primary importance (Caravello et al. 2008; Havenith et al. 2008; Holmer, 2006; Holmer, 2006). $R_{e,T}$ values are calculated statically ($R_{e,T,stat}$) or dynamically ($R_{e,T,a}$) with higher values observed when estimated under static conditions (Caravello et al. 2008). Clothing with higher porosity and smaller insulative pockets of air will generally yield lower $R_{e,T}$ estimates (Bernard et al. 2010; Gonzalez et al. 2006; Holmer, 2006). Havenith, Heus, and Lotens (1990) found that body movement and wind effects can reduce $R_{e,T}$ estimates by as much as 88%. Therefore, estimating $R_{e,T}$ under dynamic

conditions not only quantifies the ability for clothing to support evaporative cooling but it does so under environmental conditions which most closely mimic real work settings (Caravello et al. 2008). Higher $R_{e,T}$ values imply higher levels of heat stress and *vice versa* (Barker et al. 1999).

Testing Methods for Estimating Clothing Heat and Vapor Resistance

Levine, Sawka, and Gonzalez (1998) outlines the four primary testing methods for estimating clothing heat and vapor resistance: (1) heated plate; (2) heated copper manikin; (3) modeling; and, (4) human subjects. A description of each method follows.

Heated Plate

The heat transfer properties of single or multi-layered fabric samples can be determined using a temperature-controlled, heated (flat) plate confined inside an environmental chamber. Methods for measuring heat and vapor resistance using the guarded hot plate are prescribed by the ISO (ISO, 1993). The heated plate method attempts to simulate the heat exchange pathways between the skin and the environment, and provides a relatively inexpensive and rapid means for testing a large number of fabrics. Unfortunately, the heated plate does not take into account the effects of human sweat or air and body movements. Another shortfall of the heated plate method is the heat transfer properties of fabric samples can change when integrated into a clothing ensemble (Barker et al. 1999; Levine et al. 1998). Nevertheless, a number of textile studies have been performed using the heated plate or a similarly designed apparatus to characterize the affects of temperature and humidity on different fabrics, membranes, and

laminates (Huang & Chen, 2011; Fukazawa et al. 2003; Gibson, 2000, 1999a; Gibson et al. 1999b; Barnes & Holcombe, 1996).

Heated Copper Manikin

The thermal properties of protective clothing ensembles can be identified using life-sized, thermal copper manikins. Procedures for using thermal manikins are outlined by the ASTM and ISO (ASTM, 2005; ISO, 2004c). Mannequins are computer-controlled and positioned inside temperature regulated environmental chambers in order to monitor, measure, and control for different environmental and physiological conditions. Most manikins are covered completely with form-fitting cotton to simulate human skin which can be wetted with distilled water to account for human sweat. More advanced manikins can simulate limited body movement and may have 30 or more zones on the surface of the manikins to manipulate and/or record "skin" surface temperatures (Bouskill et al. 2002; Havenith et al. 2008). High costs and logistical issues associated with technically advanced manikins results in most data being collected using stationary manikins in non-sweating conditions (Bouskill et al. 2002). Using copper manikins permits the collection of temperature-controlled data for different ensembles, accounting for whole clothing ensembles, clothing configuration, sweat, and, in rare cases, partial body movements. A major limitation of manikins is they do not account, in most cases, for increases in convective heat exchange produced by body movements and air "pumping" in and out of insulative air pockets located between the wearer and outer layer of clothing. Nevertheless, they permit researchers to study the thermal properties of clothing using

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extreme temperatures beyond those permitted using human subjects (Barker et al. 1999; Levine et al. 1998).

Modeling

Although modeling does not, by itself, generate data regarding thermal stress it is worth mentioning because it is becoming a popular method for predicting physiological responses to different clothing ensembles and combinations of environmental and metabolic conditions (Levine et al. 1998). Additionally, researchers are using computer modeling in an attempt to improve scientific understanding of microclimates. Data generated from heated copper manikins or human trials are entered into different types of computer modeling software and desired outputs are calculated automatically. Ghaddar, Ghali, and Jones (2003) offer a thorough review of a variety of computer models used in heat stress investigations. Wang et al. (2011) recently evaluated the predicted heat strain (PHS) model (ISO 7933) using six human subjects, three ensembles (clothing thermal insulation between 0.63 and 2.01 clo), and two environmental conditions. Rectal and skin temperatures predicted by the PHS model using set climatic conditions were compared to data generated from human trials under the same environmental conditions. The PHS Model failed to predict accurately the skin temperatures for all three ensembles. In spite of this, the model's prediction of rectal temperatures was within 1 standard deviation (SD) of observed rectal temperatures for two of three ensembles. The predicted *versus* observed rectal temperature for the third ensemble (2.01 clo) was 3.75 SD greater than the subject average mean SD. Wang et al. (2011) suggested that revisions to the PHS model were needed to account for protective clothing with high clothing insulation

estimates. Limitations to the study included a small sample size, use of clothing ensembles beyond the validation range of the PHS model (<0.6 clo), and a potentially inaccurate instrument for measuring metabolic rate (Wang et al. 2011).

Human Subjects

Human laboratory research provides the best approximation of workplace conditions because it accounts for all of the parameters captured using manikins, in addition to air and body movements. All human subject research requires approval from institutional review boards and volunteer consent forms. Healthy volunteers are selected, medically screened, and acclimatized prior to the initiation of experiment trials. Acclimatization and experiment trials are conducted inside a climate-controlled chamber under varying environmental conditions. Vital signs, body-core temperature, among other physiological and environmental data, are closely monitored during the trial to protect human subjects and for the collection of thermoregulatory data. Disadvantages of using human subjects in heat stress trials are costs, time, medical screening requirements, ethical considerations, and variability among human subjects (Barker et al. 1999; Levine et al. 1998).

Progressive Heat Stress Protocol

The progressive heat stress protocol is a method first developed by Belding and Kamon (1973), refined by Kenney et al. (1993), and continued by Caravello et al. (2008) to identify the critical condition where the threshold of thermoregulatory balance exists. A thermal load is slowly imposed on a person by means of gradual increases in air

temperature or water vapor pressure eliciting physiological responses to maintain homeostasis. Climatic changes are made every five minutes permitting the body to arrive at a temporary thermal equilibrium at each step. Further increases in temperature, moisture, or both, eventually cause the body to reach a maximum limit where heat gain equals heat loss. The moment at which the critical condition is achieved is dependent on several factors, including differences among individuals, clothing ensembles, workload, and environmental conditions. The protocol enables $R_{e,T,a}$ values to be estimated without having to weigh subjects or measure directly the water vapor pressure of skin (Kenney et al. 1993). Furthermore, estimated $R_{e,T,a}$ values take into account air and body movements and sweat (Caravello et al. 2008).

Heat Exchange in Hot Environments

There are several important heat exchange pathways that can be used to describe heat loss or gain in hot environments. Normal heat exchange processes between the skin and environment can be modified when one or more layers of clothing are introduced. Clothing acts as a barrier to heat exchange preventing the introduction of cooler air into the ensemble or the escape of water vapor transporting heat to the environment. Potential outcomes are the development of microclimates inside a clothing ensemble and a shift in the manner with which heat exchange is accomplished. A discussion of microclimates and heat exchange pathways encountered in hot environments where clothing ensembles are worn is presented.

Microclimates and Microclimate Effects

Microclimates are produced in small pockets of air between skin and clothing layers and are characterized by extreme temperature and moisture gradients compared to ambient environmental conditions (Holmer, 2006). The significance of microclimates cannot be overemphasized as they impact the physiological responses of people wearing clothing in heat stress conditions. Clothing construction (thermal properties) and configuration largely determine the nature and magnitude of microclimates (Holmer, 2006). For example, a vapor-barrier ensemble with no openings to the environment can generate microclimates characterized by 100% relative humidity, where the saturation pressure of water in the environment (P_a) exceeds the water vapor pressure at the skin (P_{sk}). Heat exchange is reversed in $P_a > P_{sk}$ warm, humid conditions as the body receives heat from the environment, consequently exacerbating the physiological effects of heat stress. The same can be said when microclimates are produced generating extreme hot, dry conditions where the T_{db} is greater than skin temperatures (T_{sk}) (Bouskill et al. 2002). What is different between the warm, humid and hot, dry conditions are the heat exchange processes involved (Havenith et al. 2008).

Also important in the thermoregulation of microclimates is air movement inside the clothing ensemble. Air from the environment can gain access into the ensemble by (1) permeation through the garment material, (2) unabated convective air movement into openings, and (3) forced penetration caused by wind, fans, and body movements (Bouskill et al. 2002). First described by Birnbaum and Crockford (1978) and further examined by Bouskill et al. (2002) is the Ventilation Index (V_T) which is used to quantify the air exchange properties of clothing. Bouskill et al. (2002) used a manikin enclosed in

a controlled environmental chamber (T_{db} = 10°C and P_a = 0.73 kPa) under static and dynamic (moving) conditions to demonstrate that increases in V_T produced by different walking speeds and air speeds reduced I_{clo} of two ensembles. As anticipated, greater effects were observed in the single layer ensemble *versus* the triple layer ensemble. A final feature of microclimates relevant to heat exchange is the average air layer thickness between human skin and clothing. Several techniques are used to estimate trapped volume including 3D whole-body scanning, use of a thin airtight suit over the garments, and modeling. Daanen, Hatcher, and Havenith (2005) investigated all three techniques on human subjects wearing only bicycle shorts, bicycle shorts with T-shirt, and a coverall. It was determined that the microclimate volume for the coveralls was more than double that of the other two ensembles. Further, the 3D scanning method proved to supply the most accurate estimates of microclimate volumes.

Heat Exchange Pathways

Clothing interferes with heat transfer between the skin to the environment by limiting (1) dry-heat exchange or (2) evaporative-heat exchange. Dry-heat exchange is comprised of conduction, radiation, and convection while evaporative-heat exchange involves the evaporation of sweat at the skin surface directly into the environment or into a microclimate when clothing is worn. In hot environments, evaporative-heat exchange serves as the primary mechanism in maintaining thermal equilibrium. Havenith et al. (2008) emphasizes the "microclimate heat pipe" in hot environments when the skin is wet and clothing is worn. The microclimate heat pipe is an evaporation/condensation cycle triggered by the evaporation and subsequent condensation of sweat on the inside of the

outer clothing layer. The evaporation process transports heat at the surface of the skin into the microclimate where it is transferred to the clothing layer upon condensation. The heat contained in the inner layer of the wet clothing is delivered to the outer layer of clothing where it is removed by dry-heat exchange processes. The microclimate evaporation/condensation cycle is influenced by temperature effects, evaporative heat loss rate, and the water and vapor permeability of the clothing being worn. Havenith et al. (2008) also describes a process of wet conduction that takes place when clothing layers become saturated with sweat. Clothing saturation can occur either through the condensation of sweat via the heat pipe or by making direct contact with wet skin and soaking up excess perspiration (a process also known as *wicking*).

Only dry-heat exchange processes are present when the skin is dry. Dry heat loss is enhanced with increasing differences between T_{sk} and T_a. At lower temperatures and when the skin is wet, both dry- and evaporative-heat exchange processes occur simultaneously, albeit not as similar rates. At higher temperatures where T_a equals T_{sk} (generally at 34°C or greater) dry-heat exchange is largely inhibited leaving evaporative-heat exchange as the only mechanism for cooling the body. The absence of dry-heat exchange is significant because it does not permit the removal of heat from clothing as required by a fully functional microclimate heat pipe. As P_a approaches P_{sk}, evaporative-heat exchange becomes moderated, ceasing altogether when $P_a = P_{sk}$ (Havenith et al. 2008; Bouskill et al. 2002; Barker, 1999).

