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Apparent Total Evaporative Resistance Values from Human Trials Over a Range of Metabolic and Heat Stress Levels

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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DEDICATION

I dedicate this work to my family, friends, and countless supportive people encountered in my life thus far. The completion of this manuscript would not have been possible without the unconditional love offered by my dearest family members.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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_{cl} - Total Intrinsic Clothing Insulation
i_m – 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
$R_{e,T}$ – Total Evaporative Resistance
$R_{e,T,a}$ – Apparent Total Evaporative Resistance
$R_{e,T,stat}$ – Static Total Evaporative Resistance

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

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

v – Air Speed
V_{O2} – Oxygen Consumption
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

Clothing can influence heat stress depending on the design and its ability to act as a barrier. The progressive heat stress protocol permitted the collection of data to empirically estimate the apparent total evaporative resistance ($R_{e,T,a}$). Five different clothing ensembles were evaluated, which included work clothes, cotton coveralls, 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®). The study design called for three metabolic level's: low, moderate, and high (L, M, & H) and examined three heat stages: compensable, transitional, uncompensable (C, T, U). The purpose of this study was to determine if $R_{e,T,a}$ values remained constant over a range of metabolic and heat stage levels. Calculated $R_{e,T,a}$ values were compared using a four-way mixed model analysis of variance. Significant differences for $R_{e,T,a}$ were found among ensembles, metabolic levels, heat stress stages, as well as interactions among ensembles and metabolic levels along with ensembles and heat stress stages ($p < 0.0001$). Results showed $R_{e,T,a}$ values differ over a range of metabolic levels and stages of heat stress. Additionally, convection is more supportive of evaporative cooling than diffusion.

CHAPTER 1: INTRODUCTION

Problem Statement

In 2010, the Occupational Safety and Health Administration (OSHA) estimated 5-10 million workers each year work in industries where heat stress is a safety and health hazard. Although there is no promulgated regulation regarding heat stress, the employer is required to provide a safe work environment for its workers in accordance with the General Duty Clause of the OSH Act. Workers at risk for heat-related illness or death include both indoor and outdoor occupations. Common exposures occur in environments such as construction and hazardous waste sites, foundries, and boiler rooms, in addition to smelters. The Centers for Disease Control and Prevention (CDC) reports 423 workers in agricultural and nonagricultural industries have died from exposure to environmental heat in the United States during 1992 - 2006 (CDC MMWR, 2008).

Exposure to hot environments taxes the capacities of the body to maintain thermal homeostasis. There is an essential balance between heat production and dissipation. When the thermoregulatory system is unable to dissipate heat at an equivalent rate at which it is generated, deep-body temperature will increase as a result of heat accumulation. As it approaches 41°C, this system risks complete collapse, increasing the risk of heat stroke and death. As will be discussed, human thermoregulation is dependent on the following primary factors: ambient environmental conditions, metabolic activity, and clothing ensemble requirements.

Environmental conditions include ambient air temperature and vapor pressure, radiant heat as well as air velocity. The amount of water vapor pressure in the atmosphere will influence the rate of evaporation. Effective evaporative cooling is promoted when the water vapor concentration on the skin is greater than the atmospheric concentration. Maximum evaporative capacity is a function of air motion and the difference between water vapor pressures of the skin and ambient air. Air velocity can stimulate greater interaction with ambient air and human skin. This interaction may promote evaporative cooling depending upon the differences between the skin and ambient temperature. The body can gain additional radiant heat at high enough levels of ambient and surface temperatures.

Metabolic activity determines the amount of heat production. Importantly, it's a determinant of the degree of comfort or strain stemming from exposure to a hot environment. At rest, the body requires basic functions such as respiration and the cardiac cycle to sustain life. At peak physical demands, metabolic work can significantly contribute to total heat load. Metabolic rate is a measure of the energy utilized for muscular load from the conversion of chemical into mechanical and thermal energy. In particular, high levels of metabolic heat production associated with muscular work intensify heat stress, as a greater heat load must be dissipated. These high metabolic levels, if sustained, can generate body heat at a greater rate than it can be dissipated into the environment, burdening the thermoregulatory system.

Clothing can influence heat stress depending on the design and its ability to act as a barrier. The most important factors of clothing relative to heat stress include the construction, configuration, and number of layers worn by a worker. The exchange of dry heat and water vapor can be reduced by the clothing's barrier. This can greatly reduce the ability to dissipate metabolic heat. Vapor-barrier clothing has increased resistance to evaporative cooling and strongly prevents ambient air from contacting human skin. The effectiveness of evaporative cooling significantly decreases from the lessened circulation of air movement through the clothing material. Although, it has become clear that motion associated with activity changes the thermal properties by increased ventilation. Thermal properties of clothing can be described using total insulation (I_T) and total evaporative resistance ($R_{e,T}$). While evaporative resistance will modify the maximum rate of evaporative cooling, clothing insulation modifies the rate of dry heat exchange. The significance of evaporative cooling emphasizes the importance of quantifying evaporative resistance and its effects on maintaining thermal balance in hot environments.

To expand current knowledge of thermal properties of protective work clothing, this paper seeks to address the relationship between total evaporative resistance and different metabolic levels and heat stages. It will examine whether $R_{e,T}$ varies or remains constant over a range of metabolic levels and heat stages at 50% relative humidity.

Research Question

Will estimates of $R_{e,T,a}$ for five different clothing ensembles remain the same independent of metabolic rate and heat stress stage (i.e. compensable, critical, and uncompensable heat stress levels)?

Significance of Research

In a multitude of indoor and outdoor applications, personal protective clothing ensembles are commonly employed as a control method against workplace hazards such as chemical, physical, and biological agents. Environmental conditions and metabolic activity can exacerbate the intensity of heat stress while wearing protective clothing, thereby increasing the risk of heat-related injury or illness. The extent to which heat stress is induced by the use of protective clothing, external and internal, is an important issue pertaining to human health. Although knowledge of heat stress along with the associated job risk factors has progressed, further understanding of the construction and configuration characteristics of protective clothing is required to holistically identify the role of different clothing and effects it has on bodily thermal regulation.

CHAPTER 2: LITERATURE REVIEW

Heat Balance

A thermal balance model can be conceptualized using Equation 1. M is the metabolic demand and W is the rate of external work performed. M-W is always a positive value. R is the rate of radiant heat exchange between the skin and the environment. C represents the rate of convective heat transfer occurring in the air and from the skin. E represents the rate of evaporative cooling due to the vaporization of water from the skin. R, C, and E are the primary rates of which heat is dissipated from the body to the environment. Also, there is loss associated with respiratory exchange by convection (C_{res}) and evaporation (E_{res}). All terms are expressed as a rate with units in Watts per meter squared (Wm^{-2}).

$$E = (M - W) + R + C + (C_{res} + E_{res}) - S \qquad \text{Equation (1)}$$

Equation 2 quantifies net heat gain (H_{net}), which is comprised of the heat generation minus external work and storage rate. It also includes the loss attributed to respiratory exchange.

$$H_{net} = M - W - S + C_{res} - E_{res} \qquad \text{Equation (2)}$$

$$E = H_{net} + (R + C) \qquad \text{Equation (3)}$$

Equation 3 shows evaporative cooling balanced against the sum of thermal gains and losses. E is the rate at which evaporation must occur to maintain thermal balance.

$$E = (P_{sk} - P_a) / R_{e,T} \qquad \text{Equation (4)}$$

Equation 4 shows the relationship of evaporation permitted by the environment and clothing. It is determined by the differential pressure between the skin and ambient air ($P_{sk} - P_a$) divided by the total evaporative resistance (R_{e-T}).

$$R + C = (T_{db} - T_{sk}) / I_T \qquad \text{Equation (5)}$$

Dry heat exchange from the body is primarily a function of radiant and convective heat loss. This is equated through the differential temperature between the ambient air and skin ($T_{db} - T_{sk}$) divided by the total insulation of the clothing ensemble (I_T).

$$(P_{sk} - P_a) / R_{e,T} = [H_{net} + (T_{db} – T_{sk}) / I_{T,r}] \qquad \text{Equation (6)}$$

Equation 6 is the resultant from the substitution of Equations 5 and 4.
Ttotal evaporative resistance and total clothing insulation are modifiers based on the inherent thermal properties of the clothing ensemble. From this, it is clear the capacity for evaporative heat loss is attenuated as clothing forms additional resistance ($R_{e,T}$) to

vapor transport. Likewise, a reduction in the capacity for dry heat exchange is formed by the insulating barrier (I_T) of the clothing.

