

# Apparent evaporative resistance at critical conditions for five clothing ensembles

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**Abstract** A limiting factor for clothing ensembles inherent during heat stress exposures is the evaporative resistance, which can be used to compare candidate ensembles and in rational models of heat exchange. In this study, the apparent total evaporative resistance of five clothing ensembles (cotton work clothes, cotton coveralls, and coveralls made of Tyvek<sup>®</sup> 1424 and 1427, NexGen<sup>®</sup> and Tychem QC<sup>®</sup>) was estimated empirically from wear trials using a progressive heat stress protocol and from clothing insulation adjustments based on ISO 9920 (2007) and wetness. The metabolic rate was moderate at  $165 \text{ W m}^{-2}$  and relative humidity was held at 50%. Twenty-nine heat-acclimated participants (20 men and 9 women) completed trials for all clothing ensembles. A general linear mixed effects model (ensemble and participants as a random effect) was used to analyze the data. Significant differences

( $p < 0.0001$ ) among ensembles were observed for apparent total evaporative resistance. As expected, Tychem QC had the highest apparent total evaporative resistance at  $0.033 \text{ kPa m}^2 \text{ W}^{-1}$ . NexGen was next at  $0.017 \text{ kPa m}^2 \text{ W}^{-1}$ . These were followed by Tyvek 1424 at  $0.015 \text{ kPa m}^2 \text{ W}^{-1}$ , and Tyvek 1427, Cotton Coveralls and Work Clothes all at  $0.013 \text{ kPa m}^2 \text{ W}^{-1}$ . This wear test method improves on past methods using the progressive protocol to determine evaporative resistance by including the effects of movement, air motion and wetness on the estimate of clothing insulation. The pattern of evaporative resistance is the same as that for critical WBGTs and a linear relationship between apparent total evaporative resistance and WBGT clothing adjustment factor is suggested. With the large sample size, a good estimate of sample variance associated with progressive method can be made, where the standard error is  $0.0044 \text{ kPa m}^2 \text{ W}^{-1}$  with a 95% confidence interval of  $0.0040\text{--}0.0050 \text{ kPa m}^2 \text{ W}^{-1}$ .

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## Introduction

Work clothes and protective clothing are essential features of workplace protection. To varying degrees, clothing affects the level of heat stress that a person experiences. While convection and radiation play a minor role in maintaining thermal equilibrium in hot climates, evaporative resistance is the most important factor with respect to maintaining thermal balance in hot environments (Havenith 1999). There is a limit to evaporative cooling that depends on clothing. Total evaporative resistance ( $R_{e,T}$ ) and water vapour permeability ( $i_m$ ) are related and reflect the ability of

the clothing to support evaporative cooling. Static values for these parameters reflect that the clothing is worn without significant air motion and movement. In turn, resultant values adjust for more realistic conditions of air movement and activity of the wearer under specific working conditions (ISO 9920 2007). The resultant values can then be used in rational models of heat stress to assess exposure in specific working conditions. For instance, walking at a brisk pace can nearly halve the insulation of moderately thick clothes because body movements pump air in and out of the clothing (Lotens 1989; Havenith et al. 1990; Holmer et al. 1999). The insulation is further reduced if the clothing becomes wet (Kenney et al. 1993; Holmer and Nilsson 1995; Brode et al. 2008; Havenith et al. 2008). Another way to examine the thermal effects of clothing during exposures to heat stress was first proposed by Woodcock (1962). He defined the permeability index ( $i_m$ ) as the ratio of  $I_T$  (clothing insulation) to  $R_{e,T}$  divided by the Lewis number ( $16.7^\circ\text{C kPa}^{-1}$ ). Increases in air motion and body movement increase the measured value of  $i_m$  for a given clothing ensemble (Goldman 1988). Thus increases in the pumping factor also increase the water vapour permeability of a clothing ensemble and reduce the  $R_{e,T}$  (Havenith et al. 1999). The preceding discussion is a simple view of more complex mechanisms of heat transfer between a person and the environment through a clothing system (Havenith et al. 2008). Because of this complexity, it is sometimes useful to refer to experimental results under specific conditions as apparent.

