

APPARENT TOTAL EVAPORATIVE RESISTANCE AND CLOTHING ADJUSTMENT FACTORS AT DIFFERENT HUMIDITIES AND METABOLIC RATES

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INTRODUCTION

It is clear that the static thermal properties of a clothing ensemble will change with environmental and usage conditions. (Havenith et al 2008) An attempt to address the move from static to dynamic (or resultant conditions) has been addressed by Holmer and Havenith with colleagues (Holmer et al 1999, Havenith et al 1999) and codified in ISO9920 (2007). The prescribed reductions in total static insulation and evaporative resistance were based on empirical evidence from several participating laboratories.

The apparent total evaporative resistance ($R_{e,T,a}$) was proposed by Caravello et al (2008) to represent the measured evaporative resistance from wear trials based on a progressive heat stress protocol. This method did not attempt to parse out individual pathways for heat exchange (Havenith et al 2008) nor did it try to generalize to other conditions. It is, however, a useful tool to explore the relative differences among ensembles under similar conditions using wear trials and to judge the effects of different experimental conditions such as levels of humidity and metabolic rate (and associated movement).

Clothing Adjustment Factors (CAF) have come into use via the ACGIH® TLV® for Heat Stress and Strain (2009). CAF is an adjustment to the measured wet bulb globe temperature (WBGT) index for an environment to account for clothing effects as they differ from cotton work clothes. Caravello et al (2008) suggested a relationship between CAF and $R_{e,T,a}$ based on five clothing ensembles under limited trial conditions (moderate metabolic rate and 50% relative humidity).

The purpose of the current paper was (1) to expand the range of experimental conditions (relative humidity and metabolic rate) for the five ensembles reported by Caravello et al (2008) for the examination of $R_{e,T,a}$ and (2) revisit the relationship between CAF and $R_{e,T,a}$ based on an expanded data set.

METHODS

The data used for this paper were developed from three different studies, which used similar methods to estimate CAF (Bernard et al 2005, 2008) and $R_{e,T,a}$ (Caravello et al 2008). The base ensemble worn under all test ensembles was cotton tee shirt, gym shorts, briefs, socks and athletic shoes. All participants were acclimated to hot, dry conditions at a metabolic rate of 160 $W m^{-2}$ while wearing the base ensemble. All of the trials within a study were in a partially

balanced design to avoid ordering effects. All protocols were approved by the local IRB and informed consent was obtained following university practice. The differences in the studies are presented in this section.

Relative Humidity Protocol

Five different clothing ensembles over the base ensemble 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: particle-barrier ensembles (Tyvek® 1424 or 1427), water-barrier, vapor-permeable ensembles (NexGen® LS 417), and vapor-barrier ensembles (Tychem QC®, polyethylene-coated Tyvek®). The limited-use coveralls had a zippered closure in the front and elastic cuffs at the arms and legs; and they did not include a hood.

There were 14 participants who wore each ensemble at three levels of relative humidity (20%, 50%, and 70%, called R2, R5 and R7). The metabolic rate was moderate (155 W m⁻²) and called M2. (Bernard et al 2005)

Metabolic Rate Protocol

For the metabolic rate protocol, there were three metabolic rates (114, 176, and 250 W m⁻², called M1, M2, and M3) at one relative humidity (50%, R5). There were 15 participants who wore each of the five ensembles described above at the three levels of metabolic rate. (Bernard et al 2008)

Porosity Study

Six test suits, designated as P00, P01, P02, P05, P10, and P20, were fabricated from a fabric with a selectively permeable Hytrel® film laminated between two nonwoven layers that had perforations to affect porosity of 0, 1, 2, 5, 10 and 20% of the surface area. (Bernard et al 2009) In addition, there were standard cotton work clothes (as above) and a Saratoga™ Hammer chemical protective overgarments (jacket with integral hood and pants). Six acclimated participants wore work clothes, Saratoga™ Hammer, and prototype garments P00, P01, P02, and P05. Four participants also wore P10 and P20.

RESULTS

The Relative Humidity and Metabolic Rate Protocols were designed to have a common exposure pair of R5 and M2. The data for these conditions were not statistically different and thus they were pooled together. Within protocol data analysis was a mixed general linear model with two fixed effects (clothing ensemble and either humidity level or metabolic rate level) with an interaction term and participants treated as a random effect. In both protocols, $R_{e,T,a}$ was the dependent variable.

