

EFFECTS OF POROSITY ON CRITICAL WBGT AND APPARENT EVAPORATIVE RESISTANCE

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INTRODUCTION

Management of heat stress is a critical issue for those wearing clothing as a barrier to chemical agents for extended periods. One accepted design for protective apparel for such extended-wear is a relatively porous substrate fabric containing an activated charcoal adsorbent (Harrison et al, 2004). Another design uses selectively permeable membranes (SPMs) that are non-porous but effectively pass moisture by diffusion while rejecting transport of many toxic agents (Allmaras, 2007). A third approach is an adaptive barrier structure that is porous in the absence of chemical threats but becomes non-porous upon warning of the presence of a toxic agent (Trentacosta and Kapur, 2005). An unresolved issue in extended-wear protective apparel design is the relative importance of through-thickness convection versus diffusive permeability of water vapor in the capacity to support evaporative cooling.

For performance studies on alternative clothing ensembles, two approaches can be taken. A common approach is to create conditions of uncompensable heat stress by fixing the environmental conditions to one or more typical environments at a fixed metabolic rate. The average safe exposure time represents the ensemble performance. An alternative approach used in this study is to determine the critical environment at the upper limit of compensable heat stress following a progressive exposure protocol. Based on the critical environment, an estimation of the total apparent evaporative resistance ($R_{e,T,a}$) (Caravello et al 2008) and the critical Wet Bulb Globe Temperature ($WBGT_{crit}$) (Bernard et al 2005, 2008) can be determined. Both $R_{e,T,a}$ and $WBGT_{crit}$ are useful indices for the comparison of the evaporative cooling capacity of clothing ensembles.

METHODS

Materials

Six test suits, designated as P00, P01, P02, P05, P10, and P20, were fabricated from DuPont Acturel®, a selectively permeable Hytrel® film laminated between two nonwoven layers. The test suit design included a hood and elastic closures at all apertures including the wrists, ankles, and face. Porosity was incorporated into the suits with panels of Acturel® that had been punched at different densities. P01, P02, P05 and P10 achieved overall nominal open areas of 1.1, 2.2, 4.9, and 9.4%. P00 was also fabricated with panels that were not perforated, and was representative of the performance of the non-porous SPM. P20 had an open area of 18%, where the perforations covered the entire coverall.

Standard cotton work clothes (shirt and pants) were included in the test as a negative control and Saratoga™ Hammer chemical protective overgarments (jacket with integral hood and pants) were included as representative of air permeable, activated carbon filled protective apparel. The base ensemble worn under all test ensembles was cotton tee shirt, gym shorts, briefs, socks and athletic shoes.

Participants

Six adult males participated in the wear tests. The average and standard deviation of their physical characteristics are provided in Table 1. The study protocol was approved by the 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.

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 160 W m^{-2} in a climatic chamber at 50°C and 20% relative humidity (rh) for two hours while wearing the base ensemble.

Table 1. Participant characteristics and ensemble trials completed.

ID	Age (yrs)	Height (cm)	Weight (kg)	Body SA (m^2)	Ensembles and Number of Trials							
					WC	S	P00	P01	P02	P05	P10	P20
S1	40	178	69.1	1.90	2	1	1	1	1	1	1	1
S2	23	173	52.3	1.60	2	1	1	1	1	1	2	1
S3	26	196	77.3	2.10	2	1	1	1	1	1	1	1
S4	20	183	86.4	2.10	2	1	2	1	1	1	1	1
S5	20	185	83.6	2.08	2	1	1	1	1	--	--	--
S6	21	170	70.5	1.82	2	1	1	1	1	--	--	--

Progressive Heat Stress Protocol

Heat stress trials were conducted in a climatic chamber. A treadmill was used to control participants work rate at a moderate level of 160 W m^{-2} . Air movement was nominal at 0.5 m s^{-1} . Typically, the dry bulb temperature (T_{db}) was set at 34°C (but the starting point was adjusted lower for ensembles with suspected high evaporative resistance) and rh at 50%. Once the participant reached thermal equilibrium (no change in rectal temperature and heart rate for at least 15 minutes.), T_{db} was increased 0.8°C every 5 minutes. During trials, participants were allowed to drink water or a commercial fluid replacement beverage (Gatorade®) at will.

Core temperature, heart rate and ambient conditions 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 rectal temperature (T_{re}) associated with a loss of thermal equilibrium (typically 0.1°C increase per 5 min for 15 min), (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.