A progressive heat stress protocol can be used to identify the critical conditions at which the maximum heat loss due to evaporative cooling (vapour pressure difference between the environment [ $P_a$ ] and the skin [ $P_{sk}$ ] divided by the apparent total evaporative resistance [ $R_{e,T,a}$ ]) is balanced by the net heat gain due to internal sources ( $H_{net}$ ) (metabolic rate [ $M$ ] less external work [ $W_{ext}$ ], storage rate [ $S$ ] and respiratory exchange rates by convection [ $C_{res}$ ] and evaporation [ $E_{res}$ ]) and dry heat exchange (for non-radiant environments, approximated by the difference between air [ $T_{db}$ ] and skin [ $T_{sk}$ ] temperatures divided by the resultant total insulation [ $I_{T,r}$ ]) (Belding and Kamon 1973; Kenney et al. 1993). These relationships are illustrated by Eqs. (1) and (2) (Kenney et al. 1993; Barker et al. 1999)

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

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

Equation (1) is true at the critical conditions of the progressive protocol. Recognizing that there were two unknowns ( $R_{e,T,a}$ ,  $I_{T,r}$ ), Kenney et al. (1993) proposed a method based on simultaneous equations at two critical conditions (i.e., warm, humid and hot, dry) to solve for both unknowns. Their method provided a means to relate

environmental and physiological measures at two critical conditions, and hence, the thermal characteristics could be determined. The underlying assumption of this method is the constancy of the clothing insulation and evaporative resistance at both conditions. The USF group (Barker et al. 1999) has taken the approach of estimating  $I_{T,r}$  and using that value to estimate  $R_{e,T,a}$  (called  $R_{e,T}$  in their paper), believing that estimating evaporative resistance is robust to estimates of clothing insulation. In this paper, values for  $R_{e,T,a}$  were determined from wear trials using the progressive heat stress protocol across five different ensembles.

## Methods

### Participants

Twenty-nine adults participated in the wear tests. The average and standard deviation of their physical characteristics by gender are provided in Table 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.

Participants were reminded of the need to maintain good hydration. On the day of a trial, they were asked not to drink caffeinated beverages 3 h 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  $165 \text{ W m}^{-2}$  in a climatic chamber at  $50^\circ\text{C}$  and 20% relative humidity (rh) for 2 h. Participants wore a base ensemble of shorts, tee-shirt (and/or sports bra for women), socks and shoes.

### Clothing

Five different clothing ensembles were evaluated. The ensembles included work clothes ( $135 \text{ g m}^{-2}$  cotton shirt and  $270 \text{ g m}^{-2}$  cotton pants), cotton coveralls ( $305 \text{ g m}^{-2}$ )

**Table 1** Physical characteristics (mean  $\pm$  standard deviation) of the participants

	Age (years)	Height (cm)	Weight (kg)	BSA ( $\text{m}^2$ )
Women ( $n = 9$ )	$28 \pm 8$	$163 \pm 7$	$63.7 \pm 16.6$	$1.74 \pm 0.29$
Men ( $n = 20$ )	$29 \pm 9$	$179 \pm 34$	$88.7 \pm 23.2$	$2.07 \pm 0.41$
Both ( $n = 29$ )	$29 \pm 8$	$174 \pm 12$	$80.9 \pm 20.2$	$1.97 \pm 0.28$

and three limited-use protective clothing ensembles: particle-barrier ensembles (Tyvek® 1424 for half the participants and Tyvek® 1427 for the other half, because each version represented the current manufacturing method at the time the trials were conducted), water-barrier, vapour-permeable ensembles (NexGen® LS 417), and vapour-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. 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  $0.5 \text{ m s}^{-1}$ . 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  $165 \text{ W m}^{-2}$ . Assessment 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 analyser was used to determine oxygen content of expired 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 min into a trial and expressed as the rate normalized to body surface area.