Relative Humidity Protocol

The relationship between $R_{e,T,a}$ and relative humidity level for each ensemble is shown in Figure 1. There were significant differences for $R_{e,T,a}$ related to ensemble and relative humidity as well as the interaction term. The strong interaction influence came from the drop in $R_{e,T,a}$ for the vapor barrier ensemble with increasing humidity. While $R_{e,T,a}$ was generally higher at R2 for the

other ensembles, R5 and R7 were about the same. For $R_{e,T,a}$ by ensemble, there were no significant differences for work clothes, cotton coveralls and Tyvek. NexGen and vapor barrier were different from the others and each other.

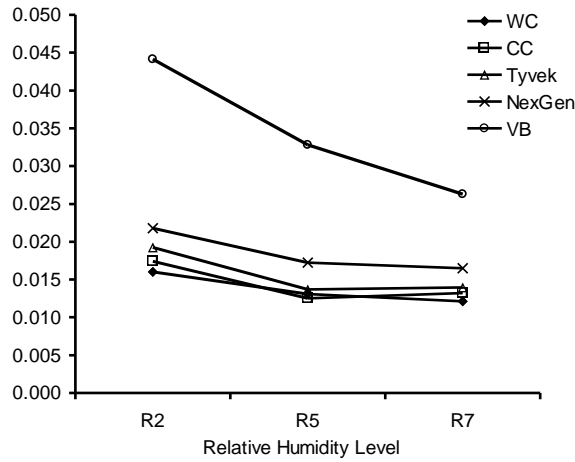


Figure 1. Apparent total evaporative resistance ($R_{e,T,a}$) [$m^2 \text{ kPa } W^{-1}$] by relative humidity level for five clothing ensembles.

Metabolic Rate Protocol

The relationship between $R_{e,T,a}$ and metabolic rate level for each ensemble is shown in Figure 2. There were significant differences for $R_{e,T,a}$ related to ensemble and metabolic rate as well as the interaction term. The strong interaction influence came from the drop in $R_{e,T,a}$ for the vapor barrier ensemble at M3. $R_{e,T,a}$ was generally higher at M1 and dropped slowly through M2 to M3 for the other ensembles. For $R_{e,T,a}$ by ensemble, there were no significant differences for work clothes, cotton coveralls and Tyvek. NexGen and vapor barrier were different from the others and each other.

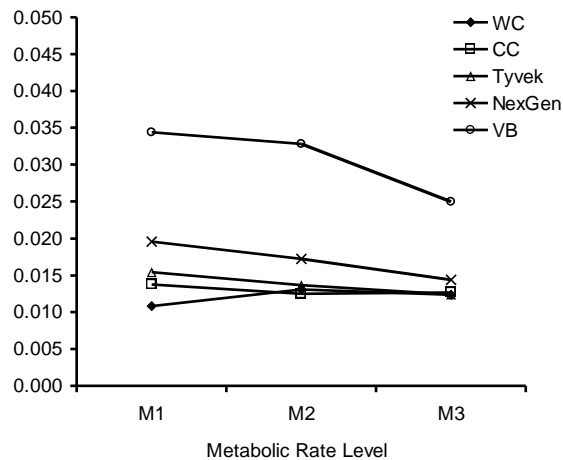


Figure 2. Apparent total evaporative resistance ($R_{e,T,a}$) [$m^2 \text{ kPa } W^{-1}$] by metabolic rate level for five clothing ensembles.

Apparent Total Evaporative Resistance and Clothing Adjustment Factor

From the relative humidity and metabolic rate protocols, there were six baseline critical WBGTs for work clothes and the CAF for the four other ensembles was determined for each of the three relative humidities and three metabolic rates. The result was 24 pairs of CAF and $R_{e,T,a}$. In a similar manner, 7 more pairs were available from the porosity study. The relationship between $R_{e,T,a}$ and CAF is shown in Figure 3. While relative humidity, metabolic rate and porosity were potential effect modifiers, there was no apparent effect on the relationship.