Equations (1) and (2) demonstrate the relevance of different heat exchange pathways in the estimation of $R_{e,T,a}$ values using the progressive heat stress protocol (Caravello et al. 2008; Kenney et al. 1993; Belding & Kamon, 1973):

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$$(P_{sk} - P_a) / R_{e,T,a} = H_{net} + (T_{db} - T_{sk}) / I_{T,r}$$ Equation (1)

$$H_{net} = M - W_{ext} - S + C_{res} - E_{res}$$ Equation (2)

According to equation (1), the critical condition represents the maximum heat loss attributed to evaporative cooling balanced by the net heat gain from internal sources and dry-heat exchange. Evaporative cooling is equivalent to the difference between P_{sk} and P_a divided by the estimated $R_{e,T,a}$. Net heat gain (H_{net}) is comprised of the sum of metabolic rate (M) and respiratory exchange rate by convection (C_{res}) less external work (W_{ext}), storage rate (S), and respiratory exchange rate by evaporation (E_{res}). Equations for estimating M, W_{ext}, S, C_{res}, and E_{res} are discussed in Chapter 3. Heat stress trials are normally conducted in non-radiant environments permitting dry-heat exchange to be estimated using the difference in T_{db} and T_{sk} divided by $I_{T,r}$ (Caravello et al. 2008; Kenney et al. 1993; Belding & Kamon, 1973).

Equation (1) is only valid for estimating $R_{e,T,a}$ at the critical conditions of the progressive protocol due to the reliance on heat balance. The method for estimating $R_{e,T,a}$ is dependent on estimates of $I_{T,r}$, a prerequisite founded on the assumption established by Kenney et al. (1993) that clothing insulation and evaporative resistance are constant in warm, humid and hot, dry conditions. Bernard et al. (2010), Caravello et al. (2008), and Barker et al. (1999), collectively known as the University of South Florida (USF) Group, adopted this approach contending that the influence of clothing insulation on evaporative resistance is negligible (Bernard et al. 2010). Building on the work of the USF Group,

the present research investigates whether $R_{e,T,a}$ will remain the same independent of environmental climatic conditions over a range of heat stress levels.

CHAPTER 3: METHODOLOGY

Overview

Environmental and physiological data collected by Caravello et al. (2008) and Bernard et al. (2005) using a progressive heat stress protocol were extracted to estimate empirically the apparent total evaporative resistance ($R_{e,T,a}$) of five clothing ensembles at a moderate metabolic rate and three levels of relative humidity (RH). A detailed methodology for data collection, extraction, and analysis is provided.

Participants

Fourteen adults (nine men and five women) participated in experimental trials. The average and standard deviation of their physical characteristics by gender are provided in Table 3.1. The study protocol was approved by the University of South Florida Institutional Review Board. A written informed consent was obtained prior to enrollment in the study. Each participant was examined by a physician and approved for participation. The participants were healthy with no chronic disease requiring medication. While smoking status was not an exclusionary factor, most were nonsmokers.

Participants were reminded of the need to maintain good hydration. On the day of the trial, they were asked not to drink caffeinated beverages 3 hours before the appointment and not to participate in vigorous exercise before the trial. Prior to

beginning the experimental trials to determine critical conditions, participants underwent a 5-day acclimatization to dry heat that involved walking on a treadmill at a metabolic rate of approximately 165 W m^{-2} in a climatic chamber at 50°C and 20% RH for 2 hours. Participants wore a base ensemble of shorts, tee-shirt (and/or sports bra for women), socks, and shoes.

Table 3.1. Physical Characteristics of Participants (Mean ± Standard Deviation)

	Age (Years)	Height (cm)	Weight (kg)	Body Surface Area (m^2)
Women (n = 5)	32 ± 9	161 ± 7	63.4 ± 17.3	1.66 ± 0.23
Men (n = 9)	29 ± 7	183 ± 5	97.4 ± 18.4	2.18 ± 0.20
Both (n = 14)	30 ± 7	175 ± 12	85.3 ± 24.2	1.99 ± 0.33

Clothing

Five different clothing ensembles were evaluated. The ensembles included work clothes (135 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants), cotton coveralls (305 g m^{-2}), and three limited-use protective clothing ensembles including a particle-barrier ensemble, Tyvek$^{®}$ 1424, water-barrier, vapor-permeable ensemble (NexGen$^{®}$ LS 417), and a vapor-barrier ensemble (Tychem QC$^{®}$, polyethylene-coated Tyvek$^{®}$). The limited-use coveralls had a zippered closure in the front and elastic cuffs at the arms and legs. None of the ensembles included a hood. The base ensemble was worn under all clothing ensembles.

Equipment

The trials were conducted in a controlled climatic chamber. Temperature and humidity were controlled according to protocol and air speed was 0.5 m s^{-1}. Heart rate

was monitored using a chest strap heart rate monitor. Core temperature (T_{re}) was measured with a flexible thermistor inserted 10 cm beyond the anal sphincter muscle. The thermistor was calibrated prior to each trial using a hot water bath.

The work demand consisted of walking on a motorized treadmill at a speed and grade set to elicit a target metabolic rate of 165 W m^{-2}. Measurement of oxygen consumption was used to assess metabolic rate. Participants breathed through a two-way valve connected to flexible tubing that was connected to a collection bag. Expired gases were collected for about 2.5 min. The volume of expired air was measured using a dry gas meter. An oxygen analyzer was used to determine oxygen content of air. A metabolic rate was recorded for each trial which was the average of three samples of oxygen consumption taken at approximately 30, 60, and 90 minutes into a trial and expressed as the rate normalized to body surface area.

Protocols

Each ensemble was worn by each participant performing exercise at a moderate rate of exertion. The order of ensembles was randomized. Any trial that had to be repeated was repeated at the end of the schedule. Most participants completed one trial per day, but some completed two trials per day with at least 3 hours of recovery between trials. The study design called for three environments: warm, humid at 70% RH (R7); hot, dry at 20% RH (R2); and a midrange 50% RH (R5). For the R7 protocol, the dry bulb temperature (T_{db}) was set at 30°C and RH at 70%. Once the participant reached thermal equilibrium (no change in T_{re} and heart rate for at least 15 minutes), T_{db} was increased 0.7^{o}C every 5 minutes. In the R2 protocol, T_{db} was set at 40°C with RH at

20%. When participants reach thermal equilibrium, T_{db} was increased $1^{\circ}C$ every 5 minutes. For the R5 protocol, T_{db} was set at $34^{\circ}C$ with 50% RH. On reaching thermal equilibrium, T_{db} was increased $0.8^{\circ}C$ every 5 minutes. During the trials, participants were allowed to drink water or a commercial fluid replacement beverage (Gatorade®) at will.

Core temperature, heart rate, and ambient conditions (dry bulb, psychrometric wet bulb, and globe temperatures; T_{db}, T_{pwb}, and T_g, respectively) were monitored continuously and recorded every 5 minutes. Trials were scheduled to last 120 minutes unless one of the following criteria was met: (1) a clear rise in T_{re} associated with a loss of thermal equilibrium (typically $0.1^{\circ}C$ increase per 5 minutes for 15 minutes); (2) T_{re} reached $39^{\circ}C$; (3) a sustained heart rate greater than 90% of the age-predicted maximum heart rate; or (4) participant wished to stop.

Inflection Point and Determination of Critical Conditions

The inflection point marked the transition from thermal balance to the loss of thermal balance, where body core temperature continued to rise as shown in Figure 3.1 for one trial. The chamber conditions existing at the time of 5 minutes before the observed increase in core temperature was defined as the critical condition. One investigator noted the critical condition and some of the decisions were randomly reviewed by a second investigator.
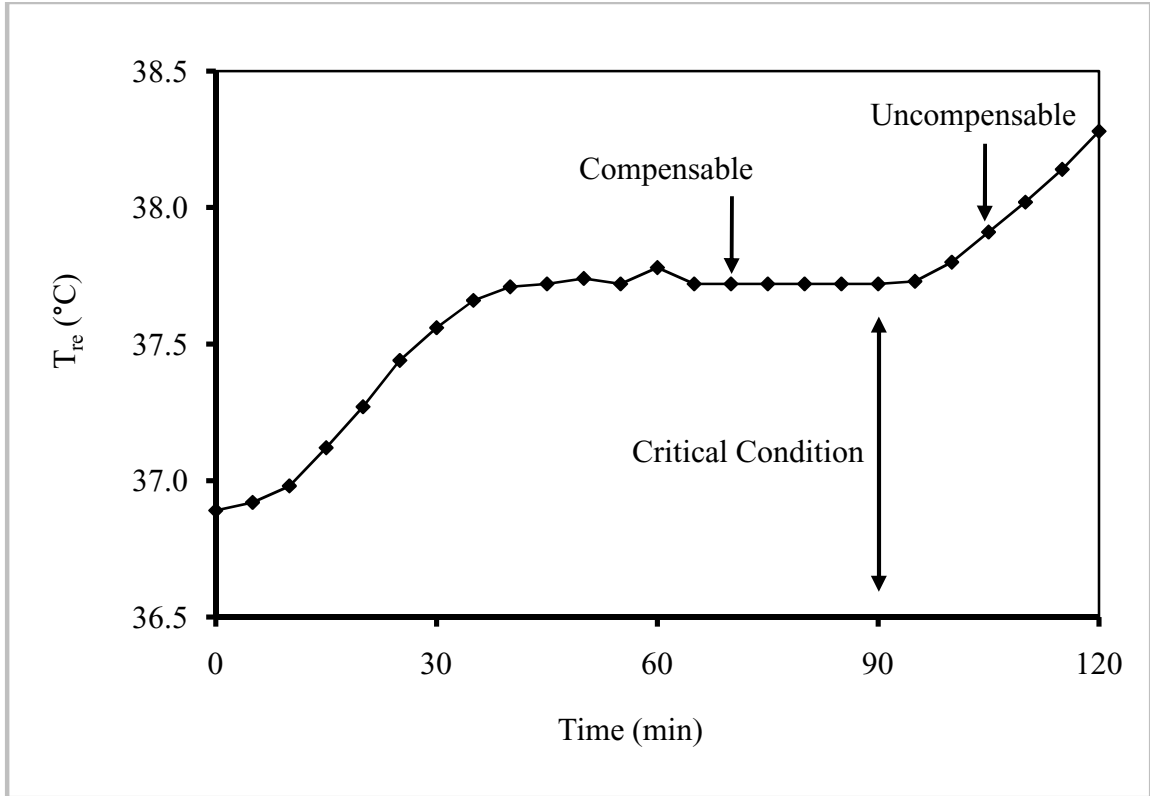
Modified from Caravello et al. (2008)

Figure 3.1. Time Course of Rectal Temperature for One Trial

Data Extraction

The progressive heat stress protocol permitted the collection of data at, near, or beyond the critical condition for each participant. Environmental and physiological data were extracted at three different stages of heat stress (compensable, transition, and uncompensable; C, T, and U, respectively). The stages included: (1) 20 minutes before the critical condition (C); (2) at the critical condition (T); and (3) 15 minutes beyond the critical condition (U). Theoretically, 630 rows of data were anticipated based on 14 participants, five ensembles, three RHs, three stages of heat stress, and a constant metabolic rate. However, 663 rows of data were extracted as 11 repeated trials were conducted. Each row incorporated 28 columns of data producing a total of 18,564 cell

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blocks containing data. Data extraction was performed by two investigators and all data were entered into Microsoft™ Excel 2007. A third investigator performed a random verification of 25% of the database following data extraction indentifying 11 errors (0.24%). Error percentage was calculated by multiplying 166 (25% of the rows) by 28 (number of columns in each row) and dividing the product into 11 (number of errors). The resultant value was multiplied by 100 yielding 0.24% error. All identified errors were corrected prior to computing $R_{e,T,a}$ values.