## Protocols

Each ensemble was worn by each participant at a moderate rate of work. The order of ensembles was randomised. Any trial that had to be repeated was repeated at the end of the schedule. Typically the dry bulb temperature ( $T_{db}$ ) was set at  $34^\circ\text{C}$  (but the starting point was adjusted lower for ensembles with suspected high evaporative resistance) and relative humidity (rh) at 50%. Once the participant reached thermal equilibrium (no change in  $T_{re}$  and heart rate for at least 15 min),  $T_{db}$  was increased  $0.8^\circ\text{C}$  every 5 min. During trials, participants were allowed to drink water or a commercial fluid replacement beverage (Gatorade®) at will.

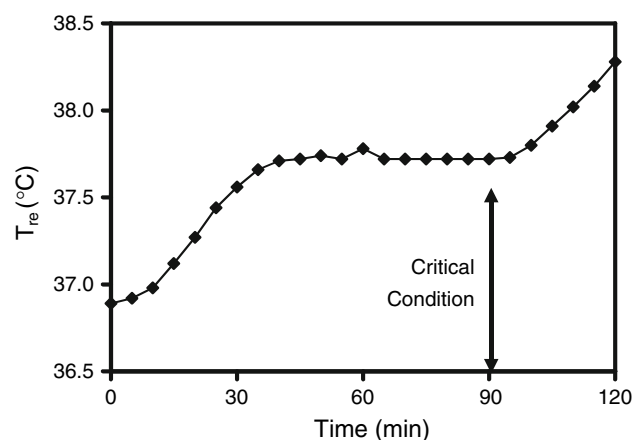
Core temperature, heart rate and ambient conditions (dry bulb, psychrometric wet bulb and globe temperatures;  $T_{db}$ ,  $T_{pwb}$  and  $T_g$ , respectively) were monitored continuously and recorded every 5 min. Trials were scheduled to last 120 min unless one of the following criteria was met: (1) a clear rise in rectal temperature ( $T_{re}$ ) associated with a loss of thermal equilibrium (typically  $0.1^\circ\text{C}$  increase per 5 min for 15 min), (2)  $T_{re}$  reached  $39^\circ\text{C}$ , (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 marks the transition from thermal balance to the loss of thermal balance, where core temperature continued to rise. Figure 1 illustrates core temperature versus time for one 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, and some of the decisions were randomly reviewed by a second investigator.

## Calculation of clothing parameters

$I_{T,stat}$  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 following is the process to compute derived values for each trial based on trial conditions for the participant and environment.



**Fig. 1** The time course of  $T_{re}$  for an example trial with an arrow to indicate the critical condition, the point 5 min prior to the steady increase in core temperature

The  $I_{T,r}$  was estimated according to ISO/FDIS 9920 (2007) (Eq. 32) as

$$\text{CFI} = \exp[-0.281(v - 0.15) + 0.044(v - 0.15)^2 - 0.492w + 0.176w^2] \quad (3a)$$

where air speed ( $v$ ) was taken as  $0.5 \text{ m s}^{-1}$  and walking speed ( $w$ ) was the treadmill speed ( $\text{m s}^{-1}$ ) for the specific trial. This adjustment for air and body movement was similar to that proposed by Holmer et al. (1999). The value of resultant clothing insulation was further reduced by 10% (multiplied by 0.9) to account for the reduction in insulation due to wetting (Brode et al. 2008)