The inflection point marked the transition from thermal balance to the loss of thermal balance, where core temperature continued to rise. The chamber conditions five minutes before the noted

increase in core temperature was taken as the critical condition. One investigator noted the critical condition, and a second investigator reviewed the decisions.

RESULTS

There were no differences among ensembles for metabolic rate by body surface area, which indicated that metabolic rate would not systematically effect the outcome for $WBGT_{crit}$ and the other environmental factors at the critical conditions used to estimate $R_{e,T,a}$. There were significant differences in $WBGT_{crit}$ and $R_{e,T,a}$, where Saratoga™ Hammer and P00 were associated with the least support of evaporative cooling and different from the other ensembles (see Table 2).

Table 2. Results of multiple comparison tests based on least squares means for the eight ensembles for $WBGT_{crit}$ and $R_{e,T,a}$. Horizontal lines represent no significant difference based on Tukey's HSD. Clothing Adjustment Factor (CAF) provided for $WBGT_{crit}$ data.

$WBGT_{crit}$ [°C]	P02	P20	P05	WC	P10	P01	S	P00
(CAF)	(-0.8)	(-0.7)	(-0.4)	(0)	(0.3)	(0.9)	(2.7)	(3.3)

$R_{e,T,a}$ [kPa m ² W ⁻¹]	P05	P20	P02	WC	P10	P01	P00	S
	0.014	0.014	0.014	0.014	0.015	0.016	0.021	0.023

Figures 1 and 2 illustrate the relationship between $WBGT_{crit}$ and the convective and diffusive permeabilities, respectively.

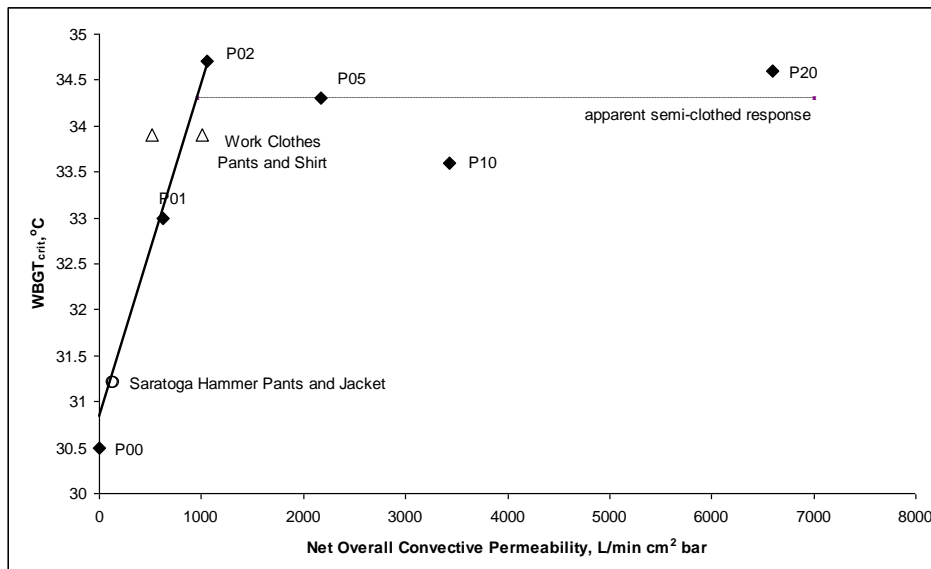


Figure 1. Mean $WBGT_{crit}$ vs. convective permeability. Solid line is linear regression of P00, P01, P02, S and WC response. Dotted line is average of P02, P05, P10, and P20 response to

reflect a flat response at high convective permeability like the semi-clothed suggested by Gonzalez et al (2006).