Calculation of Clothing Parameters

Environmental and physiological data for each of the 663 combinations were used to estimate $R_{e,T,a}$ values. The following is the process to calculate derived values for each trial based on trial conditions for the participant and environment.

Referring to Kenney et al. (1993), metabolic rate (M), external work (W_{ext}), storage rate (S), and respiratory exchange rate by convection (C_{res}) and evaporation (E_{res}) presented in equation (2) were estimated as follows. M in W m^{-2} was estimated from oxygen consumption (V_{O2}) in liters per minute:

$$M = 350 \cdot V_{O2} / A_D \hspace{4cm} \text{Equation (3)}$$

The Dubois surface area (A_D) was calculated for each subject as $A_D = 0.202m_b^{0.425} \cdot H^{0.725}$, where m_b was the mass of the body (kg) and H was the height (m). W_{ext} was calculated (W m^{-2}) in the following manner:

$$W_{ext} = 0.163 m_b \cdot V_W \cdot f_g / A_D \hspace{4cm} \text{Equation (4)}$$

V_W was the walking velocity in m min^{-1} while f_g was the fractional grade of the treadmill (%). Values for C_{res} (W m^{-2}) and E_{res} (W m^{-2}) were calculated using equations provided in ISO 7933 (2004a). The estimation of C_{res} required that expired air temperature (T_{exp}) be calculated using T_{db} and P_a:

$$T_{exp} = 28.56 + (0.115 \cdot T_{db}) + (0.641 \cdot P_a) \hspace{3cm} \text{Equation (5)}$$

$$C_{res} = 0.001516 \cdot M (T_{exp} - T_{db}) \hspace{3.5cm} \text{Equation (6)}$$

$$E_{res} = 0.00127 \cdot M (59.34 + 0.53 \cdot T_{db} - 11.63 \cdot P_a) \hspace{2cm} \text{Equation (7)}$$

Kenney et al. (1993) recognized that there may be some heat storage represented by a gradual change in T_{re}. To account for this, the rate of change in heat storage can be estimated knowing the specific heat of the body (0.97 W h $^\circ$C^{-1} kg^{-1}), m_b, and the rate of change of body temperature ($\Delta T_{re} \Delta t^{-1}$) as an average over the 20 minute period preceding the inflection point. This approach was taken by Barker et al. (1999) with some changes in sign conventions:

$$S = 0.97 m_b \cdot \Delta T_{re} A_D^{-1} \Delta t^{-1} \hspace{4cm} \text{Equation (8)}$$

Total static clothing insulation ($I_{T,stat}$) values were determined according to ASTM F 1291, *Standard Test Method for Measuring the Thermal Insulation of Clothing using a Heated Manikin*, using a fixed environment and adjusting the heat input to achieve thermal equilibrium (ASTM, 2002). In the current study, these values were treated as a fixed value for all ensembles.

The total dynamic clothing insulation ($I_{T,r}$) was estimated according to ISO 9920 (2007) (Equation 32) in two stages. First, the correction factor for insulation (CFI) was calculated according to Havenith and Nilsson (2004) (Equation 4) and ISO 9920 (2007) where v is air speed (0.5 m s^{-1}) and w refers to walking speed or speed of the treadmill (m s^{-1}) for each wear trial. This adjustment for air and body movement was similar to that proposed by Holmer et al. (1999). The equation to estimate the CFI is as follows:

$$CFI = \exp[-0.281(v - 0.15) + 0.044(v - 0.15)^2 - 0.492w + 0.176w^2] \qquad \text{Equation (9)}$$

Second, $I_{T,stat}$ and CFI values were multiplied by 0.9 (reduced by 10%) finalizing the estimated $I_{T,r}$ to account for the reduction in insulation due to wetting (Brode et al. 2008):

$$I_{T,r} = CFI \cdot I_{T,stat} \cdot 0.9 \qquad \text{Equation (10)}$$

$R_{e,T,a}$ values were calculated by rearranging equation (1).

$$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}] \qquad \text{Equation (11)}$$

Each $I_{T,r}$ value was inserted into equation (11) along with other applicable environmental and physiological data for each combination to estimate the $R_{e,T,a}$. The process was repeated yielding 663 $R_{e,T,a}$ values in all.

Statistical Analysis

JMP® (version 7.1) statistical software (SAS, Cary, North Carolina) was used to analyze data. A mixed model analysis of variance (ANOVA) in combination with Tukey's Honestly Significant Difference (HSD) multiple comparison tests were used to determine where the main differences occurred. To analyze the relationships among ensembles, RH levels, and heat stress stages, a four-way ANOVA was performed in which those factors were fixed effects and the participants were maintained as a random effect. Also evaluated were three interactions between ensembles-RH levels, ensembles-heat stress stages, and RH levels-heat stress stages. The dependent variable for the statistical test was $R_{e,T,a}$ and significance was established at $\alpha = 0.05$.

CHAPTER 4: RESULTS

Overview

A four-way mixed model analysis of variance (ANOVA) was used to test for three fixed main effects and three second order interactions. The main effects were ensemble, relative humidity (RH), and stage of heat stress. Participants were treated as a random effect. The analysis of the data demonstrated significant differences for estimated $R_{e,T,a}$ values among ensembles, RH levels, heat stress stages, and interactions among ensembles and RH levels and ensembles and heat stress stages ($p < 0.0001$). No significant interaction among RH levels and heat stress stages was found ($p = 0.67$). A Tukey's Honestly Significant Difference (HSD) multiple comparison test was used to identify where significant differences occurred ($p < 0.05$).

Main Effects

A Tukey's HSD multiple comparison test was used to identify differences among ensembles. Referring to Table 4.1, there were no significant differences among work clothes, cotton coveralls, and Tyvek[®] 1424. Significant differences ($p < 0.05$) were detected between NexGen[®] LS 417 and Tychem QC[®], and among these two ensembles and work clothes, cotton coveralls, and Tyvek[®] 1424. The highest $R_{e,T,a}$ values were observed for the vapor-barrier ensemble followed by the water-barrier, vapor-permeable ensemble, particle-barrier ensemble, cotton coveralls (CC), and work clothes (WC).

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Table 4.1. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles

Ensembles	Evaporative Resistance	Statistical Difference[*]
WC	0.014	A
CC	0.015	A
Tyvek	0.016	A
Nexgen	0.019	B
Tychem	0.034	C

*Similar letters denote no significant differences (p < 0.05)

Tukey's HSD test demonstrated significant differences (p < 0.05) for each RH level. Estimated $R_{e,T,a}$ values were highest at 20% RH and lowest at 70% RH as demonstrated by Table 4.2.

Table 4.2. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Three Relative Humidity Levels

RH (%)	Evaporative Resistance	Statistical Difference[*]
20	0.023	A
50	0.018	B
70	0.017	C

*Similar letters denote no significant differences (p < 0.05)

Every stage of heat stress was determined to be significantly different (p < 0.05) based on Tukey's HSD test. The compensable heat stress stage was characterized with the highest estimated $R_{e,T,a}$ values, while the lowest values were observed under uncompensable heat stress conditions as shown in Table 4.3.

Table 4.3. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Three Heat Stress Stages

Heat Stress Stage	Evaporative Resistance	Statistical Difference[*]
Compensable	0.024	A
Transition	0.019	B
Uncompensable	0.016	C

*Similar letters denote no significant differences ($p < 0.05$)

Interactions

The estimated $R_{e,T,a}$ values for each clothing ensemble at different RH levels are shown in Table 4.4, and $R_{e,T,a}$ values for every ensemble at 20, 50, and 70% RH are illustrated in Figure 4.1. The results from Tukey's HSD test revealed that $R_{e,T,a}$ values for the Tychem QC[®] ensemble were statistically different ($p < 0.05$) from $R_{e,T,a}$ estimates for all other ensembles at different RH levels. The NexGen[®] LS 417 ensemble at 20% RH was statistically different from all other ensembles except Tyvek[®] 1424 at 20% RH. See also Appendix E for other statistical differences for interactions.

Table 4.4. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles at Three Relative Humidity Levels

		Relative Humidity Levels		
		20%	50%	70%
Ensembles	WC	0.016	0.013	0.013
	CC	0.017	0.013	0.014
	Tyvek	0.019	0.015	0.014
	Nexgen	0.022	0.018	0.017
	Tychem	0.043	0.033	0.026
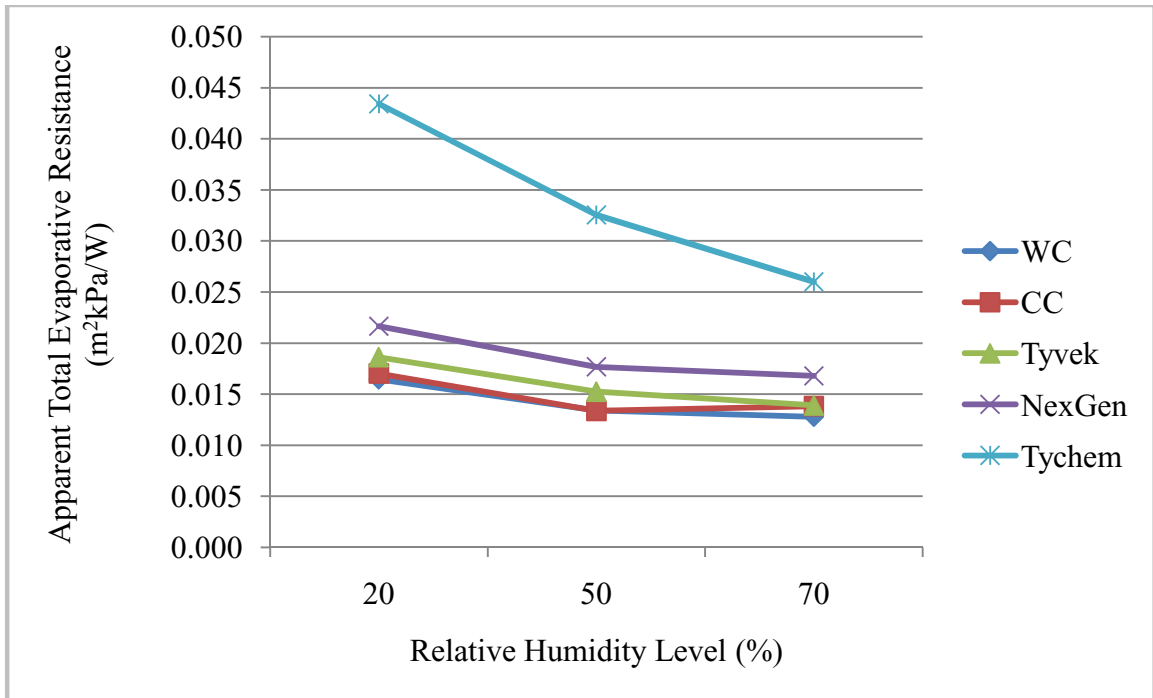
Figure 4.1. Least Squares Mean of Apparent Total Evaporative Resistance for Five Ensembles at Three Relative Humidity Levels

What was apparent from Figure 4.1 was the magnitude of differences in $R_{e,T,a}$ values of the Tychem QC[®] ensemble from those of all other ensembles, particularly at 20% RH. The Tychem QC[®] ensemble appeared to be the most sensitive to changes in RH. There were greater differences among $R_{e,T,a}$ values at 20% RH where higher $R_{e,T,a}$ values existed for all ensembles compared to 70% RH where all ensembles expressed the lowest estimates. $R_{e,T,a}$ values for the WC, CC, and Tyvek[®] 1424 were grouped in the same way at each RH level. Estimated $R_{e,T,a}$ values for the NexGen[®] LS 417 ensemble were elevated slightly above $R_{e,T,a}$ values for WC, CC, and Tyvek[®] 1424 but maintained a similar pattern at each RH level. $R_{e,T,a}$ values for the Tychem QC[®] ensemble did not mirror the pattern of any of the ensembles.