$$I_{T,r} = \text{CFI} \cdot I_{T,\text{stat}} \cdot 0.9 \quad (3b)$$

Referring to Kenney et al. (1993), the measures in Eq. (2) were computed as follows. Metabolic rate ( $M$ ) in  $\text{W m}^{-2}$  was estimated from oxygen consumption in liters per minute as  $M = 350 V_{\text{O}_2}/A_{\text{D}}$ . The Dubois surface area ( $A_{\text{D}}$ ) was calculated for each subject as  $A_{\text{D}} = 0.202 m_{\text{b}}^{0.425} \cdot H^{0.725}$ , where  $m_{\text{b}}$  was the mass of the body (kg) and  $H$  was the height (m). The external work ( $W_{\text{ext}}$ ) was calculated ( $\text{W m}^{-2}$ ) as  $W_{\text{ext}} = 0.163 m_{\text{b}} \cdot V_{\text{W}} f_{\text{g}}/A_{\text{D}}$ , where  $V_{\text{W}}$  was walking velocity in m/min and  $f_{\text{g}}$  was the fractional grade of the treadmill. Respiratory exchanges, latent respiration heat loss ( $E_{\text{res}}$ ) and dry respiration heat loss ( $C_{\text{res}}$ ), were calculated as  $C_{\text{res}} = 0.0012 M (T_{\text{db}} - 34)$  and  $E_{\text{res}} = 0.0173 M (5.62 - P_{\text{a}})$ . Kenney et al. (1993) recognized that there may be some heat storage represented by a gradual change in  $T_{\text{re}}$ . To account for this, the rate of change in heat storage can be estimated knowing the specific heat of the body ( $0.97 \text{ W h } ^\circ\text{C}^{-1} \text{ kg}^{-1}$ ), body weight ( $m_{\text{b}}$ ), and the rate of change of body temperature ( $\Delta T_{\text{re}} \Delta t^{-1}$ ) as an average over the 20 min preceding the inflection point. That is,  $S = 0.97 m_{\text{b}} \Delta T_{\text{re}} A_{\text{D}}^{-1} \Delta t^{-1}$ . This approach was taken by Barker et al. (1999) with some changes in sign conventions employed in this paper.

The apparent total evaporative resistance ( $R_{\text{e},\text{T},\text{a}}$ ) was computed by rearranging Eq. (1) to

$$R_{\text{e},\text{T},\text{a}} = (P_{\text{a}} - P_{\text{sk}})/[H_{\text{net}} + (T_{\text{db}} - T_{\text{sk}})/I_{T,r}] \quad (4)$$

where  $P_{\text{sk}}$  was the saturation pressure of water vapour at  $T_{\text{sk}}$ .

For information purposes, the total static evaporative resistance ( $R_{\text{e},\text{T},\text{stat}}$ ) was back estimated following Havenith et al. (1999) and ISO/FDIS 9920 (2007) (Eq. 37).

$$\text{CFRe} = 0.3 - 0.5 \text{CFI} + 1.2 \text{CFI}^2 \quad (5a)$$

$$R_{\text{e},\text{T},\text{stat}} = R_{\text{e},\text{T},\text{a}}/\text{CFRe} \quad (5b)$$

The apparent and static permeability index ( $i_{\text{m}}$ ) were computed using Eq. (6) with resultant and static values for total insulation and total evaporative resistance and the Lewis Number ( $16.7^\circ\text{C kPa}^{-1}$ )

$$i_{\text{m}} = I_{\text{T}}/16.7R_{\text{e},\text{T}} \quad (6)$$

## Results

Table 2 summarizes the critical conditions and selected physiological data by ensemble. Both the ambient air temperature and vapour pressure at the critical conditions decrease with clothing ensembles suspected of higher evaporative resistances. Physiological data remain consistent across ensembles.

The mean values with standard deviations for the derived clothing characteristics are provided in Table 3. To examine the derived clothing characteristics for evaporative cooling, a mixed linear model was used where the main treatment effect was ensemble and participants were treated as a random factor. In all cases, there was a significant difference among ensembles. To determine where the differences occurred, multiple  $t$  tests were used. For  $R_{\text{e},\text{T},\text{a}}$ ,  $R_{\text{e},\text{T},\text{stat}}$ ,  $i_{\text{m},\text{a}}$  and  $i_{\text{m},\text{stat}}$  there were no differences among Cotton Coveralls, Work Clothes, Tyvek 1427 and Tyvek 1424 followed by NexGen and Tychem, both of which were different from all others. The exception was  $i_{\text{m},\text{a}}$  for Cotton Coveralls, which had the highest permeability index and was different from the others except Tyvek 1427.