It is important to account for the thermal properties of clothing ensembles as it relates to the balance of an individual's heat stress (Holmer et al. 1999). Thermal insulation of clothing as well as the evaporative resistance are critical to assess the exchange of heat between the human body and environment. It is necessary to quantify these parameters accurately and precisely (Huang, 2008).

Clothing Insulation

Thermal insulation is the resistance to dry heat exchange expressed in square meters degree Celsius per watt ($m^2\ {}^{o}C\ W^{-1}$). The donning of protective clothing mediates the rate of dry heat exchange via radiation and convection. The measure of insulation depends on the temperature gradient between the skin and environment (see Equation 5). Thermal insulation is dependent upon the specific design of the clothing article, which in turn, affects the amount of body surface area covered, the fit of the ensemble, the increased surface area for heat loss, and the number of fabric layers. Fabric thickness is a significant factor due to the trapped, still air layers (Holmer, 2006).

Specific types of insulation values reported in the literature thus far include total insulation (I_T), intrinsic or basic clothing insulation (I_{cl}), and air insulation (I_a). I_T is a factor that accounts for the reduction of heat flow due to insulation caused by resistance provided by the clothing and surrounding air layer. As the value of I_T increases, the rate of dry heat exchange experiences a greater reduction (Barker et al. 1999, Holmer et al. 1999). I_T is expressed as either static ($I_{T,stat}$) for standardized conditions or resultant ($I_{T,r}$) for dynamic conditions. I_{cl} is the measure of insulation provided by the clothing only; it lacks surface air insulation. I_a is the resistance provided by the air film around a hot plate or nude manikin.

A popular unit of insulation values is the clo unit derived from using heated copper manikins. $0.155\ m^{2\circ}C\ W^{-1}$ is equivalent to 1 clo. The amount of clothing insulation required to keep a normal sedentary man comfortable at 21° C is the definition of 1 clo (Winslow et al. 1936). At that time, 1 clo was equivalent the insulation provided by a typical business suit. A more recent example of 1 clo is wearing an ensemble consisting of underwear with a short sleeve shirt, trouser pants, socks, shoes, and jacket (ISO 9920, 2007) as measured on a standing thermal manikin with an air movement less than 0.2 m/s. The clo unit subsequently advanced clothing science as it provided a standard measure of the thermal insulation (Gagge et al. 1941).

Invented in 1898, the guarded hot plate instrument is recognized as the most accurate technique for determining the insulation properties of materials (Huang, 2006). A thin, flat heater of known area is placed horizontally between specified samples of fabrics. The American Society for Testing and Materials and International Organization for Standardization have developed methods to determine the insulation using a heated flat plate (ASTM D 1518, ISO 11092). Insulation values obtained by this method are only valid under the environmental conditions of the test. This method is useful for evaluating the heat transfer of fabrics for use in garments. Comparisons between different fabric materials, weave, layers, and finishes are useful using flat plate methods. Flat plate methods are useful for evaluating the thermal properties of clothing materials and simple clothing assemblies, but there is difficulty applying the results to the actual clothing systems (Fan & Yen, 2002).

Documentation on the use of heated copper manikins dates back to the 1940's (Goldman, 1983). Early measurements of the insulation values of many clothing items and ensembles were collected at US Army, Navy and Air Force laboratories (Hall 1946, 1949; Hall and Polte 1953, 1956, 1960). During the 1960’s, thermal manikin research began to focus on the thermal burden imposed by protective clothing in hot environments. Similar to the flat plate method, life sized manikins are electronically controlled to produce a specific mean skin temperature while placed in a climatic control chamber to regulate the environmental conditions. Methods for measuring clothing insulation using life-sized, thermal copper manikins are provided by the American Society for Testing and Methods and the International Organization for Standardization (ASTM F1291-05, 2005; ISO 15831, 2004). ISO's standard on ‘‘Ergonomics of the thermal environment - Estimation of the thermal insulation and water vapor resistance of a clothing ensemble’’ (ISO 9920, 2007) provides a listing of clothing ensembles with their respective insulation values as measured on manikins ($I_{T,stat}$). Values for $I_{T,stat}$ provided in current literature are obtained on static thermal manikins in low wind conditions. Typically, the air velocity is controlled at 0.4 m/s during a test. These measurements do not account for the effects of air velocities greater than 0.4 m/s and body movement, which are experienced in working conditions. To quantify thermal stress accurately, the insulation values of clothing should reflect values observed during actual work situations ($I_{T,r}$, resultant insulation). $I_{T,r}$ is the actual thermal insulation from the body surface to the outer clothing surface including enclosed air layers under specific environmental conditions and activities. $I_{T,stat}$ represents an idealized resistance value; whereas $I_{T,r}$ is the value experienced by the user of clothing (Higenbottam, 1997).

Human wear trials occur in a climatic chamber where heart rate, body-core temperature, skin temperatures, metabolic activity and environmental data are recorded incrementally throughout the trial. Wear trials are able to account for insulation modifiers. When an individual is active in a particular clothing ensemble, the insulation will be lower than that measured on a static manikin due to movement, changes of posture, ventilation of the clothing by ambient air, and clothing fit. Of importance is the introduction of ambient air into the ensemble by permeation, convection into openings, and forced penetration caused by natural wind or fans as well as body movements (Bouskill et al. 2002). Clothing ensembles donned will, most often, have openings where the air exchange rate is increased during activity thereby reducing the insulation (Havenith et al., 1990), which has been described as the ‘‘pumping effect’’. Thick clothing shows stronger reductions in insulation due to posture and movement than ensembles with low insulation values (Havenith et al 1990). Additionally, compression of clothing material resulting from wind can reduce the thickness as well as enter layers of the fabric. The presence of wind increases heat transfer rates due to penetration, which is dependent upon the air permeability of the outer layer. Primarily, wind affects the surface air layer insulation.

Holmer (1985) compared heat exchange and thermal insulation of wool and nylon garments during wear trials. Comparing dry clothing with subjects at rest, I_T was reduced by 30-40% during walking and by 50-60% during running. The reductions were explained mostly by ventilation of clothing due to the pumping effect with minor contributions from the reduced insulation of surface air layer. Nilsson, Anttonen, and Holmer (2000) observed that I_T can be reduced as much as 20-30% by walking.

Havenith and Nilsson (2004) conducted a meta-analysis of the effect of body and air movement on the insulation provided by workwear and cold-weather clothing. Accumulated datasets were examined (Havenith at al 1990a, 1990b Holmer et al 1999, Nilsson at al. 2000, Kim and Mcullough 2000) to evaluate the validity of prediction equations correcting for walking and wind effects. The majority (80%) of the collected data were for walking speeds 0.8 - 1 ms^{-1}. They found when the wind speed was high there was only a small effect from walking. Breckenridge and Woodcock (1950) found that wind penetration reduces insulation of clothing by more than 40%. Furthermore, Holmer (1985) found that thermal insulation was significantly lower by 15% in wet clothing compared to dry clothing at rest. Sweat-wetting can reduce clothing insulation and improve the linkage between skin and the environment (Nunneley, 1989, Caravello et al. 2008).

