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Clothing ventilation air exchange can be deduced from energy balance results of clothing insulation studies on dry and sweating thermal manikins over a range of air speeds. This paper demonstrates that energy balances at the skin of the clothed dry heated manikin operating in a 20°C 50% RH environment can determine the energy carried away by ventilation air. The volume flow rates are calculated assuming intrinsic insulation is unchanged by air speed and that the ventilation air leaves the clothing system at skin temperature. Similarly energy balances on the clothed sweating manikin operating in a 35°C 50%RH environment (air temperature= skin temperature) can determine the latent energy carried away by the ventilation air assuming the ventilation air leaves saturated. Clothing ventilation rate estimates at three air speeds determined on the dry and sweating manikin are compared. Demonstration is conducted on military clothing with and without body armour and on fuel handler's protective coverall.

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Clothing Ventilation Estimates from Manikin Measurements

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Abstract

Clothing ventilation air exchange can be deduced from energy balance results of clothing insulation studies on dry and sweating thermal manikins over a range of air speeds. This paper demonstrates that energy balances at the skin of the clothed dry heated manikin operating in a 20°C 50% RH environment can determine the energy carried away by ventilation air. The volume flow rates are calculated assuming intrinsic insulation is unchanged by air speed and that the ventilation air leaves the clothing system at skin temperature. Similarly energy balances on the clothed sweating manikin operating in a 35°C 50%RH environment (air temperature=skin temperature) can determine the latent energy carried away by the ventilation air assuming the ventilation air leaves saturated. Clothing ventilation rate estimates at three air speeds determined on the dry and sweating manikin are compared. Demonstration is conducted on military clothing with and without body armour and on fuel handler's protective coverall.

Introduction

The quantification of clothing ventilation is useful for estimating the dose of air-born contaminates contacting the skin, for estimating the effects on fabric and skin moisture mechanisms and for other exposure and thermal issues of clothing design and its application. Clothing ventilation air exchange is often measured by tracer gas methods[4,5] but clothing air exchange can also be estimated from the energy balance results of clothing insulation measurements[2,3] routinely done on dry and sweating thermal manikins.

Partitioned energy balances at the skin of a clothed dry heated manikin, operating at steady state conditions at several winds speeds, can determine the energy (qvent) carried away by ventilation air as shown in Figure 1. In the figure, qskin represents the power input to maintain the manikin's skin temperature (Tsk) in steady state environmental conditions of air (Ta) and radiant (Tr) temperature, humidity (RH) and wind speed (V), qcl is the energy flow through the clothing and its boundary layer resistance.

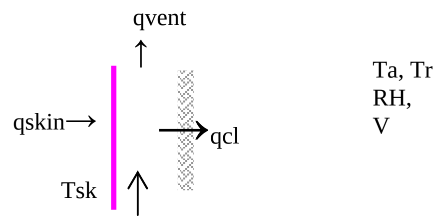

Figure 1 Schematic of energy flow paths from the thermal the manikin skin

The energy flows depicted in Figure 1 are applicable to dry and sweating manikin operations. For dry manikin skin conditions, the ventilation air is assumed to leave the clothing with a temperature equal to Tsk. For sweating manikin conditions, the ventilation air is assumed to be saturated air at Tsk. The ventilation analysis described here requires measurements over a series of different wind speeds including a low speed (V=vo) where the ventilation is assumed to be zero. Also the analysis assumes the clothing's dry thermal resistance (Rcl) and vapour resistance (Rclp) to be unaffected by wind speed and have values evaluated at the low speed where ventilation is assumed zero. To demonstrate the ventilation estimation process, calculations were done on previous measurements on a static stationary sweating thermal manikin wearing: 1) a battle dress uniform (BDU) consisting of trousers, t-shirt and long sleeved shirt worn outside of the trousers, 2) a BDU plus body armour (BDU+ armour) and 3) a fuel handlers protective coverall over shorts and a t-shirt (FPC).