## Discussion

The change in dry bulb temperature and vapour pressure at the critical conditions was a direct consequence of the ability of the clothing to allow thermal equilibrium at the upper limits of compensable heat stress. The relative relationships among the ensembles were expected based on previous reports on WBGT at the critical conditions (Bernard et al. 2008). The lack of differentiation among the ensembles for the physiological measures was noted and reported elsewhere (Ashley et al. 2008).

The first step in the current study was to estimate the total resultant insulation from the static values of a manikin test. Using the method of ISO/FDIS 9920 (2007), the typical reduction was about 35% (all but one value were between 34 and 36%). The reason for this was the relative insensitivity of the reduction factor (CFI) at walking speeds greater than  $0.75 \text{ m s}^{-1}$ . While half the walking speeds (mean  $\pm$  sd was  $1.20 \pm 0.13 \text{ m s}^{-1}$ ) were greater than the range for which the CFI was developed ( $1.2 \text{ m s}^{-1}$ ), the higher walking speeds would not be expected to play much of a role because of the insensitivity.

Resultant clothing insulation estimated from the ISO method was further reduced by 10% to account for wetting of the clothes. This was in the range reported by Brode

**Table 2** Critical conditions (critical dry bulb temperature and critical ambient water vapour pressure) and the physiological data at the critical conditions

Clothing ensemble	$T_{db, crit}$ (°C)	$P_{a, crit}$ (kPa)	$T_{re}$ (°C)	HR (bpm)	$T_{sk}$ (°C)	$P_{sk, crit}$ (kPa)
Work clothes	41.7 ± 1.8	3.64 ± 0.31	37.7 ± 0.7	117 ± 16	36.3 ± 0.5	6.05 ± 0.16
Cotton coveralls	42.1 ± 1.8	3.73 ± 0.38	37.7 ± 0.3	115 ± 15	36.3 ± 0.6	6.05 ± 0.19
Tyvek® 1424 Coveralls	42.0 ± 1.9	3.42 ± 0.42	37.8 ± 0.3	115 ± 12	36.5 ± 0.5	6.10 ± 0.18
Tyvek® 1427 Coveralls	41.2 ± 1.5	3.51 ± 0.31	37.8 ± 0.3	117 ± 17	36.2 ± 0.6	5.99 ± 0.20
NexGen® Coveralls	39.3 ± 1.8	3.25 ± 0.45	37.7 ± 0.3	115 ± 15	36.2 ± 0.5	6.02 ± 0.18
Tychem QC® Coveralls	33.1 ± 2.1	2.36 ± 0.33	37.8 ± 0.3	117 ± 20	36.3 ± 0.8	6.03 ± 0.25

**Table 3** Clothing ensembles, total static clothing insulation, derived values (mean ± sd) of resultant total insulation, apparent and static total evaporative resistance, and apparent and static total vapour permeability index