Evaporative Resistance

Evaporation of sweat is a significant cooling mechanism and crucial in thermoregulation (Nunneley, 1989, Caravello et al. 2008). Havenith et al. (2008) provides a conceptual model of different heat transfer pathways in the case of wetted skin. The rate of evaporative cooling depends on the water vapor pressure gradient between the skin and environment (Bernard and Matheen, 1999). Clothing forms a resistance to water vapor transport, which is a limiting factor of sweat evaporation (Caravello, 2004). As the value of evaporative resistance ($R_{e,T}$) increases, the evaporative cooling rate experiences a greater reduction (Barker et al. 1999). $R_{e,T}$ expressed in square meter kilopascal per watt (m^2 kPa / W) can be determined by techniques analogous to those for measuring thermal insulation.

ASTM has developed a standardized method to determine the evaporative resistance using a sweating flat plate (ASTM F 1868). Similar instrumentation is involved when determining insulation, but at the surface of the flat plate, a thin film of water is supplied to permit evaporation. Evaporative resistance is mostly measured on sweating hot plates as it provides reproducible and repeatable results. (Huang, 2006). This method can only determine static values of a piece of fabric and are only valid under the environmental conditions of the test. By design, a sweating flat plate cannot account for garment fit and movements of air or the body.

A sweating copper manikin, as its name implies, can simulate sweating and has the ability to evaporate water from its surface. ASTM F2370 (2010) “Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin” is the only published standard describing the determination of clothing evaporative resistance using a sweating thermal manikin in an environmental chamber (Wang et al., 2011). This method can be used to quantify and compare different clothing systems. However, values apply to the particular ensembles evaluated and for the specified environmental conditions of each test. Static manikin tests provide a baseline clothing measurement but neglects the effects of body position and movement. Additionally, the accurate simulation of human perspiration in thermal manikins remains a challenge (Fan & Chen, 2002).

A human wear trial is able to account for evaporative resistance modifiers such as dynamic body movements, ventilation, air permeability, clothing fit and posture changes. When an individual is active in a particular clothing ensemble, the evaporative resistance decreases ($R_{e,T,a}$) when compared to the static sweating manikin ($R_{e,T,stat}$) (Caravello et al. 2008). Havenith, Heus, and Lotens (1990) saw a reduction as great as 88% when examining body movement and wind effects. $R_{e,T,a}$ quantifies the evaporative cooling ability of clothing accounting for dynamic body movements and environmental conditions found in real work settings (Caravello et al. 2008).

$R_{e,T}$ can be estimated on the basis of thermal insulation of clothing ensemble or by its permeability index. However, these calculations require corrections due to influence of air and body movements to determine the reduction of $R_{e,T}$. The amount of reduction ($R_{e,T,r}$) is shown to be related to the reduction of I_T (ISO 9920, 2007). The determination of $R_{e,T}$ found within ISO 9920 is quite complex, time consuming, and costly (Havenith et al. 2008).

The traditional method to determine the rate of evaporative heat loss (H_e) is quantifying the mass change of the clothed body per unit time multiplied by the latent heat of evaporation with corrections for respiration and metabolic mass changes (Havenith et al. 2010). However, Havenith et al. (2008) concluded that the traditional way of calculating evaporative heat loss of a clothed person can lead to substantial errors due to an lessened evaporative efficiency. Evaporative efficiency is the proportion of secreted sweat which actually vaporizes removing heat. Evaporation at the surface of the skin provides maximum cooling potential, but sweat can accumulate on the inner surface of impermeable clothing and wet intervening layers due to condensation and re-evaporate from wetted clothing, but the body cooling potential is reduced because it is remote from the skin. Additionally, when the temperature is below skin temperature, heat can be transferred to the environment without the loss of moisture (weight) from the clothing ensemble.

$$R_{e,T,a} = (P_{sk} – P_a) / [H_{net} + (T_{db} – T_{sk}) / I_{T,r}] \quad \text{Equation (8)}$$

Equation 8 resulted from isolating $R_{e,T}$ in Equation 6.

Hypothesis

A reasonable evaluation of selected protective clothing garments is determining their heat exchange characteristics based on the total evaporative resistance properties. The purpose of this paper is to analyze evaporative resistance over a range of metabolic activity levels and heat stress stages. The null hypothesis is there will be no differences among $R_{e,T,a}$ values and five different clothing ensembles, three metabolic levels, as well as three stages of heat stress.

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 three metabolic levels and three heat stages with a fixed relative humidity (RH) of 50%. A detailed methodology is provided regarding data collection, extraction, and analysis.

Participants

Sixteen adults (twelve men and four women) participated in experimental trials. Table 3.1 provides the physical characteristics of the participants (mean ± standard deviation). 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 for approval to participate. The participants were healthy with no chronic disease requiring medication. While smoking status was not an exclusionary factor, most were nonsmokers.

On the day of the trial, participants were asked not to consume caffeinated beverages 3 hours before the appointment and not to participate in vigorous exercise before the trial. Participants were reminded of the need to maintain good hydration. Prior to beginning the experimental trials to determine critical conditions, a 5-day acclimatization to dry heat occurred which involved walking on a treadmill at a metabolic rate of approximately 165 W m^{-2} in a climatic chamber at 50^{o}C and 20% RH for 2 hours. A base ensemble of clothing consisted of shorts, tee-shirt (and/or sports bra for women), socks, and shoes. All participants wore the same base ensemble throughout the trials.

Table 1. Physical Characteristics of Participants (Mean ± Standard Deviation)

	Age (Years)	Weight (kg)	Height (cm)	Body Surface Area (m^2)
Women (n = 4)	23.0 ± 4.69	64.2 ± 18.0	165 ± 6	1.69 ± 0.22
Men (n = 12)	27.3 ± 9.41	84.5 ± 14.4	176 ± 11	2.01 ± 0.20
Both (n = 16)	26.2 ± 8.54	79.4 ± 17.3	174 ± 11	1.93 ± 0.24

Study Treatments: Clothing and Metabolic Rate

Five different clothing ensembles were evaluated, which 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 along with elastic cuffs at the arms and legs. None of the ensembles included a hood. The base ensemble was worn under all clothing ensembles.

The study design called for three metabolic levels: low, moderate, and high (L, M, & H). These were established per individual using metabolic rates at 115, 175, and 250 W/m^2 to approximate light, moderate, or heavy work. The metabolic rate was assigned independent of an individual's aerobic capacity.

Equipment

The trials were conducted in a controlled climatic chamber. Temperature and humidity were controlled according to protocol while air speed was about 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, which was calibrated prior to each trial using a controlled temperature water bath.

The work demand consisted of walking on a motorized treadmill at a speed and grade set to elicit three targeted metabolic levels. Measurement of oxygen consumption was used to assess the metabolic level. Participants breathed through a two-way valve connected to flexible tubing ending at a collection bag. Expired gases were collected for approximately 2.5 minutes. The volume of expired air was measured using a dry gas meter, then an oxygen analyzer is utilized to determine the amount of oxygen content in the expired breathe. For each metabolic level (L, M, & H), three samples of oxygen consumption were documented at approximately 30, 60, and 90 minutes into a trial, and from which central tendency is determined. These levels can be expressed as a rate when normalized to an individual's body surface area using the Dubois surface area (AD = $0.202m_b^{0.425} \cdot H^{0.725}$, where m_b was the mass of the body [kg] and H was the height [m]).

Protocols

Each of the five ensembles was worn by participants performing exercise at three systematically increased levels of exertion. The order of ensembles by metabolic level was randomized. Any trial that had to be repeated because of a failure to obtain an inflection point was repeated at the end of the schedule. Most participants completed one trial per day, although some completed two trials per day granted at least 3 hours of recovery between trials.