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The estimated $R_{e,T,a}$ values for every clothing ensemble at different heat stress stages were compiled in Table 4.5, and the $R_{e,T,a}$ values for each ensemble at compensable, transition, and uncompensable conditions were graphed in Figure 4.2.

Table 4.5. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles at Three Heat Stress Stages

		Heat Stress Stages		
		Compensable	Transition	Uncompensable
Ensembles	WC	0.017	0.014	0.012
	CC	0.018	0.014	0.012
	Tyvek	0.019	0.016	0.013
	Nexgen	0.024	0.018	0.015
	Tychem	0.042	0.033	0.027
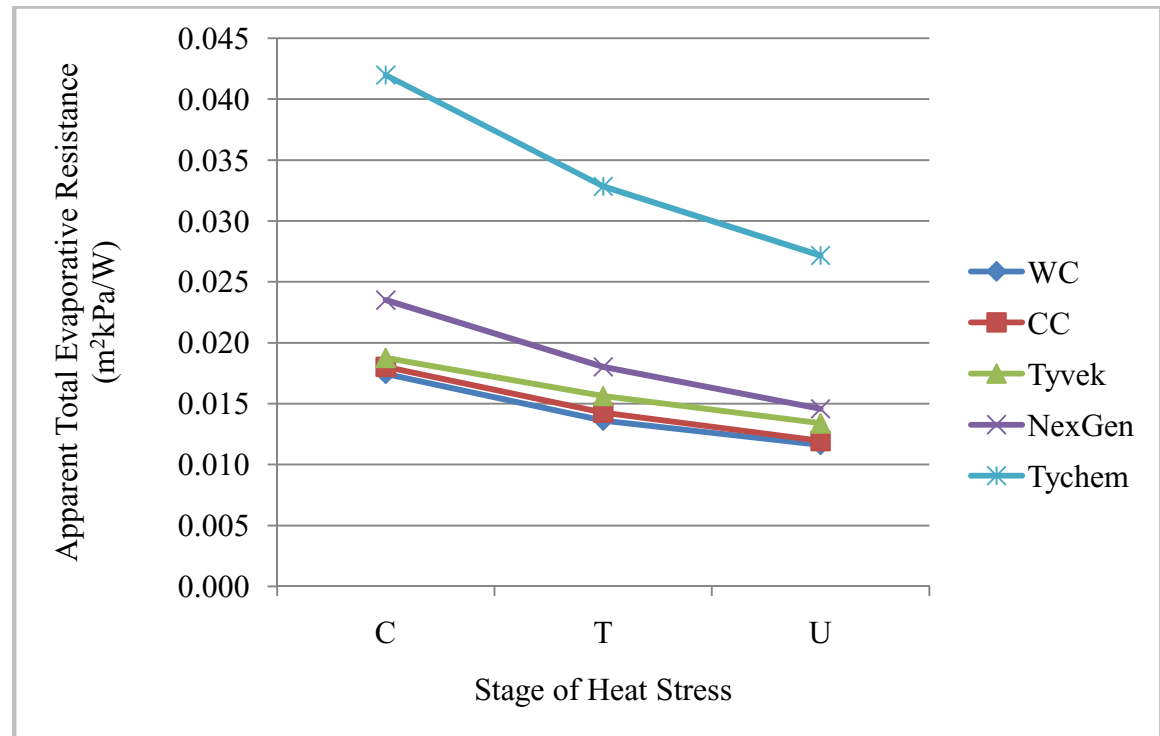
C = Compensable, T = Transition, U = Uncompensable

Figure 4.2. Least Squares Mean of Apparent Total Evaporative Resistance for Five Ensembles at Three Heat Stress Stages

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$R_{e,T,a}$ values for Tychem QC® and NexGen® LS 417 decreased more rapidly from compensable to uncompensable stages of heat stress than the other three clothing ensembles. Figure 4.2 displayed a similar pattern seen in Figure 4.1 where the greatest differences among $R_{e,T,a}$ values were observed under compensable heat stress conditions, which was characterized with the highest $R_{e,T,a}$ values for all ensembles. The patterns demonstrated by estimated $R_{e,T,a}$ values for each ensemble indicated that the Tychem QC® ensemble was most sensitive to different stages of heat stress, followed by NexGen® LS 417 and Tyvek® 1424. WC and CC ensembles maintained a similar pattern along the stages of heat stress which was reinforced by the fact that there were no significant differences between $R_{e,T,a}$ values for each ensemble at the same RH level.

Similar estimated $R_{e,T,a}$ values among RH levels and heat stress stages yielded no significant differences (p = 0.05) from Tukey's HSD test.

Temperature and Vapor Pressure Gradients

The changes observed in $R_{e,T,a}$ values for RH and heat stress stages might be explained by changes in temperature and water vapor pressure. Average temperature differences were calculated by averaging the differences of skin temperatures (T_{sk}) from ambient air temperatures (T_{db}). Average temperature differences ($T_{db} - T_{sk}$) can be indicative of the direction and magnitude of dry-heat exchange. Average vapor pressure differences were estimated by averaging the differences of ambient water vapor pressures (P_a) from skin (P_{sk}). Average vapor pressure differences ($P_{sk} - P_a$) provided information regarding the magnitude of evaporative-heat exchange.

The average temperature differences for different clothing ensembles at three RH levels were graphed in Figure 4.3, and the average temperature differences for different clothing ensembles at three stages of heat stress were illustrated in Figure 4.4.
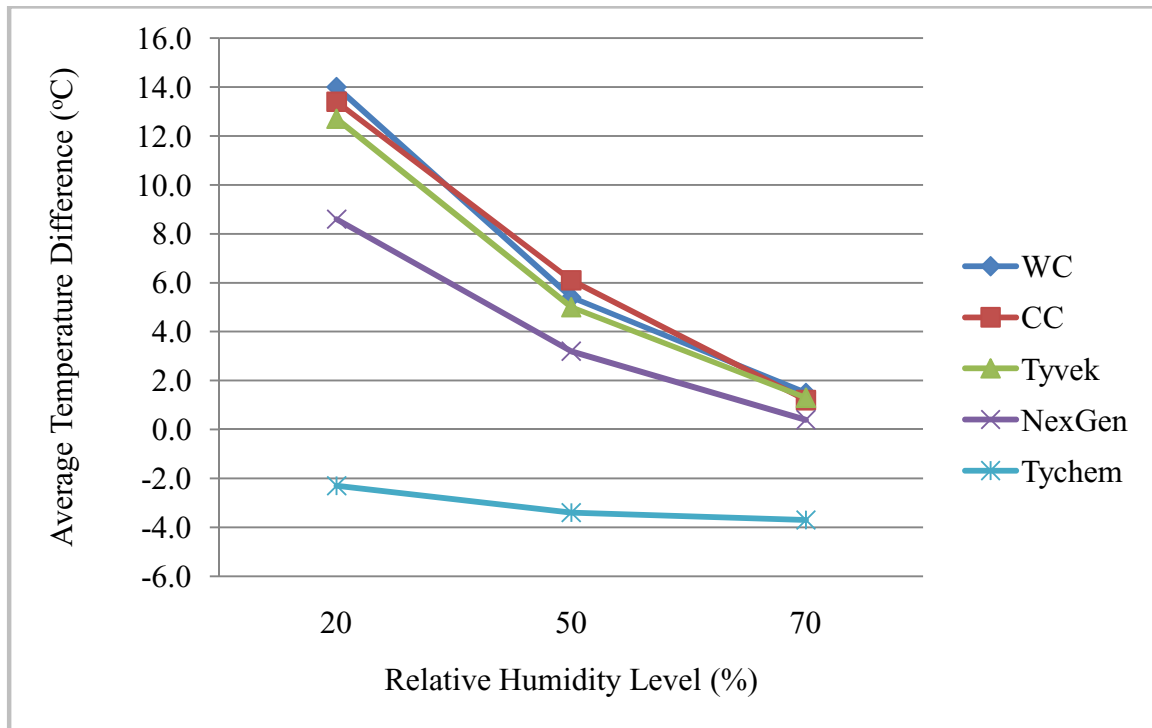
Figure 4.3. Average Temperature Differences for Five Ensembles at Three Relative Humidity Levels

As expected, greater temperature differences were observed at 20% RH with lowest differences occurring at 70% RH. For three ensembles there was a greater dry-heat loss at 20% RH (117 W m^{-2}) than at 70% RH (12 W m^{-2}). The NexGen[®] LS 417 ensemble was not much different. Only the Tychem QC[®] ensemble exhibited negative average temperature differences ($T_{sk} > T_{db}$) resulting in dry-heat losses of -22 W m^{-2} at 20% RH and -35 W m^{-2} at 70% RH. Additionally, the Tychem QC[®] ensemble did not

follow the pattern observed with other ensembles as less than 2°C of difference existed between temperature gradients at 20 and 70% RH levels.
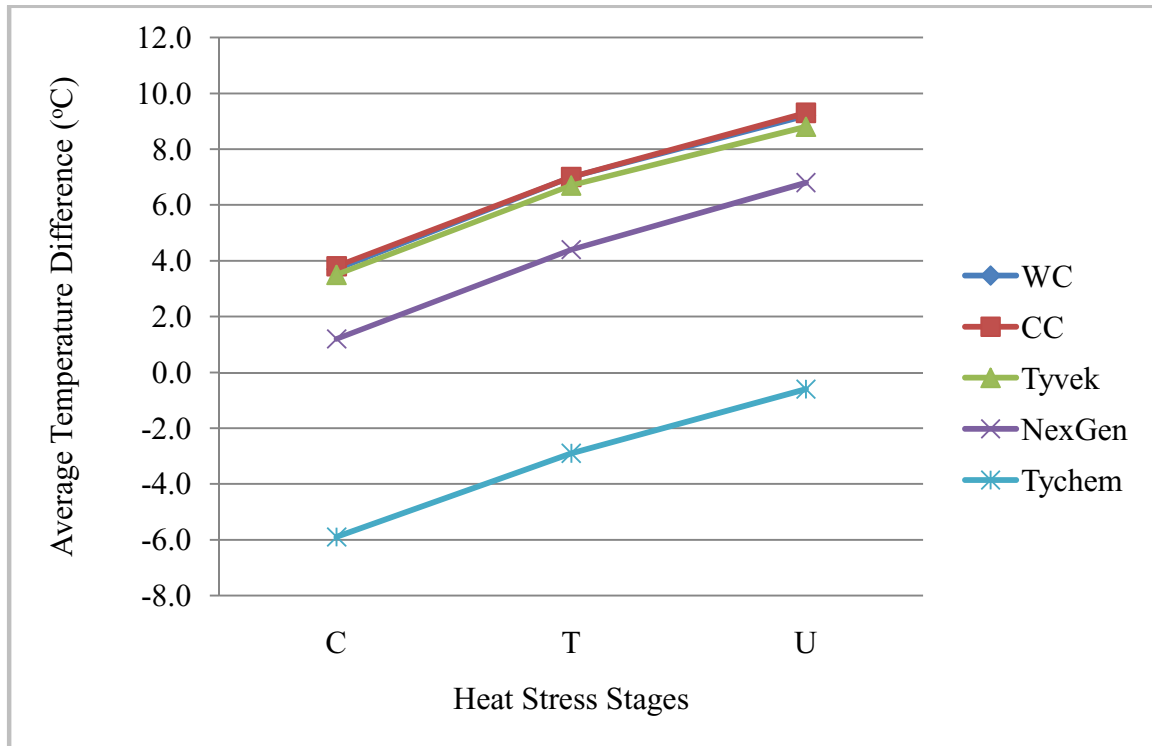
Figure 4.4. Average Temperature Differences for Five Ensembles at Three Heat Stress Stages

Similar average temperature differences for WC and CC ensembles prohibited the line-plot for the WC ensemble from being detected in Figure 4.4. Again, as expected, greater average temperature differences were associated with the uncompensable stage of heat stress among all clothing ensembles. For three ensembles there was a greater dry-heat loss under uncompensable conditions (83 W m^{-2}) than under compensable conditions (35 W m^{-2}). The NexGen$^®$ LS 417 ensemble was slightly different experiencing a dry-heat loss of 61 W m^{-2} and 10 W m^{-2} under uncompensable and compensable conditions, respectively. Only the Tychem QC$^®$ ensemble exhibited negative average temperature

differences ($T_{sk} > T_{db}$) leading to a dry-heat loss of -6 W m^{-2} and -54 W m^{-2} under uncompensable and compensable conditions, respectively. Every ensemble followed a relatively consistent pattern among RH levels.