Clothing ensemble	$I_{T,stat}^a$ (m <sup>2</sup> °C W <sup>-1</sup> )	$I_{T,r}$ (m <sup>2</sup> °C W <sup>-1</sup> )	$R_{e,T,a}^b$ (m <sup>2</sup> kPa W <sup>-1</sup> )	$R_{e,T,stat}^b$ (m <sup>2</sup> kPa W <sup>-1</sup> )	$i_{m,a}^b$ (-)	$i_{m,stat}^b$ (-)
Work clothes	0.180	0.118 ± 0.004	0.013 <sup>a</sup> ± 0.003	0.028 <sup>a</sup> ± 0.006	0.56 <sup>a,b</sup> ± 0.14	0.41 <sup>a</sup> ± 0.10
Cotton coveralls	0.196	0.128 ± 0.001	0.013 <sup>a</sup> ± 0.003	0.027 <sup>a</sup> ± 0.006	0.63 <sup>b</sup> ± 0.15	0.47 <sup>b</sup> ± 0.12
Tyvek® 1427 Coveralls	0.190	0.124 ± 0.001	0.013 <sup>a</sup> ± 0.002	0.026 <sup>a</sup> ± 0.004	0.54 <sup>a,b</sup> ± 0.10	0.45 <sup>a,b</sup> ± 0.09
Tyvek® 1424 Coveralls	0.190	0.125 ± 0.001	0.015 <sup>a</sup> ± 0.004	0.031 <sup>a</sup> ± 0.009	0.49 <sup>a</sup> ± 0.13	0.40 <sup>a</sup> ± 0.11
NexGen® Coveralls	0.189	0.123 ± 0.001	0.018 ± 0.005	0.036 ± 0.010	0.45 ± 0.12	0.33 ± 0.09
Tychem QC® Coveralls	0.185	0.121 ± 0.001	0.032 ± 0.007	0.066 ± 0.013	0.24 ± 0.05	0.17 ± 0.04

<sup>a</sup> Fixed value from manikin trials

<sup>b</sup> Values with the same letter in a column are not statistically different by multiple *t* tests at  $\alpha = 0.05$

et al. (2008) (up to 9%). Kenney et al. (1993) used two critical conditions at warm, humid and hot, dry environments to solve for the two unknowns in Eq. (1). In this way, they included the effects of wet clothing as well as other factors that may influence the observed heat transfer characteristics of clothing (Havenith et al. 2008). In reporting values for work clothes (military BDU), they found a total resultant insulation of 0.09 m<sup>2</sup> °C W<sup>-1</sup> as compared to 0.12 m<sup>2</sup> °C W<sup>-1</sup> for the current study. Similarly for vapour barrier, they reported 0.14 m<sup>2</sup> °C W<sup>-1</sup>, which was somewhat higher than the current study (0.12 m<sup>2</sup> °C W<sup>-1</sup>), although a lower value would be expected because the current study did not use a hood. Because the values were similar and considering that Barker et al. (1999) argued that the effect of clothing insulation on the estimation of evaporative resistance near the critical environmental conditions was small, the process for setting a value for resultant insulation using ISO 9920 and a further 10% reduction was reasonable.

The apparent total evaporative resistances reported in Table 3 were influenced by the errors inherent in Eqs. (1)–(3a, 3b) and thus Eq. (4). Equation (1) depends on the precision of knowing the environmental conditions, which was good, and the estimation of mean skin temperature which has a significant influence on the estimation of water

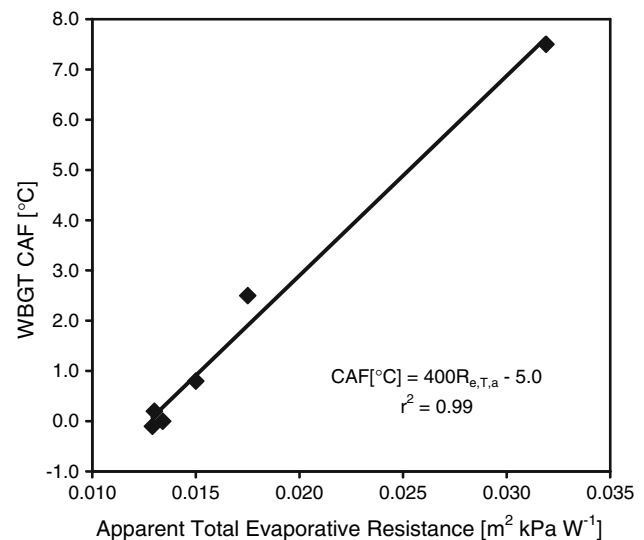
vapour pressure on the skin. The errors in Eq. (2) were dominated by the estimation of metabolic rate by oxygen consumption with some error in the estimation of respiratory heat exchange and the presumption of no external work when the treadmill was set a zero slope (the case for most trials). Some additional error was added by estimating the resultant insulation from empirically derived relationships (Eq. 3a, 3b). Further, pathways for heat exchange involving mass transfer were lumped into evaporative cooling. The back estimation of static total evaporative cooling has the additional error associated with the empirical relationship used (Eq. 5a, 5b).