From past experience with the progressive protocol for the clothing ensembles at 50% RH, the dry bulb temperature (T_{db}) was set at 34°C to provide a low level of heat stress. Once the participant reached thermal equilibrium (no change in T_{re} and heart rate for at least 15 minutes.), T_{db} was increased 0.8°C every 5 min. During trials, participants were allowed to drink water or a commercial fluid replacement beverage.

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°C increase per 5 minutes for 15 minutes); (2) T_{re} reached 39°C; (3) a sustained heart rate greater than 90% of the age-predicted maximum heart rate; or (4) participant wished to stop. Criteria 1 marked a successful trial while Criteria 2 through 4 were based on IRB requirements for participant safety.

Inflection Point and Determination of Critical Conditions

The inflection point marked the transition from thermal balance to the loss of thermal balance. After the inflection point, core temperature continued to rise. Figure 3.1 illustrates one example of core temperature vs. time for a trial. The chamber conditions 5 min before the noted increase in core temperature was taken as the critical condition. One investigator noted the critical condition, which were randomly reviewed by a second investigator.

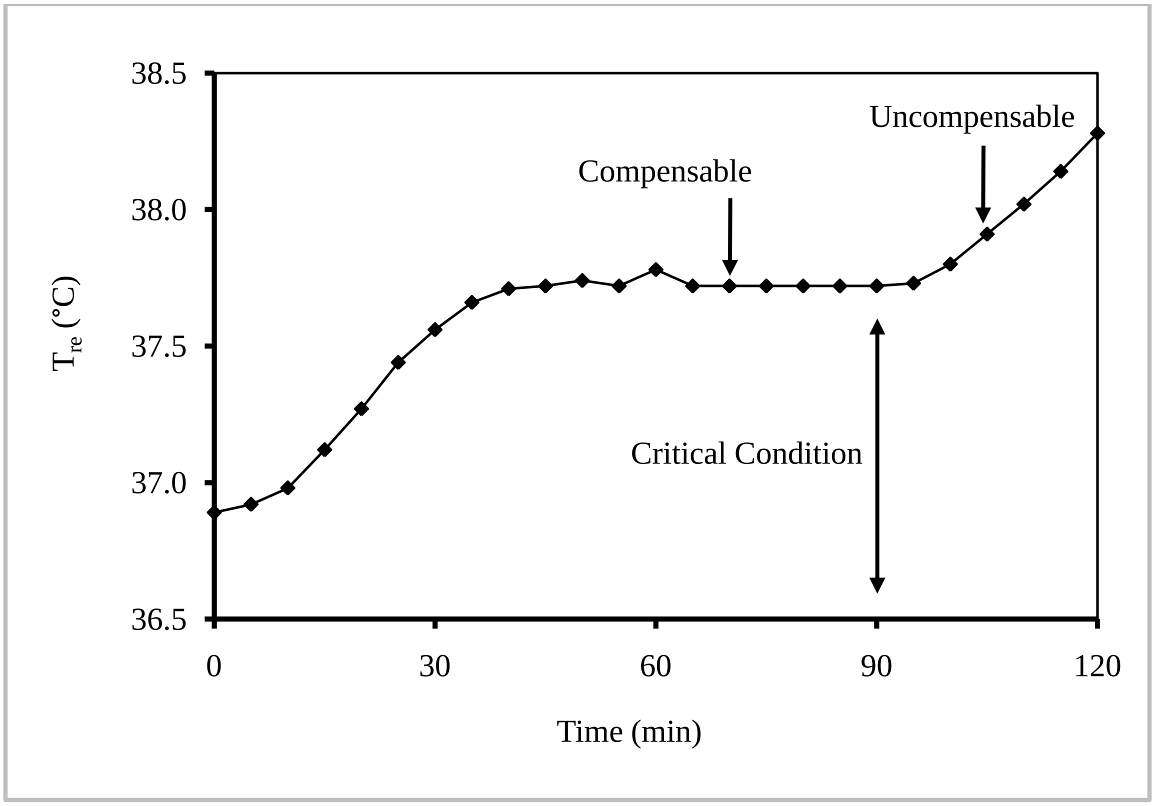


Figure 3.1. Time Course of Rectal Temperature for One Trial

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). 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 computed 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 percentage yielded 0.24% error. All identified errors were corrected with appropriate values prior to computing $R_{e,T,a}$ values. For this particular study, a total of 905 rows of data were utilized containing 6 repeated trials. Each row incorporated 28 columns of data producing a total of 25,340 cell blocks containing data.

Calculation of Clothing Parameters

Environmental and physiological data were used to estimate $R_{e,T,a}$ values for each of the 905 combinations. The following describes the process to compute, based on trial conditions for the participant and environment, the derived values for each trial.

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 (Wm^{-2}) was estimated from oxygen consumption (V_{O2}) in liters per minute:

$$M = 350 \cdot V_{O2} / A_D \qquad \text{Equation (9)}$$

The Dubois surface area (A_D) was calculated for each subject as $A_D = 0.202 m_b^{0.425} \cdot H^{0.725}$, 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:

$$W_{ext} = 0.163 m_b \cdot V_W \cdot f_g / A_D \qquad \text{Equation (10)}$$

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 computed 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:

$$T_{exp} = 28.56 + (0.115 \cdot T_{db}) + (0.641 \cdot P_a) \qquad \text{Equation (11)}$$

$$C_{res} = 0.001516 \cdot M (T_{exp} - T_{db}) \qquad \text{Equation (12)}$$

$$E_{res} = 0.00127 \cdot M (59.34 + 0.53 \cdot T_{db} - 11.63 \cdot P_a) \qquad \text{Equation (13)}$$

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 $^oC^{-1}$ kg^{-1}), m_b, and the rate of change of body temperature (ΔT_{re} Δt^{-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:

$$S = 0.97m_b \cdot \Delta T_{re} A_D^{-1} \Delta t^{-1} \qquad \text{Equation (14)}$$

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:

$$\mathrm{CFI} = \exp[-0.281(v - 0.15) + 0.044(v - 0.15)^2 - 0.492w + 0.176w^2] \qquad \text{Equation (15)}$$

Secondly, $I_{T,stat}$ 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):

$$I_{T,r} = \mathrm{CFI} \cdot I_{T,stat} \cdot 0.9 \qquad \text{Equation (16)}$$

$R_{e,T,a}$ values were computed using equation (8).

$$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}] \qquad \text{Equation (8)}$$

Each $I_{T,r}$ value was inserted into Equation 8 along with other applicable environmental and physiological data for each combination to estimate the $R_{e,T,a}$.

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, metabolic levels, and heat stress stages, a four-way ANOVA was performed in which those factors were fixed effects while the participants were maintained as a random effect. Also evaluated were three interactions between ensembles-metabolic levels, ensembles-heat stress stages, and metabolic 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

Using a four-way mixed model analysis of variance (ANOVA), three fixed main effects were analyzed along with three second order interactions. Main effects include ensemble (5 levels), metabolic rate (3 levels), and stage (3 levels) while the participants were treated as a random effect. The analysis of the data demonstrated significant differences for estimated values of $R_{e,T,a}$ among ensembles, metabolic levels, heat stress stages ($p < 0.0001$) in addition to interactions among ensembles and metabolic levels and ensembles and heat stress stages. Tukey's Honestly Significant Difference (HSD) multiple comparison test distinguished where the significant differences occurred ($p < 0.05$).

Main Effects

$R_{e,T,a}$ values observed were greatest for the vapor-barrier ensemble followed by the water-barrier, vapor-permeable ensemble, particle-barrier ensemble, cotton coveralls (CC), and work clothes (WC). Using Tukey's HSD, significant differences ($p < 0.05$) were detected between Tyvek® 1424, NexGen® LS 417, Tychem QC®, and work clothes. There were no significant differences between work clothes and cotton coveralls in addition to cotton coveralls and Tyvek® 1424 (refer to Table 4.1). NexGen® LS 417 and Tychem QC® were significantly different from every ensemble.