Methods

Dry Manikin

Measurements were made in a climate chamber at 20°C and 50%RH with the manikin skin dry and its skin temperature (Tsk) maintained at 35 °C. The measurements were made following the procedures of ASTM F1291[2] at 3 horizontal wind speeds, with the manikin facing into the wind. Assuming the ventilation air leaves at skin temperature, the mass and volume flow rates can be calculated from the following energy balance.

$$\text{qvent} = \text{qskin} - \text{qcl} \tag{1}$$

where

$$\text{qcl} = (\text{Tsk}-\text{Ta})/(\text{Rcl}+\text{Rb}) \tag{2}$$

and

$$Rb = 1/(fcl \bullet (hr+hc)) \quad (3)$$

Where Rb is the boundary layer resistance between the clothing's outer surface and the ambient, hr and hc are heat transfer coefficients for radiation and convection, respectively[1] . The clothing surface area relative to the manikin's skin area (fcl) effective for heat transfer was estimated from an iterative process[1] at V=vo. At V=vo, where no ventilation is assumed, Rcl is evaluated as Rcl=Rclt – Rb, where Rclt is the total thermal resistance from skin to ambient calculated from manikin data. Rcl is assumed to be unchanged at higher wind speeds.

Then, in terms of ventilation air (Vent) flowing under the clothing next to the skin:

$$qvent = Vent \bullet cpa \bullet (Tsk-Ta)/ \nu \quad (4)$$

where Vent is the flow of ventilation air, cpa is the specific heat of air (j/(g C)) and ν is the specific volume of air (L/g). The Vent calculations for the dry manikin wearing the BDU is summarized in Table 1.

Wind m/s	qskin w/m^2	Rclt Cm^2/w	hc w/m^2	hr w/m^2	fcl	Rcl_vo Cm^2/w	Rclt Cm^2/w	qcl w/m^2	qvent Cm^2/w	Vent L/(s m^2)
0.42	76.4	0.196	5.45	4.47	1.22	0.114	0.196	76.4	0	0
1.26	98	0.151	9.82	4.47	1.22	0.114	0.171	87.7	10.3	0.77
2.1	114	0.132	12.89	4.47	1.22	0.114	0.161	93.2	20.8	1.56

Table 1: Summary of ventilation estimate calculations for BDU clothing on dry manikin

Sweating Manikin

Similarly energy balances at the skin under the clothed sweating manikin operating in a 35C 50%RH environment (Ta=Tsk) can determine the latent energy carried away by the ventilation air. Assuming the skin of the manikin is 100% wet and that the ventilation air leaves saturated, the mass and volume flow rates can be determined. The measurements made in compliance with ASTM F2370[3] were at chamber conditions of Ta=Tr=35°C, 50%RH, and three wind speeds. The sweating energy balances are similar to the dry manikin equations 1, 2 and 3 except vapour resistances (Rclp, Rbp) and torr terms replace thermal resistances (Rcl, Rb) and °C and qskin and qcl are followed by a p.

$$qvent = qskinp - qclp \quad (5)$$

where

$$qclp = (Psk-Pa)/(Rclp+Rbp) \quad (6)$$

and

$$Rbp = 1/(fcl \bullet he) \quad (7)$$

where the evaporative heat loss coefficient (he) equals LR*hc[1] and the Lewis ratio LR = 2.2 °C/torr. As in the estimate for a dry manikin, at v=vo, where no ventilation is assumed, Rclp is evaluated as Rclp = Rcltp – Rbp. Rcltp is the total parallel vapour resistance from skin to ambient and Rclp is assumed to be unchanged at higher wind speeds.

The ventilation air (Vent) flowing under the clothing next to the skin is calculated:

$$qvent = Vent \bullet hfg \bullet (Wsk-Wa)/ \nu \quad (8)$$

where hfg is the latent heat of vaporization and Wsk and Wa are humidity ratios of ventilation air. A summary of the Vent calculations for a 100% wet sweating thermal manikin wearing the same BDU is summarized in Table 2.