In the current study, the apparent total evaporative resistance for Work Clothes was 0.014 m<sup>2</sup> kPa W<sup>-1</sup>. This compares well with the value of 0.013 m<sup>2</sup> kPa W<sup>-1</sup> of Barker et al. (1999) and the value of 0.016 m<sup>2</sup> kPa W<sup>-1</sup> found by Kenney et al. (1993). The values for Tyvek in the current study were 0.015 and 0.013 m<sup>2</sup> kPa W<sup>-1</sup> while the value of about 0.017 m<sup>2</sup> kPa W<sup>-1</sup> in Barker et al. (1999) was higher. The lower values were probably due to the change in the Tyvek formulation from 1422A to 1424, which evolved from Nonwoven Prototypes C and D to 0.013 (Barker et al. 1999), and 1427. Further, there was some evidence of lower heat stress associated with the newer versions of Tyvek with lower WBGT adjustments

(O'Connor and Bernard 1999 vs. Bernard et al. 2005). For the vapour barrier ensemble, the apparent total evaporative resistance was  $0.032 \text{ m}^2 \text{ kPa W}^{-1}$  and Kenney et al. (1993) reported  $0.038 \text{ m}^2 \text{ kPa W}^{-1}$  for a two piece ensemble over military fatigues. While the evaporative resistances were supported by other values reported in the literature, caution must be used for vapour permeable water barriers. NexGen in a coverall configuration had an apparent total evaporative resistance of  $0.018 \text{ m}^2 \text{ kPa W}^{-1}$ , which is different from the  $0.014$  to  $0.026 \text{ m}^2 \text{ kPa W}^{-1}$  reported by Barker et al. (1999) for three prototype garments had similar construction with hoods. From the Barker et al. paper, it is possible that different films have different evaporative resistances.

Using the ISO 9920 (2007) method for adjusting evaporative resistance (see Eq. 5a, 5b), the resultant resistance was used to back-estimate a total static evaporative resistance. The results are provided in Table 3. Work Clothes had a value of  $0.028 \text{ m}^2 \text{ kPa W}^{-1}$  in the current study as compared to the ISO 9920 Appendix C.2 and C.3 Ensemble 3 (Men's Casual, short sleeve shirt) of  $0.027$ . Looking at the permeability index in Table 2, the apparent values were higher than the static values and this was expected. Referring back to ISO 9920 (2007), Appendix C.1 suggested a value of  $0.38$  for normal clothing, which compares well to the value of  $0.41$  for Work Clothes in Table 2. The back calculation to static values should be viewed with some care because the basis is an experimentally estimated (apparent) value and the ISO method does not account for heat transfer mechanisms that may be present. The static values in Table 2 were provided for reference if needed by others in future work.

A principal advantage of the progressive protocol method is no requirement to measure sweat evaporation which has some error associated with the inclusion of non-steady state sweat rate and measurement error. An assumption of the method is that the skin is fully wetted, which is not difficult to achieve with clothing typical of most workplaces. A disadvantage of the method is that it is limited to a narrow range of heat stress conditions; that is, those conditions around the critical environment for the combination of clothing and metabolic rate. Specifically for the 50% relative humidity variation of the protocol, the pressure gradient for water vapour must increase with evaporative resistance to reach the upper limit of thermal balance. The method cannot be used to demonstrate the constancy of evaporative resistance in other environments, especially for neutral or cold where wetting the clothes may not be significant. Further, the progressive protocol in wear trials lumps several pathways for heat exchange. For this reason, the apparent total evaporative resistance may include among others the effects condensation and re-evaporation of water in the clothing (Havenith et al. 2008).