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

Ensembles	Evaporative Resistance	Statistical Difference*
WC	0.012	A
CC	0.012	AB
Tyvek	0.013	B
Nexgen	0.016	C
Tychem	0.027	D

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

Tukey's HSD test demonstrated significant differences ($p < 0.05$) between low and high as well as moderate and high metabolic levels. However, no significant difference was determined between low and moderate. Estimated $R_{e,T,a}$ values were greatest at low metabolic rate while lowest at high metabolic rate as demonstrated by Table 4.2.

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

Metabolic Level	Evaporative Resistance	Statistical Difference*
Low	0.017	A
Moderate	0.016	A
High	0.015	B

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

Each stage of heat stress was determined to be significantly different ($p < 0.05$) as shown in Table 4.3. Compensable stage of heat stress presented the greatest estimated $R_{e,T,a}$ followed by transition, and finally, uncompensable having the lowest.

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	0.020	A
Transition	0.016	B
Uncompensable	0.013	C

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

Interactions

First, estimated $R_{e,T,a}$ values for each clothing ensemble at different metabolic levels are shown in Table 4.4 and illustrated in Figure 4.1. Tukey’s HSD test resulted in statistically different ($p < 0.05$) $R_{e,T,a}$ values for each metabolic level for Tychem QC® from every other ensemble $R_{e,T,a}$ estimates and corresponding metabolic levels. Furthermore, Tychem QC® low and moderate metabolic level's were not significantly different from each other, however, they were both significant against high metabolic level. Remaining ensembles resulted in more complex inter-relationships.

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

		Metabolic Rate		
		L	M	H
Ensembles	WC	0.011	0.012	0.012
	CC	0.013	0.012	0.012
	Tyvek	0.014	0.014	0.012
	Nexgen	0.018	0.016	0.014
	Tychem	0.029	0.028	0.024

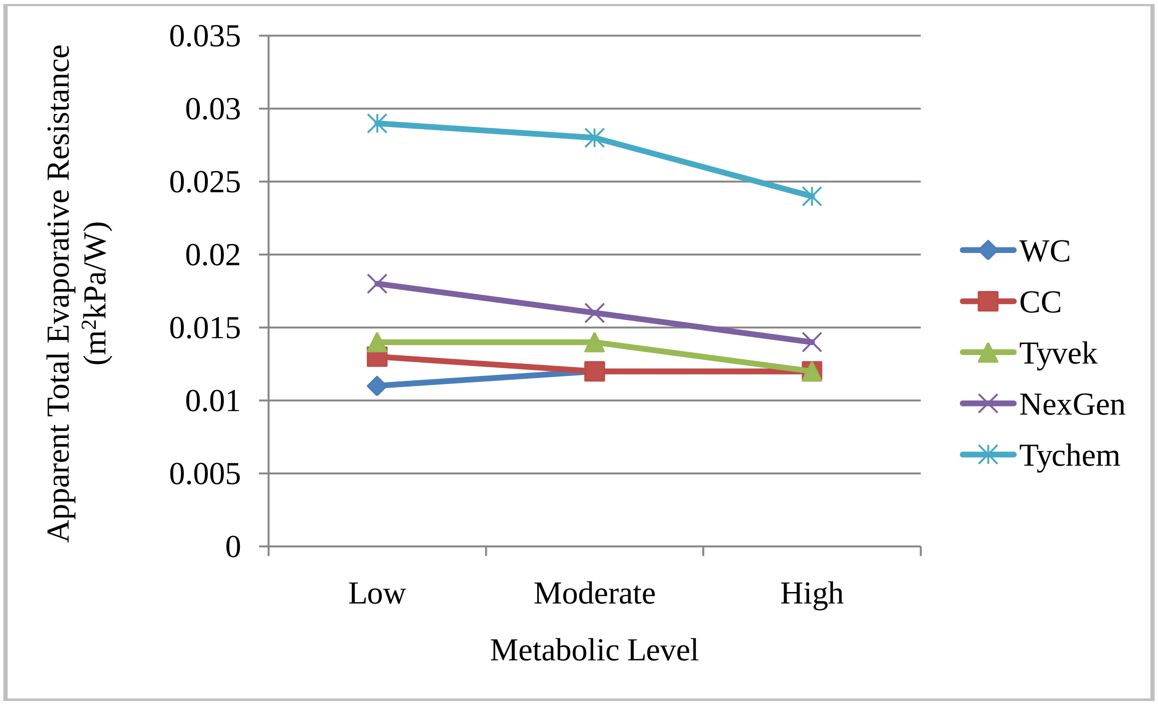


Figure 4.1. Least Squares Mean of Apparent Total Evaporative Resistance for Five Ensembles at Three Metabolic Level's

Figure 4.1 represents the magnitude of $R_{e,T,a}$ values per ensemble. Each ensemble experienced a decrease among $R_{e,T,a}$ values between moderate and high metabolic level's except for CC as it remained equal and WC as it slightly increased. NexGen® LS 417 experienced the most linear declination of $R_{e,T,a}$ values and following second behind Tychem QC®, the gap between becomes apparent in the figure above. Tychem QC®, which is greater than each of the remaining ensembles, experiences the greatest decrease of $R_{e,T,a}$ when transitioning from moderate to high metabolic level.

Second, the interaction of clothing ensemble at different heat stress stages is examined. Table 4.5 presents the $R_{e,T,a}$ values for each ensemble at compensable, transition, and uncompensable conditions. This is graphically represented 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

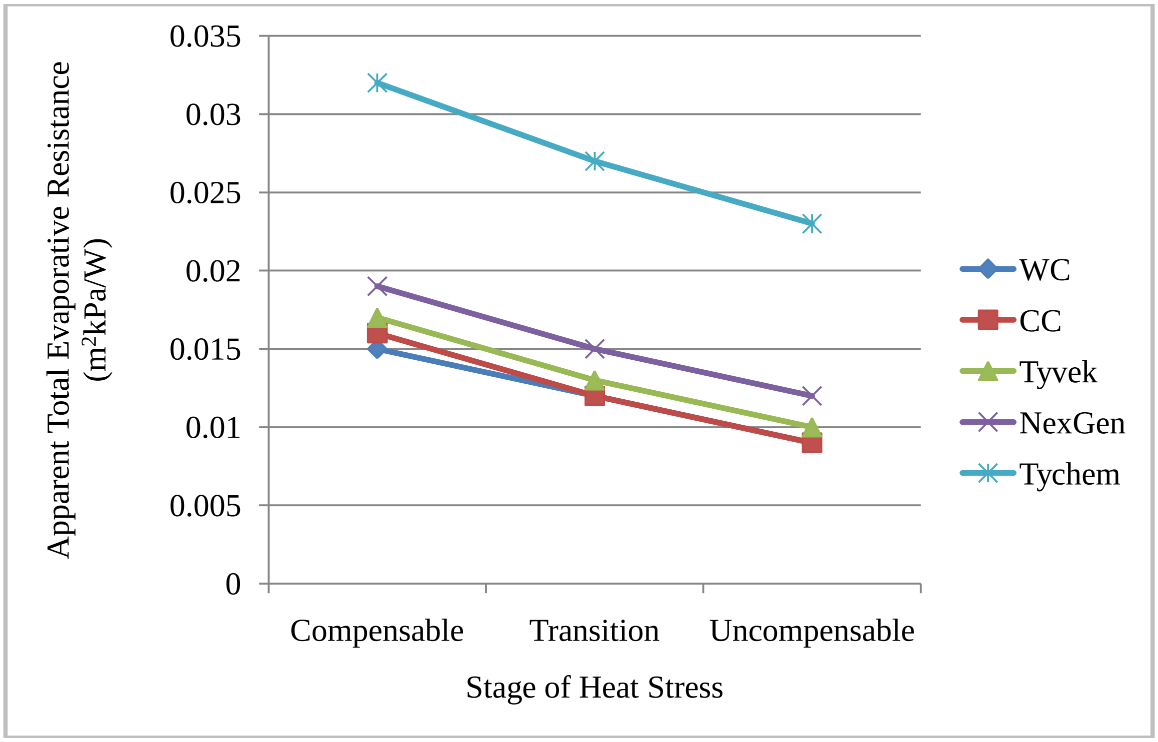


Figure 4.2. Least Squares Mean of Apparent Total Evaporative Resistance for Five Ensembles at Three Heat Stress Stages

As seen in Figure 4.2, $R_{e,T,a}$ values for Tychem QC® are much greater in comparison to the other four clothing ensembles and feature a sharper decline transitioning through the stages of heat stress. Per stage, compensable has the greatest $R_{e,T,a}$, values for each of five ensembles followed by declination.