The average pressure differences for different clothing ensembles at three RH levels were illustrated in Figure 4.5, while the average pressure differences for different clothing ensembles at three heat stress stages were displayed in Figure 4.6.
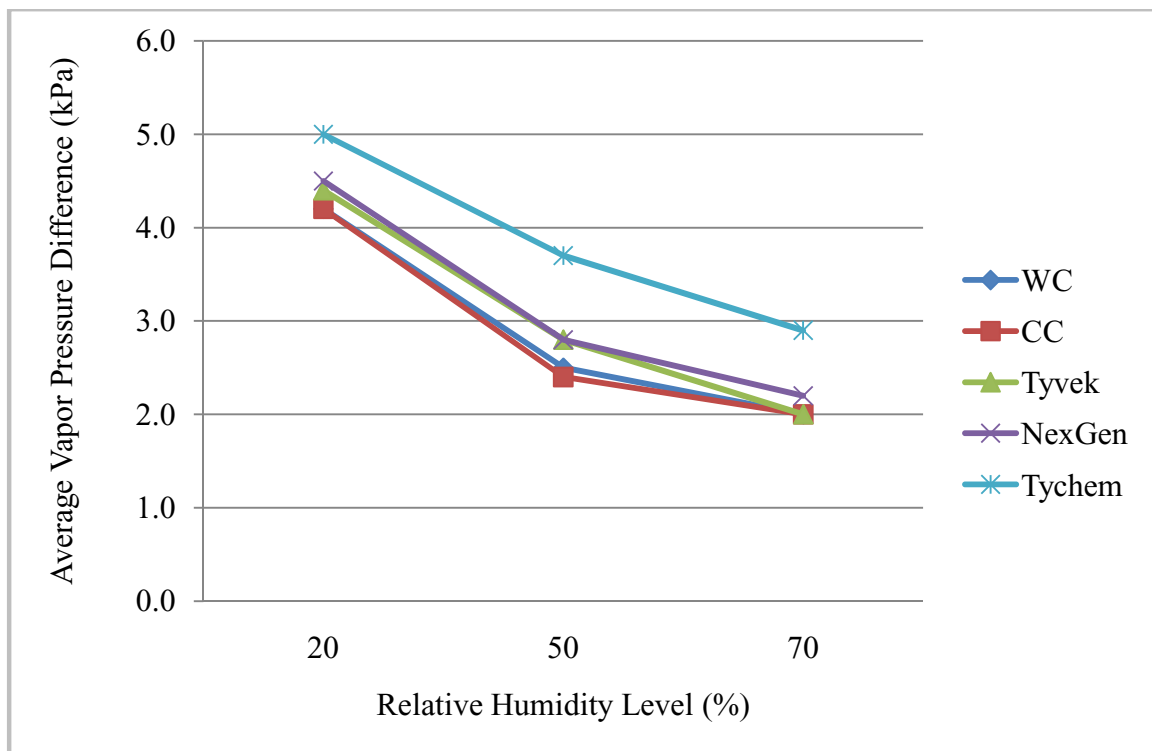
Figure 4.5. Average Vapor Pressure Differences for Five Ensembles at Three Relative Humidity Levels

Greater average vapor pressure differences were observed at 20% RH with lowest differences occurring at 70% RH. The greatest pressure gradients were associated with the Tychem QC® ensemble at all RH levels.
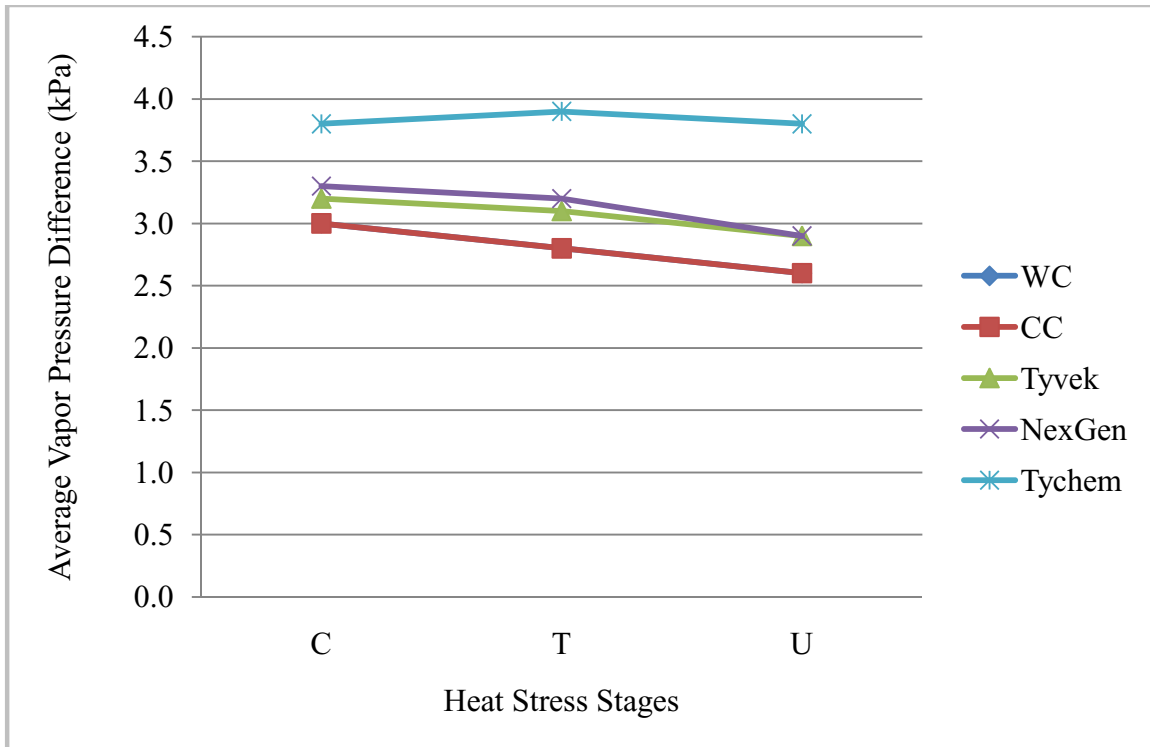
C = Compensable, T = Transition, U = Uncompensable

Figure 4.6. Average Vapor Pressure Differences for Five Ensembles at Three Heat Stress Stages

Similar vapor pressure differences for WC and CC ensembles prohibited the visibility of the WC ensemble line-plot in Figure 4.6. All clothing ensembles with the exception of Tychem QC$^®$ experienced slight decreases in average vapor pressure differences (0.3-0.4 kPa) from compensable to uncompensable heat stress stages. The average vapor pressure of the Tychem QC$^®$ ensemble remained fairly stable over heat stress stages with a small increase under the transitional heat stress condition.

CHAPTER 5: DISCUSSION

Analysis of Results

Differences among ensembles were anticipated based on the results published by Caravello et al. (2008). Caravello et al. (2008) reviewed the same ensembles used in this study but only at 50% relative humidity (RH) and at critical conditions. The apparent total evaporative resistance ($R_{e,T,a}$) values recorded by Caravello et al. (2008) at 50% RH were 0.013 m^2 kPa W^{-1} for work clothes (WC), 0.013 m^2 kPa W^{-1} for cotton coveralls (CC), 0.015 m^2 kPa W^{-1} for Tyvek® 1424, 0.018 m^2 kPa W^{-1} for NexGen® LS 417, and 0.032 m^2 kPa W^{-1} for Tychem QC®. The $R_{e,T,a}$ values presented in Table 4.1, while including the effects of the three RH levels and stages of heat stress, were virtually the same.

The $R_{e,T,a}$ values reported by Bernard et al. (2010), Barker et al. (1999), and Kenney et al. (1993) for WC were 0.014 m^2 kPa W^{-1}, 0.013 m^2 kPa W^{-1}, and 0.016 m^2 kPa W^{-1}, respectively, and were comparable to the $R_{e,T,a}$ value of 0.014 m^2 kPa W^{-1} calculated for WC in this study. The reported $R_{e,T,a}$ value of 0.016 m^2 kPa W^{-1} for Tyvek® 1424 in this study was also close to the $R_{e,T,a}$ value of 0.017 m^2 kPa W^{-1} documented at 50% RH by Barker et al (1999). The $R_{e,T,a}$ value of 0.019 m^2 kPa W^{-1} obtained in this study for NexGen® LS 417 was inside the range of $R_{e,T,a}$ values 0.014 m^2 kPa W^{-1} to 0.026 m^2 kPa W^{-1} reported by Barker et al. (1999) at 50% RH for microporous barriers. The three garments used by Barker et al. (1999) were constructed similarly but had different films

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and included integral hoods. Because no hoods were used in this study, differences among $R_{e,T,a}$ values may have been due to the use of hoods. It was, however, more likely that the different films modified the thermal properties of the ensembles. The only comparable ensemble to the Tychem QC$^{®}$ ensemble in the literature was a two-piece ensemble over military fatigues used by Kenney et al. (1993). He reported a $R_{e,T,a}$ value of 0.038 m^2 kPa W^{-1} for the ensemble which is higher than 0.034 m^2 kPa W^{-1} estimated in this study.

Statistical differences among RH levels, heat stress stages, and interactions among ensembles and RH levels and ensembles and heat stress stages were not anticipated. In order to gain insight into the differences observed among $R_{e,T,a}$ values for RH levels, heat stress stages, and interactions among ensembles and RH levels and ensembles and heat stress stages, the relationship between temperature and vapor pressure gradients was explored and evaluated. For this work, equation (11) from Chapter 3 used to calculate $R_{e,T,a}$ values was revisited.

$$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}] \qquad \text{Equation (11)}$$

As mentioned previously, water vapor pressure gradients were represented by the differences between skin vapor pressure and ambient air vapor pressure ($P_{sk} - P_a$), and differences between ambient air temperature and skin temperature ($T_{db} - T_{sk}$) denoted temperature gradients. Net heat gain (H_{net}) and total resultant insulation ($I_{T,r}$) remain about the same for each trial and among each ensemble demonstrating that the only variables in equation (11) which can vary are differences in vapor pressure and

temperature. Dry-heat loss (DH) is characterized by $(T_{db} - T_{sk}) / I_{T,r}$ and is influenced significantly by changes in temperature gradients. Decreases in temperature gradients or increases in vapor pressure gradients led to higher $R_{e,T,a}$ values.