**Fig. 2** Relationship between apparent total evaporative resistance and WBGT-based clothing adjustment factors (CAFs)

Bernard et al. (2008) have reported WBGT clothing adjustment factors (CAFs) for the same experiments reported here. As the clothing adjustment factor increases, it is reasonable to believe that there would be a reduction in the total resultant evaporative resistance. To examine the relationship, the data were plotted as shown in Fig. 2. There appears to be a linear relationship for the 50% relative humidity conditions in the current study. The WBGT is heavily influenced by the ability of the environment to support evaporative cooling of the natural wet bulb. The apparent evaporative resistance is also a measure of how well evaporative cooling is supported. In this way, the strong relationship between CAF and apparent evaporative resistance is not surprising. The absence of data between the vapour-barrier at the high end and the other ensembles near the low end does not preclude a non-linear relationship. Further, the clothing adjustment factor for vapour-barrier clothing changes with the relative humidity (decreases from 20 to 70% rh) (Bernard et al. 2005), but not for the other ensembles. This actually means that there may be a family of lines with different slopes depending on the relative humidity that pivot around the data at the lower end. Therefore some caution is needed in using this relationship to generalize the data available.

The standard deviations for the resultant evaporative resistances in the current study ranged from  $0.003$  to  $0.007 \text{ kPa m}^2 \text{ W}^{-1}$ ; and the standard error of the mean for 29 subjects would be  $0.001$ . Barker et al. (1999) also reported standard error of the mean around  $0.001 \text{ kPa m}^2 \text{ W}^{-1}$  following the same protocol. For comparison, Kenney et al. (1993) reported standard errors of the mean of  $0.001$ ,  $0.003$  and  $0.007 \text{ kPa m}^2 \text{ W}^{-1}$  for three different ensembles using the simultaneous equations method over

six trials. Although the values for Kenney et al. (1993) were somewhat higher using the simultaneous equations, the three studies suggest similar levels of confidence in the mean values. Using a one-way analysis of variance based on ensembles, the root mean square of the error (standard deviation) was estimated, which included the random effect of subjects as well as other experimental factors. For the 150 observations over five ensembles in the current study, the degrees of freedom of the error term was 145 and the standard deviation was  $0.0044 \text{ kPa m}^2 \text{ W}^{-1}$  with a 95% confidence interval of  $0.0040\text{--}0.0050 \text{ kPa m}^2 \text{ W}^{-1}$  or about  $\pm 10\%$ . Based on the upper limit of the standard error, the resolution of the mean value for estimations of total evaporative resistance following the single point progressive protocol is less than 0.005 with a sample size of 4, drops to 0.003 with  $n = 11$ , and does not get much better than 0.002 with large sample sizes (greater than 23).

## Conclusions

The progressive heat stress protocol is considered a useful method to estimate the apparent total evaporative resistance, which does not rely on the direct determination of sweat rate. The results indicate that there was no significant difference among single layer configurations with the base ensemble (e.g., tee shirt and shorts plus socks and shoes) of work clothes, cloth coveralls and Tyvek coveralls. There were significant increases in evaporative resistance for a specific vapour-permeable water-barrier coverall (NexGen) and for a vapour-barrier coverall.

Under the current test conditions, specifically a progressive heat stress protocol at 50% relative humidity, there appears to be a linear relationship between apparent total evaporative resistance and WBGT CAFs, also developed from the same protocol. The relationship may break down at different relative humidity's when the evaporative resistance is high (above  $0.02 \text{ kPa m}^2 \text{ W}^{-1}$ ); and this requires further investigation. The large study also allowed for a good estimate of the standard error for the progressive protocol method of determining total resultant evaporative resistance, which is  $0.0044 \text{ kPa m}^2 \text{ W}^{-1}$ .

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