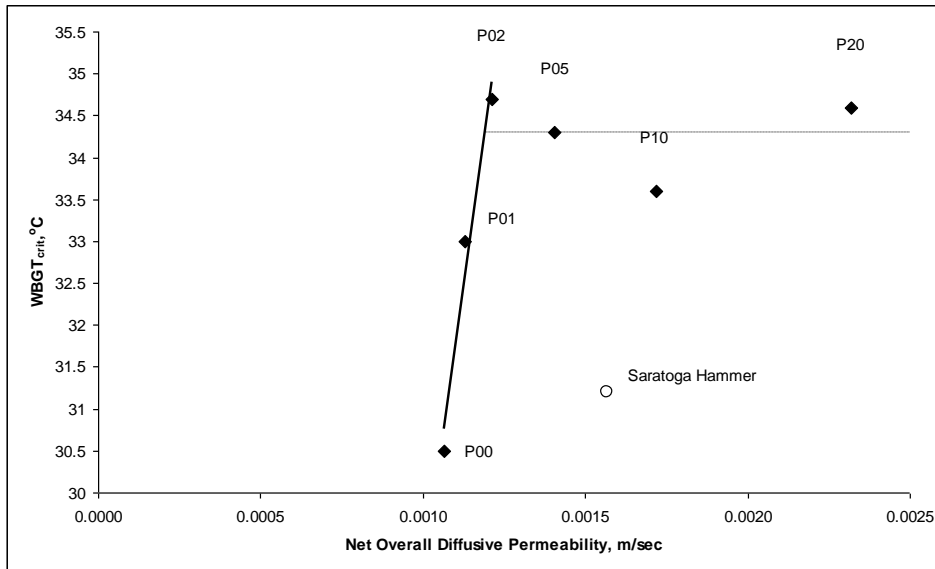


Figure 2. Mean WBGT_{crit} vs. diffusive permeability. Solid line is linear regression of P00, P01, and P02 response. Dotted line is average of P02, P05, P10, and P20 again assuming a flat response similar to semi-clothed as shown in Figure 2.

CONCLUSIONS

In the context of WBGT_{crit}, the P02 through P20 ensembles were similar to work clothes. With the inability to distinguish between P01 and Saratoga or between Saratoga and P00, there is some room to argue for progressive effects from no porosity to modest porosity with no further gains in WBGT_{crit} for increases in porosity beyond 1% (P01). The clothing adjustment factor for the Saratoga™ Hammer ensemble was about 3 °C-WBGT, which was similar to the microporous ensemble NexGen and was much less than 8°C-WBGT a vapor barrier ensemble at 50% relative humidity (Bernard et al 2005).

In the analysis of the apparent total evaporative resistance in Table 2, the inability to distinguish among the prototype ensembles with porosity is similar to that for the critical WBGT. P02, P05 and P20 occupy the lower end of the range of evaporative resistance; followed by Work Clothes, P10 and P01. It was clear that the P00 and Saratoga were different from the others but not from each other. These data further supported the notion that once there is some opportunity for convective transfer through the fabric (presence of porosity) there were not significant or important gains in the ability to support sweat evaporation.

Figure 1 illustrates the mean WBGT_{crit} vs. convective permeability for the various ensembles. Mean WBGT_{crit} showed a strong correlation ($r^2=0.88$) with convective permeability for ensembles P00, P01, P02, Saratoga™ Hammer (S) and Work Clothes (WC). At convective permeability above a nominal 1000 L/min cm² bar, WBGT_{crit} appeared to level off suggesting that ensembles with permeability above this value respond equivalently to the so-called semi-clothed ensemble described by Gonzalez et al (2006). The Gonzalez critical convective permeability data indicated that the semi-clothed critical condition would be achieved at a

nominal permeability of 2000 L/min cm² bar in reasonably good agreement with our finding of 1000 L/min cm² bar.

In Figure 2, mean WBGT_{crit} vs. diffusive permeability for the various ensembles is shown. Based on the response to convective permeability just described above, it was not surprising that WBGT_{crit} correlated with diffusive permeability for the P00, P01 and P02 ensembles and then appeared to level off at higher permeability. Unlike the response to convective permeability in Figure 4, it was clear that the Saratoga™ Hammer ensemble WBGT_{crit} response was outside the PXX ensemble series response to diffusive permeability. Although the Saratoga™ Hammer ensemble has relatively high diffusive permeability, it has very low convective permeability - only about 20% of the level achieved with the P01 ensemble. This was likely a consequence of the long path length characteristic of this compound fabric structure. Consistent with the Gonzalez et al (2006) results, convective permeability explained the cooling capacity better than diffusive permeability. Specifically, measuring the diffusive permeability of a fabric or garment will underestimate the level of heat stress that is actually experienced.

Clothing with lower porosity had relatively higher values of total apparent evaporative resistance and lower critical WBGT. In conclusion, porosity and the associated convective permeability were more predictive of the capacity of an ensemble to support evaporative cooling than diffusive permeability. The upper limit of convective permeability at a moderate rate of work before there are diminishing returns was about 1000 L/min cm² bar.

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