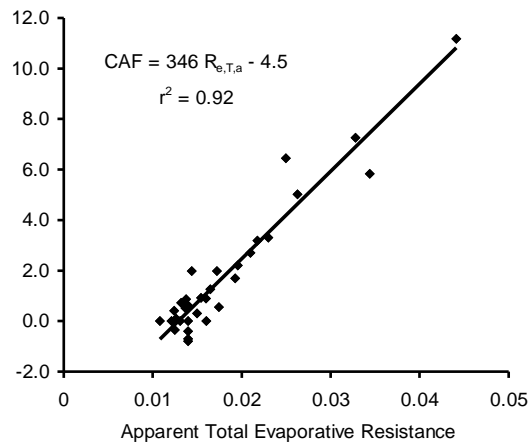


Figure 3. Clothing Adjustment Factor (CAF) [$^{\circ}\text{C}$ -WBGT] as a function of apparent total evaporative resistance ($R_{e,T,a}$) [$\text{m}^2 \text{kPa W}^{-1}$].

CONCLUSIONS

As seen in Figure 1, relative humidity level clearly affected the apparent total evaporative resistance for the vapor barrier ensemble with lesser effects for the other ensembles. At the lower relative humidity (hot dry conditions), $R_{e,T,a}$ was higher than the moderate and warm humid conditions. While there is not direct evidenced of a heat pipe effect, an evaporation/condensation cycle was more easily established in the R5 and R7 conditions that would make the overall evaporative resistance appear to be lower (Havenith et al 2008). With the higher temperatures associated with the hot dry conditions (R2), it was less likely that condensation could occur at the inner surface of the clothing. Because the difference in $R_{e,T,a}$ can be substantial with ensembles of high evaporative resistance, air temperature and humidity may be additional candidates for adjusting static evaporative resistance values for actual wear conditions as suggested for air speed and walking speed (Havenith et al 1999).

$R_{e,T,a}$ was also affected by metabolic rate (see Figure 2). There was no surprise in this general finding, but the change was greater for greater levels of $R_{e,T,a}$. With the higher values of $R_{e,T,a}$, the role of convective heat transfer through openings in the clothing may account for the drop in apparent evaporative resistance. While the usual adjustments for evaporative resistance include air and walking speed (Havenith et al 1999), some consideration to the overall level of evaporative resistance as an effect modifier may be appropriate.

Clothing Adjustment Factors (CAFs) are used for a limited number of clothing ensembles in WBGT-based exposure assessment methods (ACGIH 2009, Bernard et al 2005). Because these are empirically determined from wear trials, a predictive method based on evaporative resistance can be used to generalize CAF to an unlimited range of ensembles. To this end, the relationship between $R_{e,T,a}$ and CAF was explored in Figure 3. Across the experimental conditions of relative humidity, metabolic rate and ensembles, the relationship appeared to be consistent and linear. The line is similar to one posited earlier by Caravello et al (2008) using some of the same data for one relative humidity and metabolic rate level.

In summary, there was a consistent linear relationship between $R_{e,T,a}$ and CAF that can be used to predict a CAF for an estimated resultant total evaporative resistance based on static evaporative resistance adjusted for the usage conditions. In addition, there was some suggestion that the determination of resultant total evaporative resistance might include air temperature and humidity as well as the metabolic rate.

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REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH®): 2009 Threshold Limit Values and Biological Exposure Indices for Chemical Substances and Physical Agents. Cincinnati, Ohio: ACGIH.

Bernard TE, Ashley CD, Trentacosta J, Kapur V, Tew S (2009) Effects of porosity on critical WBGT and apparent evaporative resistance. Proceedings of the ICEE, Boston.

Bernard TE, Luecke CL, Schwartz SW, Kirkland KS, Ashley CD (2005) WBGT clothing adjustment factors for four clothing ensembles under three humidity levels. *Journal of Environmental and Occupational Hygiene* 2:251-256

Bernard, TE, Caravello V, Schwartz SW, Ashley CD (2008) WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. *Journal of Environmental and Occupational Hygiene* 5:1-5

Caravello, V, E. A. McCullough, C. D. Ashley, T. E. Bernard (2008) Apparent Evaporative Resistance at Critical Conditions for Five Clothing Ensembles. *European Journal of Applied Physiology* 104:361-7

Havenith G, Holmer I, den Hartog EA, Parsons KC (1999) Clothing evaporative heat resistance—proposal for improved representation in standards and models. *Ann Occup Hyg* 43:339–346

Havenith G, Richards M, Wang X, Brode P, Candas V, den Hartog E, Holmer I, Kuklane K, Meinander H, Nocker W (2008) Apparent latent heat of evaporation from clothing: attenuation and heat pipe effects. *J Appl Physiol* 104:142-9

Holmer I, Nilsson H, Havenith G, Parsons K (1999) Clothing convective heat exchange—proposal for improved prediction in standards and models. *Ann Occup Hyg* 43:329–337