V	qskinp	Psk	Pa	Rcltp	he	Rclp_vo	Rcltp	qclp	qvent	Vent
m/s	w/m^2	torr	torr	torr m^2/w	w/(torr m^2)	(torr m^2)/w	(torr m^2)/w	w/m^2	w/m^2	L/(s m^2)
0.36	107	42.2	21.2	0.196	10.65	0.123	0.196	107	0	0
1.15	148.3	42.2	21.4	0.14	19.62	0.123	0.163	127.5	20.8	0.41
1.94	179.9	42.2	21.6	0.115	25.9	0.123	0.153	134.5	45.4	0.89

Table 2: Summary of ventilation estimate calculations for BDU clothing on sweating manikin

Results

Clothing ventilation rates (L/(s m^2)) at 3 air speeds from energy balances on the dry manikin and those found from latent energy balances on the sweating manikin are displayed in Figures 2, 3 and 4 for the BDU, BDU+ armour, and fuel handlers protective clothing respectively.

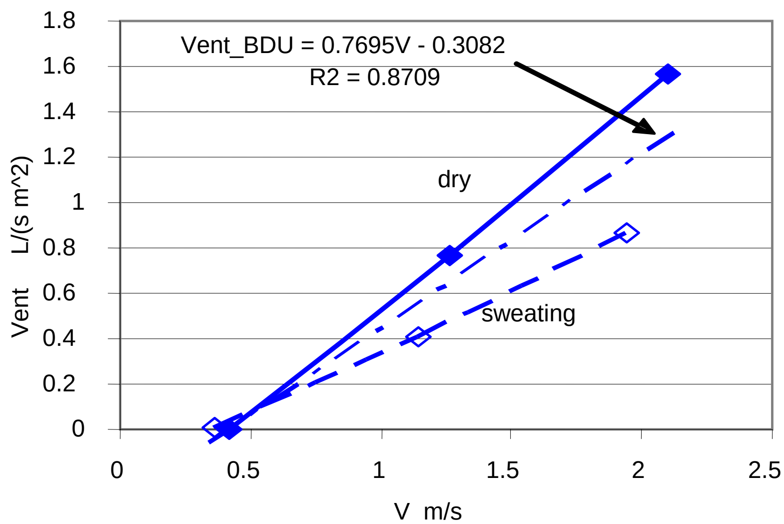

Figure 2 Ventilation estimates (Vent) for BDU (long sleeved shirt, t-shirt and trousers) at several wind speeds (V)