For the third interaction, $R_{e,T,a}$ values among metabolic levels and heat stress stages resulted in significant differences (p = 0.05). In the case of compensable heat stress, significant difference occur among each metabolic level. There was an interaction such that the proportional drop in $R_{e,T,a}$ was greater with a higher overall evaporative resistance.

Table 4.6 Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Three Metabolic Levels at Three Heat Stress Stages

		Heat Stress Stage		
		Compensable	Transition	Uncompensable
Metabolic Level	Low	0.022	0.017	0.013
	Moderate	0.020	0.016	0.013
	High	0.017	0.015	0.012

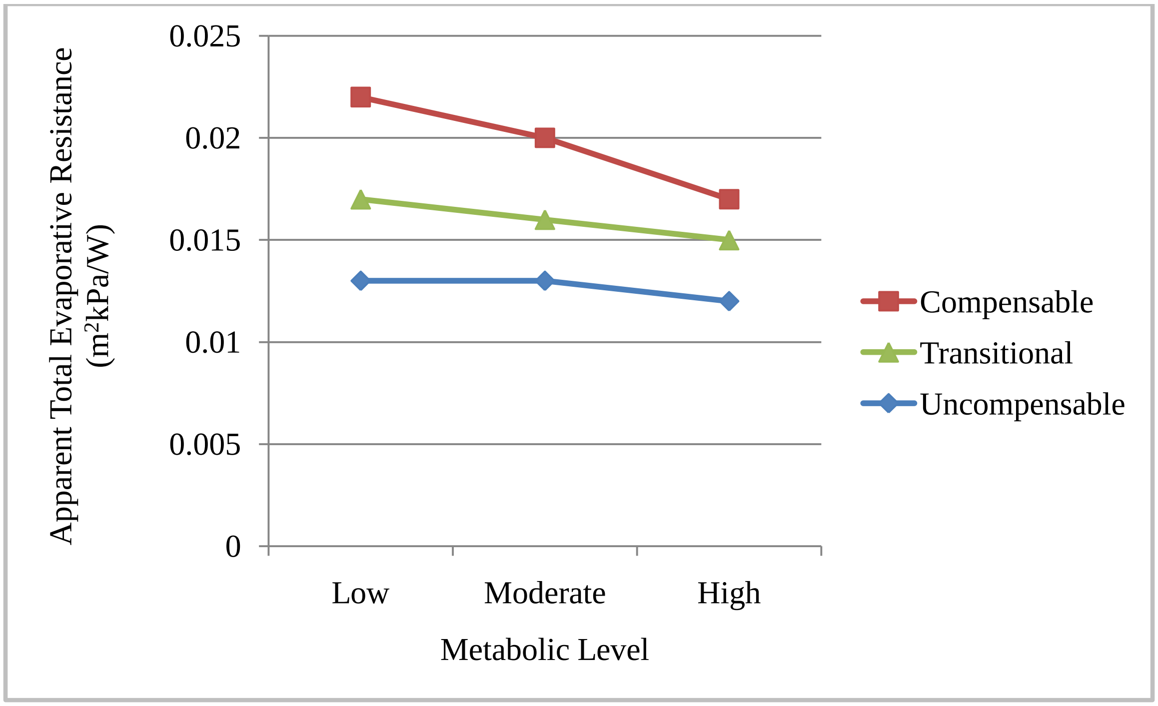


Figure 4.3. Least Squares Mean of Apparent Total Evaporative Resistance for Three Metabolic Levels at Three Heat Stress Stages

CHAPTER 5: DISCUSSION

Analysis of Results

The apparent total evaporative resistance ($R_{e,T,a}$) values observed (refer to Table 4.1) were greatest for the vapor-barrier ensemble followed by the water-barrier, vapor-permeable ensemble, with similar values resulting for particle-barrier ensemble, cotton coveralls (CC), and work clothes (WC). $R_{e,T,a}$ values recorded by Caravello et al. (2008) were within range of this study as they found 0.013, 0.013, 0.015, 0.018, and 0.032 m^2 kPa W^{-1} for work clothes (WC), cotton coveralls (CC), Tyvek® 1424, NexGen® LS 417, and Tychem QC® respectively. Bernard et al. (2010), Barker et al. (1999), and Kenney et al. (1993) reported 0.014, 0.013, and 0.016 m^2 kPa W^{-1} respectively for WC. This study found 0.012 m^2 kPa W^{-1} for WC. Barker et al. (1999) reported a $R_{e,T,a}$ of 0.017 m^2 kPa W^{-1} for Tyvek® 142, which is close to 0.013 m^2 kPa W^{-1} found in this study. Barker et al. (1999) reported a range of 0.014 - 0.026 m^2 kPa W^{-1} for microporous barriers. NexGen® LS 417 $R_{e,T,a}$ of 0.016 m^2 kPa W^{-1} was inside the range. Kenney et al. (1993) reported a $R_{e,T,a}$ value of 0.038 m^2 kPa W^{-1} for an ensemble comparable to Tychem QC® which is higher than 0.027 m^2 kPa W^{-1} estimated in this study.

Significant differences were anticipated for NexGen® LS 417 and Tychem QC® between all other ensembles given the characteristics of the ensembles and based on previous results (Caravello et al., 2008). However, statistical differences were not anticipated among metabolic levels, heat stress stages, in addition to, the interactions among ensembles and metabolic levels and among ensembles and heat stress stages.

To further examine the differences observed among $R_{e,T,a}$ values for metabolic levels, heat stress stages, and the interactions, the gradients of temperature ($T_{db} - T_{sk}$) and vapor pressure ($P_{sk} - P_a$), dry-heat loss (DH), and net heat gain (H_{net}) were explored in more depth. DH is influenced significantly by changes in temperature gradients. Note that if both net heat gain (H_{net}) and total resultant insulation ($I_{T,r}$) remain approximately equal, any difference in vapor pressure and temperature will have a variable effect on $R_{e,T,a}$. A reduction in either of the gradients will increase $R_{e,T,a}$.