In order to explain study results, each component comprising equation (11) was tabulated for two clothing ensembles at different RH intervals (Table 5.1) and heat stress stages (Table 5.2). WC was one of two ensembles chosen because it represented a baseline ensemble used frequently in industry while the Tychem QC® ensemble was different from all other ensembles under every environmental condition.

Table 5.1. Apparent Total Evaporative Resistance Values, Temperature and Pressure Gradients, and Net Heat Gain Plus Dry-Heat Loss Values for Two Ensembles at Three Relative Humidity Levels

Ensembles	WC			Tychem		
RH Levels	20%	50%	70%	20%	50%	70%
$R_{e,T,a}$ (m^2kPa/W)	0.016	0.013	0.013	0.043	0.033	0.026
ΔP (kPa)	4.2	2.5	2.0	5.0	3.7	2.9
ΔT (^{o}C)	14.0	5.4	1.5	-2.3	-3.4	-3.7
H_{net} (W m^{-1})	133	142	151	149	151	158
DH^* (W m^{-1})	132	52	14	-21	-31	-34
$H_{net} + DH^*$ (W m^{-1})	265	194	165	128	120	124

* $DH = (T_{db} - T_{sk}) / I_{T,r}$

The relationships among $R_{e,T,a}$ values, vapor pressure gradients, and H_{net} plus DH for WC and Tychem QC® ensembles at three different RH levels were illustrated in Figure 5.1.

Figure 5.1. Least Squares Mean of Apparent Total Evaporative Resistances (A), Average Pressure Differences (B), and Net Heat Gain Plus Dry-Heat Loss (C) for Two Ensembles at Three Relative Humidity Levels

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The changes among data in Table 5.1 progressed in the same direction. $R_{e,T,a}$ values and vapor pressure gradients were greatest at 20% RH and lowest at 70% RH. For WC, higher temperature gradients were observed at 20% RH with the lowest values recorded at 70% RH. Temperature gradients as well as H_{net} plus DH remained fairly stable for the Tychem QC® ensemble across RH levels. Referring to equation (11), higher vapor pressure gradients (numerator) in conjunction with stable H_{net} plus DH values (denominator) yielded higher $R_{e,T,a}$ values for the Tychem QC® ensemble. The elevated vapor pressure and temperature gradients for the WC ensemble countered each other, resulting in $R_{e,T,a}$ values that were nearly the same across RH levels.

Table 5.2. Apparent Total Evaporative Resistance Values, Temperature and Pressure Gradients, and Net Heat Gain Plus Dry-Heat Loss Values for Two Ensembles at Three Heat Stress Stages

Ensembles	WC			Tychem		
Heat Stress Stages	C	T	U	C	T	U
$R_{e,T,a}$ (m²kPa/W)	0.017	0.014	0.012	0.042	0.033	0.027
ΔP (kPa)	3.0	2.8	2.6	3.8	3.9	3.8
ΔT (°C)	3.7	7.0	9.2	-5.9	-2.9	-0.6
H_{net} (W m⁻¹)	143	143	142	153	153	152
DH^* (W m⁻¹)	35	66	87	-54	-27	-6
$H_{net} + DH^*$ (W m⁻¹)	178	209	229	99	126	146

* $DH = (T_{db} - T_{sk}) / I_{T,r}$; C = Compensable, T = Transition, U = Uncompensable

The relationships among $R_{e,T,a}$ values, vapor pressure gradients, and H_{net} plus DH for WC and Tychem QC® ensembles at different stages of heat stress were illustrated in Figure 5.2.
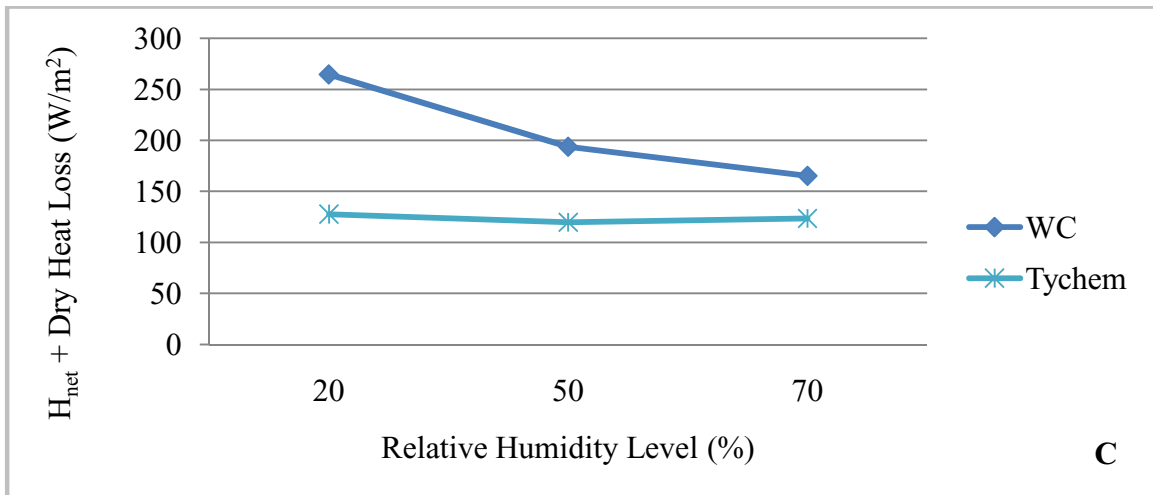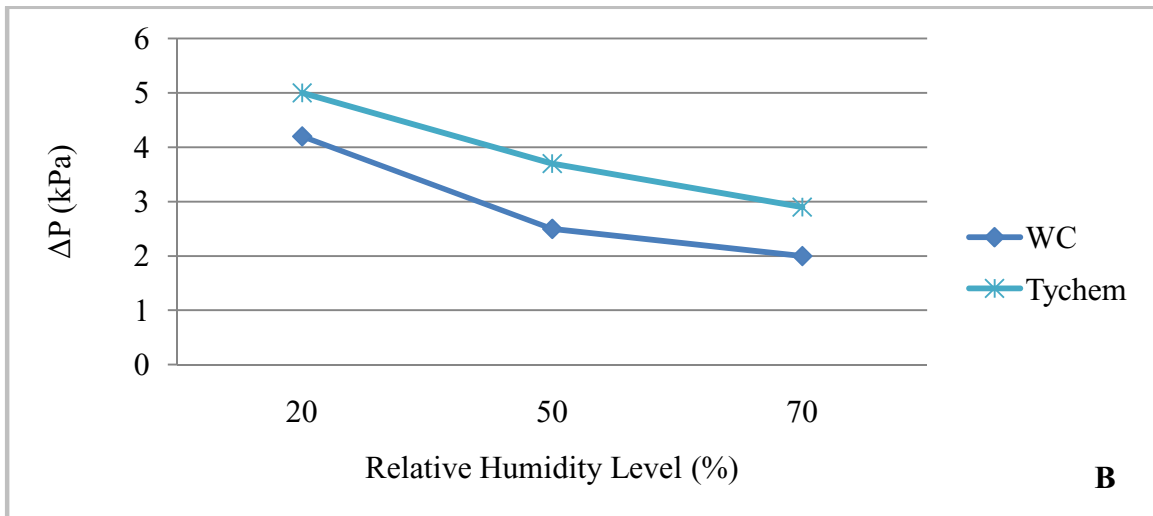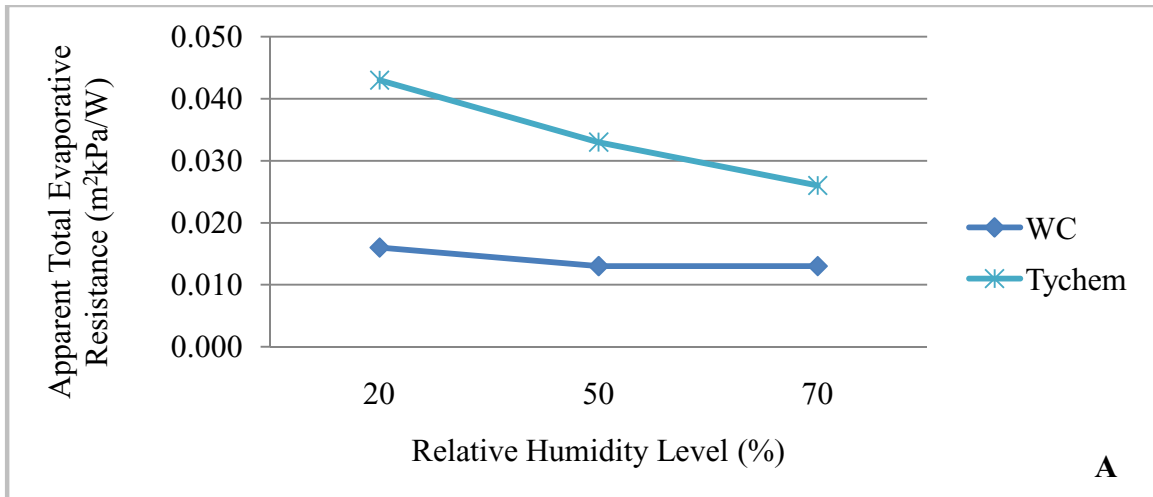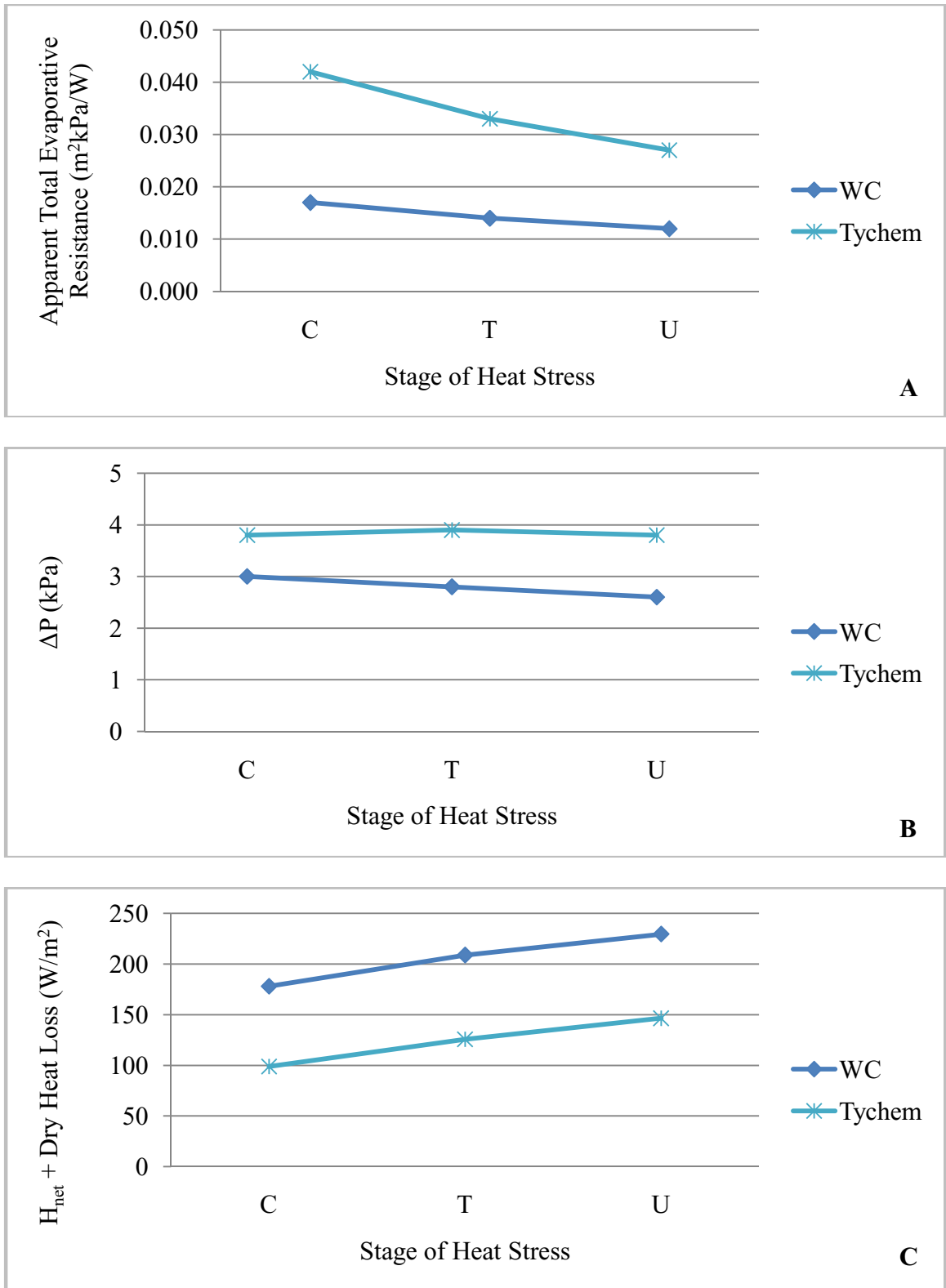
Figure 5.2. Least Squares Mean of Apparent Total Evaporative Resistances (A), Average Pressure Differences (B), and Net Heat Gain Plus Dry-Heat Loss (C) for Two Ensembles at Three Heat Stress Stages