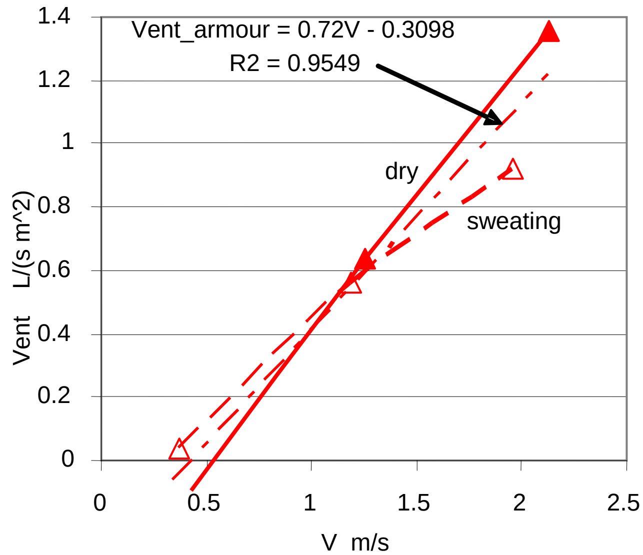

Figure 3 Ventilation estimates for BDU plus body armour

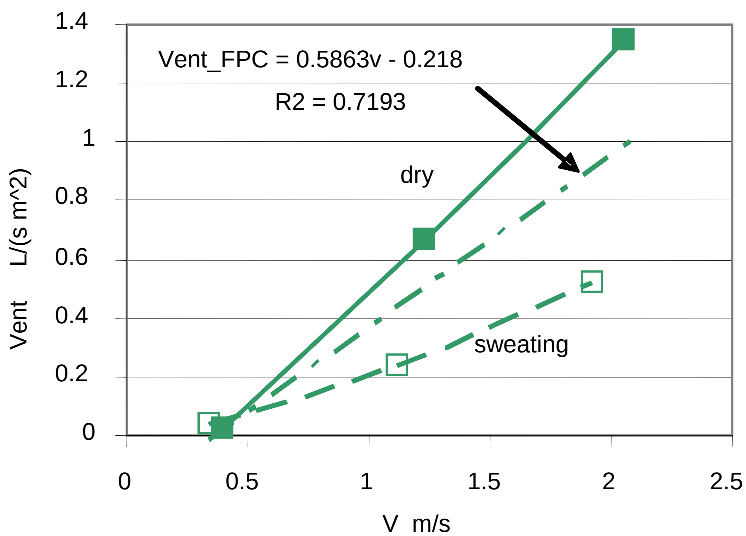

Figure 4 Ventilation estimates for fuel handler's protective clothing.

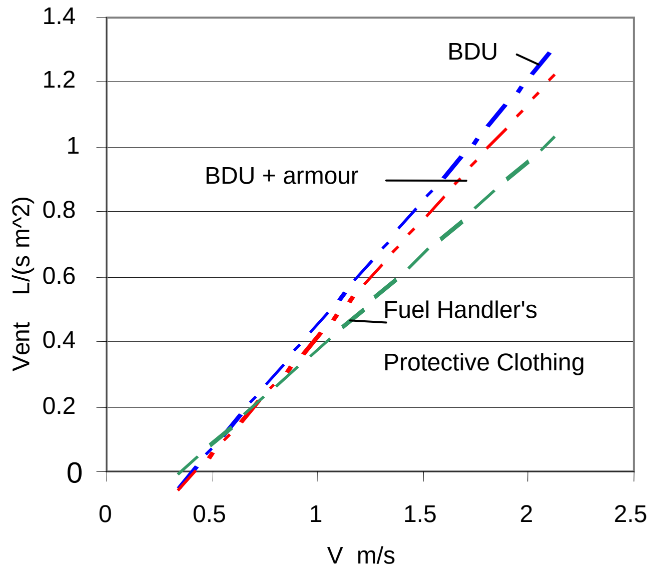

Figure 5: Comparison of regression results through ventilation estimates of BDU, BDU+ armour and fuel handlers' protective coverall over -shirt and shorts

Discussion and Conclusions

The estimates of clothing ventilation developed from dry and sweating manikin clothing insulation test data for three different clothing systems increased consistently with wind speed. The ventilation estimated from the dry manikin data was generally greater than the ventilation estimated from the sweating manikin data. The comparison of regression results for the three clothing systems in Fig 5 shows the ventilation decreased when heavy body armour was added and decreased further for the fuel handler's protective clothing. The fuel handler's protective clothing is similar to chem-bio clothing but made from water vapour semi-permeable fabric.

The energy balance ventilation estimates are a straight forward calculation procedure on manikin clothing insulation test data and the data may already exist as in this study. The ventilation estimates are useful to compare clothing systems ventilation capabilities. The estimates as done here depend on a number of assumptions, such as ventilation air leaving in equilibrium with skin temperatures and vapour pressure, no ventilation at the low wind speed (vo) and unchanging intrinsic clothing insulation (Rcl and Rclp) with wind speed. As a result of the assumptions, the energy balance method may underestimate the ventilation found by tracer gas techniques. However, clothing ventilation can be repeatably estimated from energy balances using the data from standard clothing insulation measurement tests. The ventilation estimates found are useful to compare ventilation capabilities of clothing systems and may be useful for design and application.

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