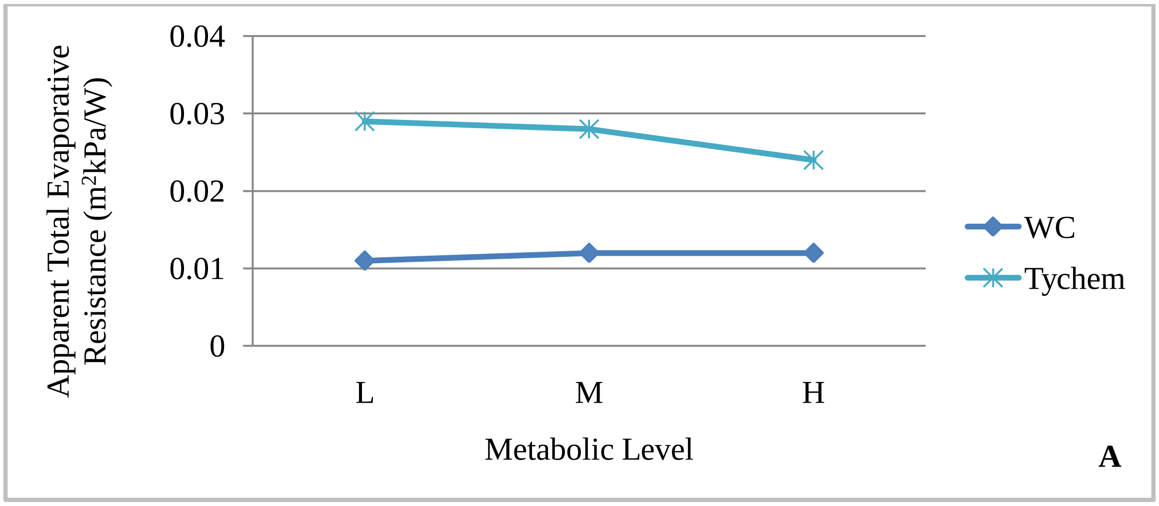
Each component used for the calculation of $R_{e,T,a}$ is tabulated for two clothing ensembles representing different extremes over a range of metabolic levels (Table 5.1) and heat stress stages (Table 5.2). WC is considered the baseline ensemble used frequently in industry and features a low value for $R_{e,T,a}$. Tychem QC® is the other extreme as it features the greatest $R_{e,T,a}$.

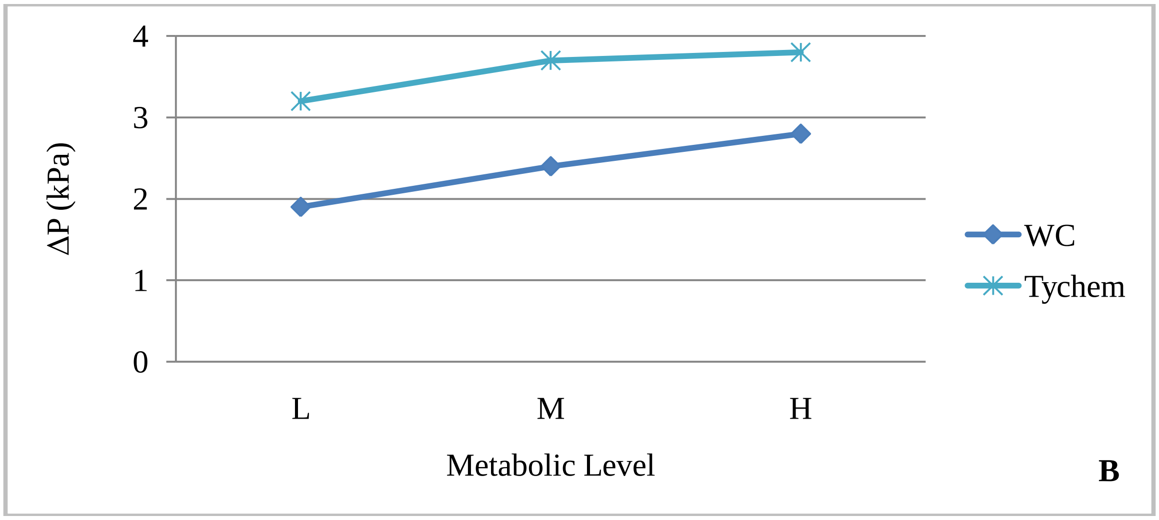
Table 5.1. Apparent Total Evaporative Resistance Values, Temperature and Pressure Gradients, and Net Heat Gain Plus Dry-Heat Loss Values for Two Ensembles at Three Metabolic Levels

Ensembles	WC			Tychem		
MR Levels	L	M	H	L	M	H
$R_{e,T,a}$ (m^2kPa/W)	0.011	0.012	0.012	0.029	0.028	0.024
ΔP (kPa)	1.9	2.4	2.8	3.2	3.7	3.8
ΔT (°C)	7.7	4.5	1.9	0.7	-3.0	-5.3
H_{net} ($W\ m^{-2}$)	113	167	221	108	163	219
DH^* ($W\ m^{-2}$)	63	42	18	6	-27	-49
$H_{net} + DH^*$ ($W\ m^{-2}$)	177	210	240	114	136	170

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

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 metabolic levels are illustrated below.





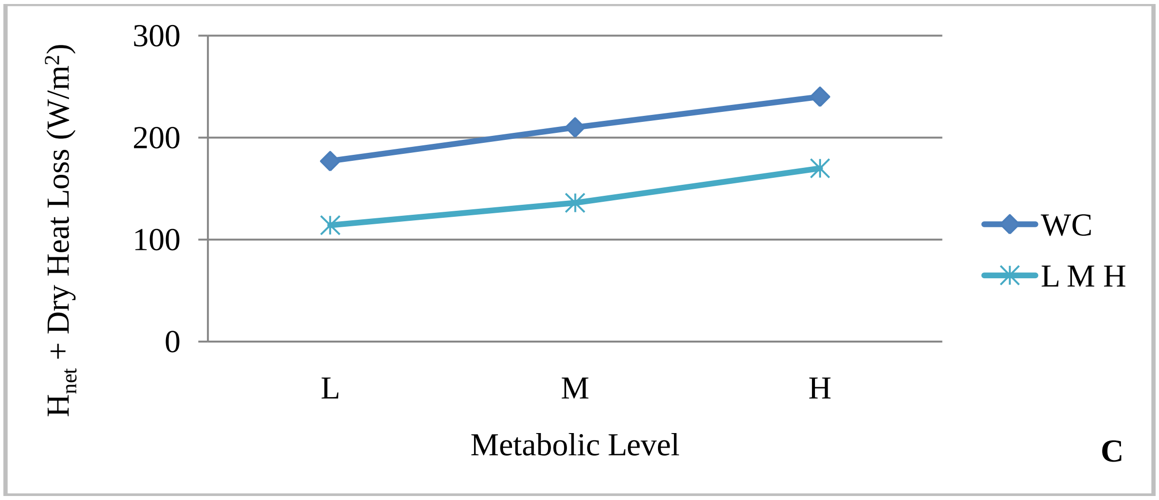


Figure 5.1. Least Squares Mean of Apparent Total Evaporative Resistances (A), Average Pressure Differences (B), and Net Heat Gain Plus Dry-Heat Loss (C) for Two Ensembles at Three Metabolic Levels

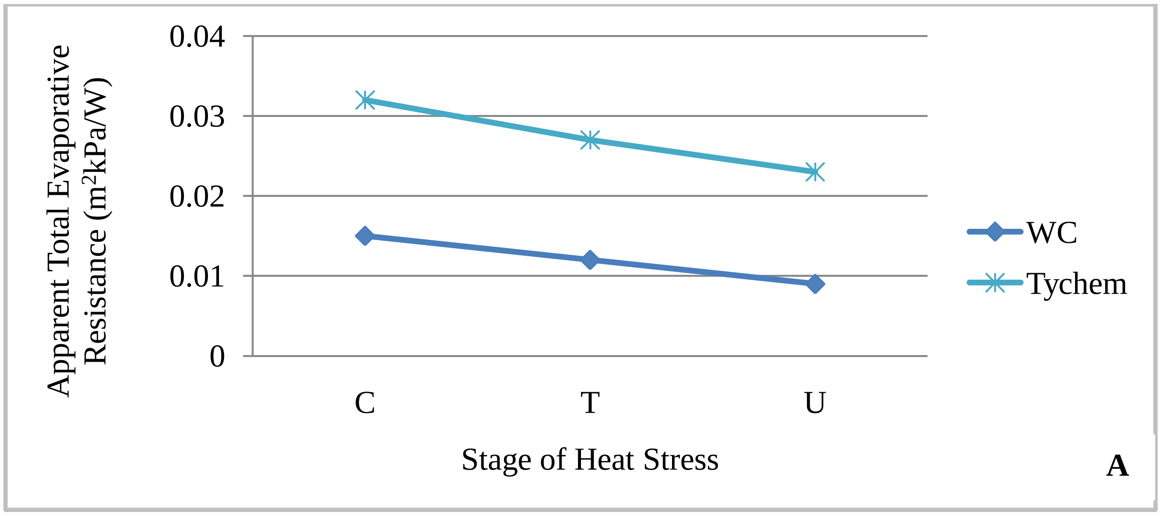
$R_{e,T,a}$ values remained stable at varying metabolic levels for WC but Tychem QC® experienced a decrease at high metabolic activity. The vapor pressure gradients increase from low to high metabolic levels. However, Tychem QC® features a flattening of its slope. H_{net} + DH experienced an increasing trend. $R_{e,T,a}$ is expected to be reduced if ΔP remains stable while H_{net} + DH continue to increase (refer to Equation 8).