The changes among data in Table 5.1 were also monotonic. $R_{e,T,a}$ values were greatest at the compensable stage of heat stress and lowest under uncompensable conditions. Lower temperature gradients and H_{net} plus DH values were observed under compensable conditions with the highest values seen under uncompensable conditions. Vapor pressure gradients remained relatively similar for both ensembles across heat stress stages. Using equation (11), it was evident that stable vapor pressure gradients (numerator) combined with lower H_{net} plus DH values (denominator) resulted in higher $R_{e,T,a}$ values for both ensembles.

Describing the relationships among variables in equation (11) at different RH levels and stages of heat stress provided a foundation to explain heat-exchange pathways which may have been present during heat stress trials. Average temperature differences for WC, CC, Tyvek$^{®}$ 1424, and NexGen$^{®}$ LS 417 were positive implying that "microclimate heat pipes" were not present, and any sweat accumulated on the ensembles was the result of the wicking of sweat from the skin prior to evaporation. A negative average temperature difference of $-3.1 \pm 2.8^{o}C$ ($T_{sk} > T_{db}$) for the Tychem QC$^{®}$ ensemble may have supported a "microclimate heat pipe" but because the magnitude of the temperature gradient was small its presence was unlikely. These findings were consistent with the results published by Havenith et al. (2008) who observed microclimate evaporation/condensation cycles at lower temperatures (below $20^{o}C$) and among ensembles with higher evaporative resistances and temperature gradients of $20^{o}C$ or greater (Havenith et al. 2008). While clothing saturation reduced the total insulation (I_T) of clothing, thus increasing radiation and convective heat exchange, it only affected estimated $R_{e,T,a}$ values minimally (Caravello et al. 2008; Holmer, 2006; Barker et al.

1999; Bernard & Matheen, 1999; Havenith, 1999). Also important to consider was the fact that tight-fitting clothing saturated with sweat increased the water vapor permeability properties of an ensemble. However, evaporative cooling may be reduced when sweat was wicked by clothing because a percentage of the heat which would have been emitted during skin evaporation was left behind or dissipated by other, less efficient heat-exchange processes (Hes & Aruajo, 2010; Havenith et al. 2008; Cain & McLellan, 1998). In hot climates ($T_{db} \geq T_{sk}$), it was possible for the heat energy in the environment to be substituted as a driving force for evaporation further reducing body heat loss (Holmer, 2006; Bouskill et al. 2002).

Eliminating the presence of a microclimate evaporation/condensation cycle left only two major pathways for heat-exchange: convection and diffusion (Havenith et al. 2008). The convection pathway was driven by air movement (ventilation) through clothing layers and resulted in the transfer of heat and water vapor (evaporated sweat) from the skin to the environment. The diffusion pathway, incorporating conduction and radiation heat transfer, and molecular diffusion of water vapor, continues to be maintained as the traditional theory for heat-exchange in hot environments (Havenith, 1999). However, results published by Bernard et al. (2010) and Gonzalez et al. (2006), and reinforced by Havenith et al. (2010), found that evaporative cooling was better supported by the air permeability properties of the fabric than by molecular diffusion. Increasing levels of air permeability (porosity) improved the capability of clothing ensembles to support the convective transfer of water vapor for evaporative cooling (Bernard et al. 2010; Gonzalez et al. 2006). Clothing with greater porosity (WC, CC, Tyvek[®] 1424) can ventilate evaporated water vapor with greater efficiency resulting in

lower $R_{e,T,a}$ values. Clothing with lower porosity (NexGen[®] LS 417 followed by Tychem QC[®]) exhibited lower capacities to ventilate leading to higher $R_{e,T,a}$ values. Clearly, convection was the dominant pathway and had a greater impact on $R_{e,T,a}$ values than the diffusion (Bernard et al. 2010; Havenith et al. 2010; Gonzalez et al. 2006).

What remained unclear were the factor(s) which gave rise to the experimental results observed in this study. Different $R_{e,T,a}$ values were calculated despite the fact that the work demand and convective air movement were about the same at every RH level and stage of heat stress. Theoretically, larger vapor pressure gradients would have been more supportive of evaporative cooling, promoting convective transport of evaporated water vapor from the skin to the environment and lower $R_{e,T,a}$ values. However, the opposite finding was observed. The results of this study suggested that the heat-exchange processes present in hot environments were not as clear as conceived previously.

Conclusion

The results of the study established that $R_{e,T,a}$ values do change with RH levels and stages of heat stress and that the theoretical framework for explaining heat-exchange in hot environments is not yet well-established. Also confirmed was the dominance of the convection pathway over the diffusion pathway in hot environments.

Future Research

Further research to verify the findings of this study is warranted.   Also recommended is a close examination of the current model used to evaluate heat stress to evaluate its reliability under different stages of heat stress and environmental conditions.

New models may need to be developed around the convective properties of clothing ensembles to understand the relationship between temperature and vapor pressure gradients on $R_{e,T,a}$ values.

Study Limitations

Study results may have been influenced by random and systematic error. The order of testing ensembles was randomized among study participants to limit confounding but some level of random error may have been introduced. Systematic errors related to the precision and accuracy of heat lab instruments, as well as data recording, were likely present. Errors, although very small, were detected during random verification of the database following data extraction. Such errors would have impacted $R_{e,T,a}$ values, which are also vulnerable to errors inherent in the quantitative method used in the study protocol described by Bernard et al. (2010) and Caravello et al. (2008). Most notably, the assumption regarding skin being fully wet may have been violated for experimental trials conducted at the compensable stage of heat stress. Additionally, $R_{e,T,a}$ values were estimated 20 minutes before and 15 minutes after the critical condition when equation (1) may not be true (Bernard et al. 2010; Caravello et al. 2008). The data were collected in a controlled climatic chamber where other factors, which may contribute to heat stress, were absent or not measured. Finally, study results can be extended to only the five specific ensembles tested in the experiment.

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APPENDICES

APPENDIX A: Aggregate Apparent Total Evaporative Resistance Data

Table A1. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles at Three Heat Stress Stages and 20% Relative Humidity

		Heat Stress Stages		
		Compensable	Transition	Uncompensable
Ensembles	WC	0.019	0.016	0.014
	CC	0.020	0.017	0.016
	Tyvek	0.020	0.018	0.017
	Nexgen	0.027	0.021	0.019
	Tychem	0.054	0.041	0.034

Table A2. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles at Three Heat Stress Stages and 50% Relative Humidity

		Heat Stress Stages		
		Compensable	Transition	Uncompensable
Ensembles	WC	0.017	0.013	0.011
	CC	0.017	0.013	0.010
	Tyvek	0.019	0.015	0.013
	Nexgen	0.022	0.018	0.014
	Tychem	0.040	0.032	0.027

Table A3. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Ensembles at Three Heat Stress Stages and 70% Relative Humidity

		Heat Stress Stages		
		Compensable	Transition	Uncompensable
Ensembles	WC	0.017	0.012	0.010
	CC	0.017	0.013	0.010
	Tyvek	0.017	0.013	0.011
	Nexgen	0.022	0.015	0.011
	Tychem	0.033	0.025	0.019

APPENDIX B: Aggregate Environmental Data

Table A4. Average Temperature Difference ($^{\circ}$C) for Five Ensembles at Three Heat Stress Stages and Three Relative Humidity Levels (Mean ± Standard Deviation)

RH (%)	Heat Stress Stages	Clothing Ensembles				
		WC	CC	Tyvek	NexGen	Tychem
20	C	10.5 ± 2.8	10.0 ± 2.6	9.7 ± 3.0	5.4 ± 3.0	-5.5 ± 2.2
20	T	14.3 ± 2.5	13.7 ± 2.8	13.0 ± 4.0	8.9 ± 2.8	-1.9 ± 2.2
20	U	17.0 ± 2.6	16.4 ± 3.2	15.5 ± 3.8	11.6 ± 3.1	0.5 ± 1.8
50	C	2.6 ± 1.9	3.1 ± 1.8	2.1 ± 2.4	0.4 ± 1.6	-5.8 ± 1.9
50	T	5.9 ± 1.4	6.5 ± 1.7	5.4 ± 1.9	3.5 ± 1.9	-3.5 ± 1.9
50	U	7.8 ± 1.5	8.6 ± 1.6	7.4 ± 2.0	5.7 ± 1.9	-1.0 ± 1.8
70	C	-1.1 ± 1.7	-1.4 ± 1.7	-1.2 ± 1.0	-2.5 ± 1.2	-6.3 ± 1.0
70	T	1.7 ± 2.0	1.4 ± 2.3	1.5 ± 1.4	0.6 ± 1.7	-3.4 ± 1.1
70	U	3.7 ± 2.2	3.5 ± 2.3	3.5 ± 1.6	3.0 ± 1.5	-1.3 ± 1.0

$\Delta T = T_{db} - T_{sk}$

Table A5. Average Vapor Pressure Difference (kPa) for Five Ensembles at Three Heat Stress Stages and Three Relative Humidity Levels (Mean ± Standard Deviation)

RH (%)	Heat Stress Stages	Clothing Ensembles				
		WC	CC	Tyvek	NexGen	Tychem
20	C	4.2 ± 0.4	4.2 ± 0.4	4.4 ± 0.5	4.5 ± 0.7	4.8 ± 0.3
20	T	4.2 ± 0.4	4.2 ± 0.4	4.5 ± 0.4	4.4 ± 0.9	5.0 ± 0.3
20	U	4.1 ± 0.7	4.2 ± 0.5	4.5 ± 0.5	4.4 ± 1.1	5.0 ± 0.6
50	C	2.7 ± 0.3	2.6 ± 0.2	3.0 ± 0.3	2.9 ± 0.7	3.6 ± 0.4
50	T	2.4 ± 0.3	2.3 ± 0.4	2.8 ± 0.5	2.8 ± 0.4	3.7 ± 0.2
50	U	2.2 ± 0.5	2.1 ± 0.5	2.6 ± 0.6	2.6 ± 0.4	3.7 ± 0.2
70	C	2.3 ± 0.3	2.2 ± 0.3	2.2 ± 0.3	2.5 ± 0.3	3.1 ± 0.3
70	T	1.9 ± 0.4	2.0 ± 0.3	2.0 ± 0.3	2.2 ± 0.4	2.9 ± 0.3
70	U	1.7 ± 0.4	1.6 ± 0.6	1.8 ± 0.3	1.8 ± 0.4	2.7 ± 0.3