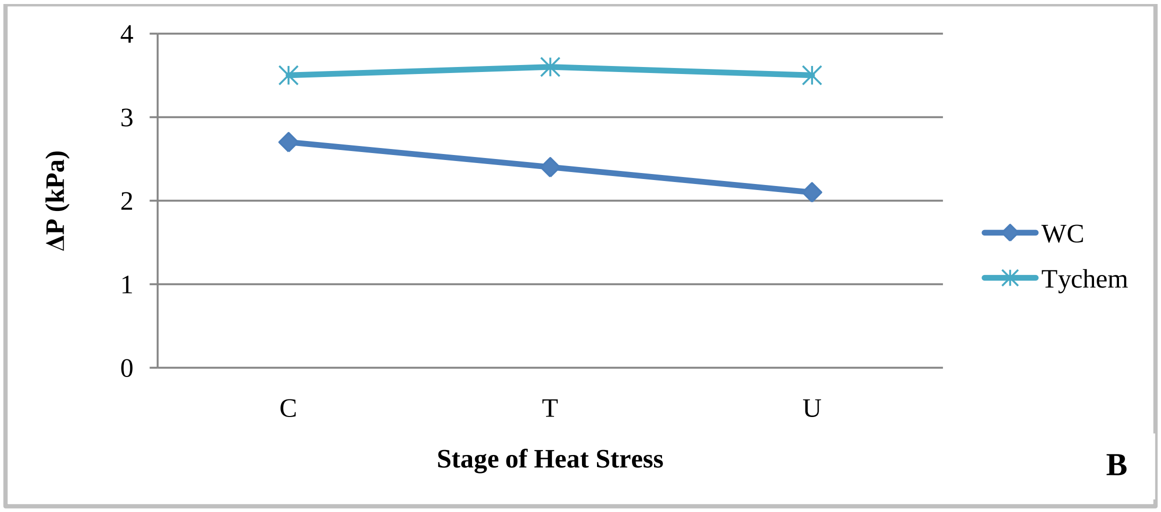
Table 5.2. Apparent Total Evaporative Resistance Values, Temperature and Pressure Gradients, and Net Heat Gain Plus Dry-Heat Loss Values for Two Ensembles at Three Heat Stress Stages

Ensembles	WC			Tychem		
Heat Stress Stages	C	T	U	C	T	U
$R_{e,T,a}$ (m^{2}kPa/W)	0.015	0.012	0.009	0.032	0.027	0.023
ΔP (kPa)	2.7	2.4	2.1	3.5	3.6	3.5
ΔT (^{o}C)	2.0	4.9	7.2	-5.1	-2.5	0.0
H_{net} (W m^{-2})	167	167	167	164	164	163
DH* (W m^{-2})	17	43	64	-47	-24	-1
H_{net} + DH* (W m^{-2})	185	210	232	118	140	162

* 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 are illustrated below.





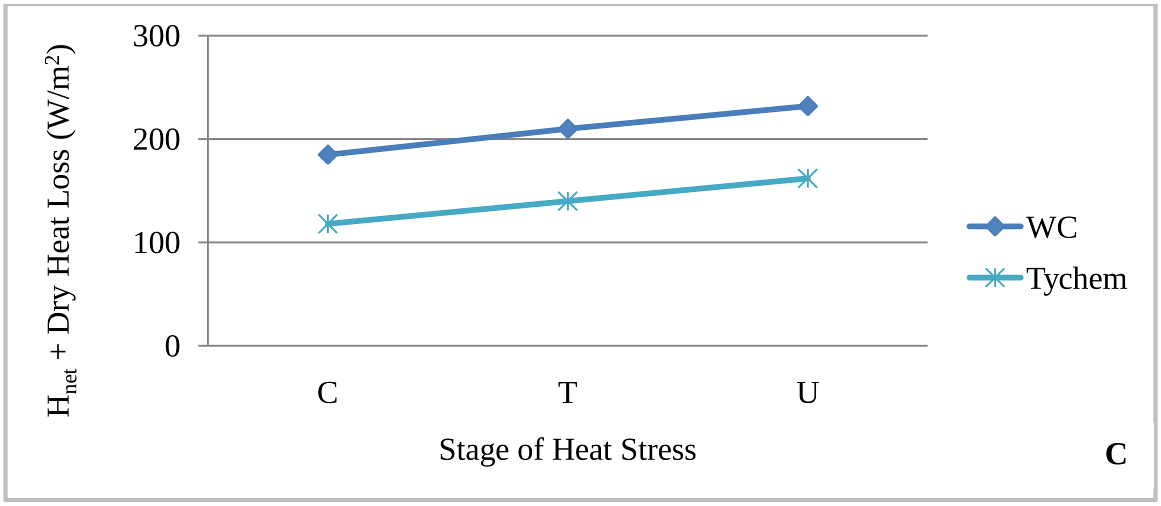


Figure 5.1. Least Squares Mean of Apparent Total Evaporative Resistances (A), Average Pressure Differences (B), and Net Heat Gain Plus Dry-Heat Loss (C) for Two Ensembles at Three Stages of Heat Stress

$R_{e,T,a}$ values were greatest at the compensable stage of heat stress and experience a decreasing linear trend for both ensembles. Vapor pressure gradients decrease for WC but remain stable Tychem QC®, which features a flatter slope of ΔP. H_{net} + DH experienced an increasing trend. Again, $R_{e,T,a}$ is expected to reduce if ΔP remain stable while H_{net} + DH continue to increase as is the case for Tychem QC®.

Both ensembles experience a decreasing linear trend for $R_{e,T,a}$ values. The influence of convection, which provides increased air movement through clothing layers, is noticeable. This is more pronounced for clothing ensembles featuring high air permeability (WC, CC, Tyvek® 1424) because of the improved capability of convective transfer of water vapor (Bernard et al. 2010). This results in lower $R_{e,T,a}$ values. The opposite is true for clothing ensembles featuring low air permeability (NexGen® LS 417, Tychem QC®). The reason for the decreasing trend for Tychem QC® is not fully understood at this present time. Although, the assumption of fully wetted skin may be a contributing factor.

Conclusion

$R_{e,T,a}$ values for five different clothing ensembles differ over a range of metabolic levels and stages of heat stress. Additionally, convection is more supportive of evaporative cooling than diffusion.

Future Research

It is recommended that further investigation into the relationship between temperature and vapor pressure gradients on $R_{e,T,a}$ values for specific clothing ensembles and heat stages.

Study Limitations

Systematic and random error may have been influenced the results found in this study. Systematic error may occur due to the precision and accuracy of heat lab instruments, as well as data recording. A major assumption necessary for progressive heat stress protocol is that the skin is fully wet, which may have been violated. Random errors within database following data extraction may occur. Lastly, study results only apply to the five specific ensembles tested in this study.

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