$\Delta P = P_{sk} - P_{a}$

APPENDIX C: Environmental Data for Main Effects

Table A6. Temperature and Water Vapor Pressure Levels for Five Ensembles (Mean ± Standard Deviation)

Ensembles	T_{db} (°C)	T_{sk} (°C)	ΔT (°C)[*]	ΔP (kPa)[+]
WC	43.1 ± 6.5	36.5 ± 1.0	6.7 ± 6.0	2.8 ± 1.0
CC	43.1 ± 6.5	36.3 ± 1.0	6.7 ± 5.9	2.8 ± 1.1
Tyvek	42.7 ± 6.5	36.4 ± 1.0	6.4 ± 5.9	3.1 ± 1.1
Nexgen	40.5 ± 5.2	36.4 ± 1.0	4.1 ± 4.6	3.1 ± 1.2
Tychem	32.9 ± 3.7	36.0 ± 1.2	-3.1 ± 2.8	3.8 ± 0.9

[*]$\Delta T = T_{db} - T_{sk}$; [+] $\Delta P = P_{sk} - P_a$

Table A7. Temperature and Water Vapor Pressure Levels for Three Relative Humidity Levels (Mean ± Standard Deviation)

RH (%)	T_{db} (°C)	T_{sk} (°C)	ΔT (°C)[*]	ΔP (kPa)[+]
20	45.7 ± 7.7	36.6 ± 0.9	9.1 ± 7.2	4.5 ± 0.6
50	39.5 ± 5.1	36.3 ± 1.0	3.2 ± 4.5	2.8 ± 0.6
70	36.2 ± 4.1	36.1 ± 1.2	0.1 ± 3.2	2.2 ± 0.5

[*]$\Delta T = T_{db} - T_{sk}$; [+] $\Delta P = P_{sk} - P_a$

Table A8. Temperature and Water Vapor Pressure Levels for Three Heat Stress Stages (Mean ± Standard Deviation)

Heat Stress Stage	T_{db} (°C)	T_{sk} (°C)	ΔT (°C)[*]	ΔP (kPa)[+]
Compensable	36.6 ± 6.2	35.4 ± 0.9	1.2 ± 5.7	3.3 ± 1.0
Transition	40.8 ± 6.3	36.4 ± 0.7	4.4 ± 6.0	3.2 ± 1.1
Uncompensable	43.9 ± 6.3	37.2 ± 0.7	6.7 ± 6.2	3.0 ± 1.3

[*]$\Delta T = T_{db} - T_{sk}$; [+] $\Delta P = P_{sk} - P_a$

APPENDIX D: Environmental Data for Interactions

Table A9. Temperature and Water Vapor Pressure Levels for Five Ensembles at Three Relative Humidity Levels (Mean ± Standard Deviation).

Configuration	T_{db} (^{o}C)	T_{sk} (^{o}C)	ΔT (^{o}C)*	ΔP (kPa)+
A2	50.7 ± 4.3	36.7 ± 0.8	14.0 ± 3.7	4.2 ± 0.5
A5	41.8 ± 3.4	36.4 ± 0.9	5.4 ± 2.7	2.5 ± 0.4
A7	37.8 ± 3.7	36.3 ± 1.1	1.5 ± 2.8	2.0 ± 0.4
B2	49.9 ± 4.2	36.6 ± 0.7	13.4 ± 3.9	4.2 ± 0.4
B5	42.6 ± 3.5	36.5 ± 0.9	6.1 ± 2.8	2.4 ± 0.4
B7	37.1 ± 3.8	36.0 ± 1.2	1.2 ± 2.9	2.0 ± 0.5
C2	49.4 ± 5.0	36.6 ± 0.9	12.7 ± 4.3	4.4 ± 0.5
C5	41.4 ± 3.6	36.4 ± 0.9	5.0 ± 3.0	2.8 ± 0.5
C7	37.3 ± 3.3	36.1 ± 1.1	1.3 ± 2.4	2.0 ± 0.3
D2	45.4 ± 4.4	36.7 ± 0.9	8.6 ± 3.9	4.5 ± 0.9
D5	39.4 ± 3.4	36.2 ± 0.9	3.2 ± 2.8	2.8 ± 0.5
D7	36.7 ± 3.6	36.4 ± 1.1	0.4 ± 2.7	2.2 ± 0.5
E2	33.9 ± 4.0	36.2 ± 1.1	-2.3 ± 3.2	5.0 ± 0.4
E5	32.5 ± 3.7	35.9 ± 1.3	-3.4 ± 2.7	3.7 ± 0.3
E7	32.3 ± 3.4	35.9 ± 1.3	-3.7 ± 2.3	2.9 ± 0.3

A = Work Clothes, B = Cotton Coveralls, C = Tyvek, D = NexGen, E = Tychem
2 = 20% Relative Humidity, 5 = 50% Relative Humidity, 7 = 70% Relative Humidity
*$\Delta T = T_{db} - T_{sk}$; + $\Delta P = P_{sk} - P_a$

Table A10. Temperature and Water Vapor Pressure Levels for Five Ensembles at Three Heat Stress Stages (Mean ± Standard Deviation)

Configuration	T_{db}(°C)	T_{sk} (°C)	ΔT (°C)[*]	ΔP (kPa)[+]
AC	39.4 ± 5.7	35.7 ± 0.8	3.7 ± 5.3	3.0 ± 0.9
AT	43.5 ± 5.9	36.5 ± 0.7	7.0 ± 5.6	2.8 ± 1.0
AU	46.5 ± 6.2	37.3 ± 0.7	9.2 ± 5.9	2.6 ± 1.1
BC	39.3 ± 5.6	35.5 ± 0.9	3.8 ± 5.1	3.0 ± 0.9
BT	43.4 ± 5.8	36.4 ± 0.6	7.0 ± 5.5	2.8 ± 1.0
BU	46.5 ± 6.0	37.1 ± 0.7	9.3 ± 5.8	2.6 ± 1.2
CC	39.0 ± 5.6	35.5 ± 0.8	3.5 ± 5.2	3.2 ± 1.0
CT	43.1 ± 5.9	36.5 ± 0.7	6.7 ± 5.6	3.1 ± 1.1
CU	46.1 ± 5.9	37.2 ± 0.6	8.8 ± 5.8	2.9 ± 1.3
DC	36.7 ± 4.2	35.6 ± 0.8	1.2 ± 3.8	3.3 ± 1.0
DT	40.9 ± 4.3	36.5 ± 0.7	4.4 ± 4.0	3.2 ± 1.1
DU	44.0 ± 4.3	37.2 ± 0.8	6.8 ± 4.2	2.9 ± 1.3
EC	29.0 ± 2.1	34.8 ± 1.0	-5.9 ± 1.8	3.8 ± 0.8
ET	33.2 ± 2.1	36.1 ± 0.7	-2.9 ± 1.9	3.9 ± 0.9
EU	36.5 ± 2.1	37.1 ± 0.5	-0.6 ± 1.7	3.8 ± 1.1

A = Work Clothes, B = Cotton Coveralls, C = Tyvek, D = NexGen, E = Tychem
C = Compensable, T = Transition, U = Uncompensable
*$\Delta T = T_{db} - T_{sk}$; + $\Delta P = P_{sk} - P_a$

APPENDIX E: Statistical Differences for Interactions

Table A11. Statistically Significant Differences for Five Ensembles at Three Relative Humidity Levels

	A2	A5	A7	B2	B5	B7	C2	C5	C7	D2	D5	D7	E2	E5	E7
A2	-	-	-	-	-	-	-	-	-	S	-	-	S	S	S
A5	-	-	-	-	-	-	S	-	-	S	S	-	S	S	S
A7	-	-	-	S	-	-	S	-	-	S	S	S	S	S	S
B2	-	-	S	-	-	-	-	-	-	S	-	-	S	S	S
B5	-	-	-	-	-	-	S	-	-	S	S	-	S	S	S
B7	-	-	-	-	-	-	S	-	-	S	S	-	S	S	S
C2	-	S	S	-	S	S	-	-	S	-	-	-	S	S	S
C5	-	-	-	-	-	-	-	-	-	S	-	-	S	S	S
C7	-	-	-	-	-	-	S	-	-	S	S	-	S	S	S
D2	S	S	S	S	S	S	-	S	S	-	S	S	S	S	S
D5	-	S	S	-	S	S	-	-	S	S	-	-	S	S	S
D7	-	-	S	-	-	-	-	-	-	S	-	-	S	S	S
E2	S	S	S	S	S	S	S	S	S	S	S	S	-	S	S
E5	S	S	S	S	S	S	S	S	S	S	S	S	S	-	S
E7	S	S	S	S	S	S	S	S	S	S	S	S	S	S	-

S = Statistically Significant (p < 0.05), - = Not Statistically Significant
A = Work Clothes, B = Cotton Coveralls, C = Tyvek, D = NexGen, E = Tychem
2 = 20% Relative Humidity, 5 = 50% Relative Humidity, 7 = 70% Relative Humidity

Table A12. Statistically Significant Differences for Five Ensembles at Three Heat Stress Stages

	AC	AT	AU	BC	BT	BU	CC	CT	CU	DC	DT	DU	EC	ET	EU
AC	-	-	S	-	-	S	-	-	S	S	-	-	S	S	S
AT	-	-	-	S	-	-	S	-	-	S	S	-	S	S	S
AU	S	-	-	S	-	-	S	S	-	S	S	-	S	S	S
BC	-	S	S	-	-	S	-	-	S	S	-	-	S	S	S
BT	-	-	-	S	-	-	S	-	-	S	S	-	S	S	S
BU	S	-	-	S	-	-	S	-	-	S	S	-	S	S	S
CC	-	S	S	-	S	S	-	-	S	S	-	S	S	S	S
CT	-	-	S	-	-	-	-	-	-	S	-	-	S	S	S
CU	S	-	-	S	-	-	S	-	-	S	S	-	S	S	S
DC	S	S	S	S	S	S	S	S	S	-	S	S	S	S	-
DT	-	S	S	-	-	S	-	-	S	S	-	-	S	S	S
DU	-	-	-	-	-	-	S	-	-	S	-	-	S	S	S
EC	S	S	S	S	S	S	S	S	S	S	S	S	-	S	S
ET	S	S	S	S	S	S	S	S	S	S	S	S	S	-	S
EU	S	S	S	S	S	S	S	S	S	S	S	S	S	S	-

S = Statistically Significant ($p < 0.05$), - = Not Statistically Significant
A = Work Clothes, B = Cotton Coveralls, C = Tyvek, D = NexGen, E = Tychem
C = Compensable, T = Transition, U = Uncompensable

ABOUT THE AUTHOR

Lieutenant Matthew Dooris of the United States Coast Guard was born in Tampa and raised in Brooksville, Florida, and graduated from Saint Leo University in 1999 with a Bachelor of Science in Biology. He was an environmental consultant and wetland ecologist for the civil engineering firm, Reynolds, Smith & Hills, Inc., prior to joining the Coast Guard in January 2001. As a Coast Guard Officer, he has served at Officer Candidate School in New London, Connecticut, Naval Flight School, Pensacola, Florida, Sector New Orleans, New Orleans, Louisiana, and Sector St. Petersburg, Tampa, Florida. In December 2008, Lieutenant Dooris completed a Master's Degree in Security Studies from the Naval Postgraduate School, Center for Homeland Defense and Security. Following graduation from the University of South Florida, Lieutenant Dooris will assume responsibilities of Safety, Environmental, and Health Officer, Coast Guard Eleventh District in San Pedro, California.