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The thermal insulation difference of clothing ensembles on the dry and perspiration manikins

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Abstract
There are about a hundred manikin users around the world. Some of them use the manikin such as 'Walter' and 'Tore' to evaluate the comfort of clothing ensembles according to their thermal insulation and moisture resistance. A 'Walter' manikin is made of water and waterproof breathable fabric 'skin', which simulates the characteristics of human perspiration. So evaporation, condensation or sorption and desorption are always accompanied by heat transfer. A 'Tore' manikin only has dry heat exchange by conduction, radiation and convection from the manikin through clothing ensembles to environments. It is an ideal apparatus to measure the thermal insulation of the clothing ensemble and allows evaluation of thermal comfort. This paper compares thermal insulation measured with dry 'Tore' and sweating 'Walter' manikins. Clothing ensembles consisted of permeable and impermeable clothes. The results showed that the clothes covering the 'Walter' manikin absorbed the moisture evaporated from the manikin. When the moisture transferred through the permeable clothing ensembles, heat of condensation could be neglected. But it was observed that heavy condensation occurred if impermeable clothes were tested on the 'Walter' manikin. This resulted in a thermal insulation difference of clothing ensembles on the dry and perspiration manikins. The thermal insulation obtained from the 'Walter' manikin has to be modified when heavy condensation occurs. The modified equation is obtained in this study.

Keywords: thermal insulation, manikins, condensation, impermeable clothing

1. Introduction

It was estimated that there are about a hundred thermal manikin users around the world. Some of them use a manikin to evaluate the comfort of clothing ensembles according to their thermal insulation and evaporative resistance. There have been many discussions about the thermal insulation difference of clothing ensembles on different manikins, especially when the sweating manikin 'Walter' (Fan and Chen 2002) was developed in 2002. Shen *et al* (2003) compared the garment thermal insulation on two dry manikins and Gao *et al* (2006) compared protective clothing on the dry and perspiration manikins.

It was noticed that condensation occurs if heavy or impermeable clothes are tested on 'Walter'. In fact the clothes covering 'Walter' absorb the moisture evaporated from the manikin. Actually, moisture collection in cloth can be regarded as water diffusion to textile material. It influences the heat transfer of the clothing assemblies. Fan *et al* (2000) found that the effective thermal conductivity of pore fibres' batting such as wool and polypropylene is related to the water content. Li and Holcombe (1998) also used the relationship between heat conduction rate and moisture retention of cotton and wool in their model. Havenith *et al* (2008) employed the 'Newton' manikin to find that, when evaporative heat loss from a clothed person is determined from his/her weight change, substantial errors, which can result in overestimations of evaporative heat loss, may be made. It depends on the climate and clothing type, especially in cold climate and for clothing with low permeability. Wissler and Havenith (2009) analysed heat and vapour transport when condensation occurs within a garment. They developed a rather simple technique to prevent large errors in heat assessment caused by neglecting condensation in clothing. Gao and Holmer (2006) measured moisture gain inside hygroscopic underwear, and hydrophobic and permeable outer wear as a function of time, to investigate mass loss from 'skin' on the 'Tore' manikin, as well as quantify evaporative heat loss and total heat loss from the manikin and to determine evaporative resistance of clothing. To compare the garment thermal insulation on dry and perspiration manikins it is necessary to know the quantity of moisture in the clothing piece on 'Walter'.

(*a*) (*b*)

Figure 1. The manikins used in the experiment.

2. Methods

2.1. Manikins

The thermal 'Tore' manikin (Hänel 1983, Kuklane *et al* 2006) is the ideal apparatus to measure thermal insulation of a clothing ensemble and it allows evaluation of thermal comfort. Dry heat exchange by conduction, radiation and convection exists among the manikin, clothing ensemble and environment.

As another technique, the 'Walter' manikin (Fan and Chen 2002) is used for measuring and providing results of two key clothing parameters, which are thermal insulation and moisture vapour resistance, in a single step. This fabric manikin is made of water and waterproof breathable fabric 'skin', which simulates the characteristics of human perspiration. So evaporation, condensation or sorption and desorption are always accompanied by heat transfer.

2.2. Samples

Test samples included three T-shirts and two pairs of trousers. The T-shirts were made of different textile materials: cotton, moisture management fibre (Moisture M) and thermal fibre. They had the same yarn count (32S) and fabric structure (Jersey). They weighed about 120 g. The moisture management fibre and thermal fibre are modifications of PET (polyethylene terephthalate). The moisture management fibre is a new kind of fibre with honeycomb paths and these paths run through from inside to outside. The thermal fibre also has honeycomb-like structure with many small holes inside. One pair of trousers was jute (J) jeans weighing 480 g and the other pair was tight wool (W) pants weighing 190 g. Another sample was an impermeable coverall (IM, polyamide coated by PVC). Its weight was 700 g.

2.3. Test conditions and the experimental details

The 'Tore' manikin with an impermeable coverall is described in figure 1(*a*). The 'Walter' manikin is covered by a T-shirt and a pair of trousers as shown in figure 1(*b*). All tests were conducted at the ambient air temperature of 20 ± 0.5 °C and the relative humidity of 65% ± 5 %. The wind velocity was set at 0.16 m s^{-1} measured behind the 'Tore' manikin. It was set to 0.13 m s^{-1} in front of the 'Walter' manikin.

The experimental data on the manikins together with results are listed in table 1. In the experiments, all the skin temperatures of the 'Tore' manikin were kept at 34 °C. Each experiment took 20 min and the system recorded data every 20 s. It was repeated twice. The core temperature of the 'Walter' manikin was set at 37 °C. The system also records data every 20 s and displays measurement data in an hour. The average values of three measurements are listed in table 1, and the coefficient of variation is less than 5%.

The thermal 'Tore' manikin is made of metal and plastic and divided into 17 zones. According to the parallel model (ISO 2003), the total thermal insulation on the 'Tore' manikin is calculated based on the test results, using the formula

$$R_t = \frac{(T_s - T_a) \times A}{H} \ (\mathrm{m^2\,K\,W^{-1}}), \tag{1}$$

where

$$T_s = \sum_{i=1}^{17} \frac{A_i}{A} \times T_{si} \quad (^\circ\mathrm{C}),$$

$$H = \sum_{i=1}^{17} H_i \ (\mathrm{W}).$$

According to the evaporation heat of water being 0.672 W h g^{-1} at 35 °C, the total thermal insulation on the 'Walter' manikin can be calculated based on the test results using the formula

$$R_t = \frac{(T_s - T_a) \times A}{H - E \times Q} \ (\mathrm{m^2\,K\,W^{-1}}), \tag{2}$$

where

$$H = H_e + H_d$$

$$H_e = E \times Q \ (\mathrm{W}).$$

The total surface areas (A) of Tore and Walter are 1.774 m^2 and 1.79 m^2, respectively.

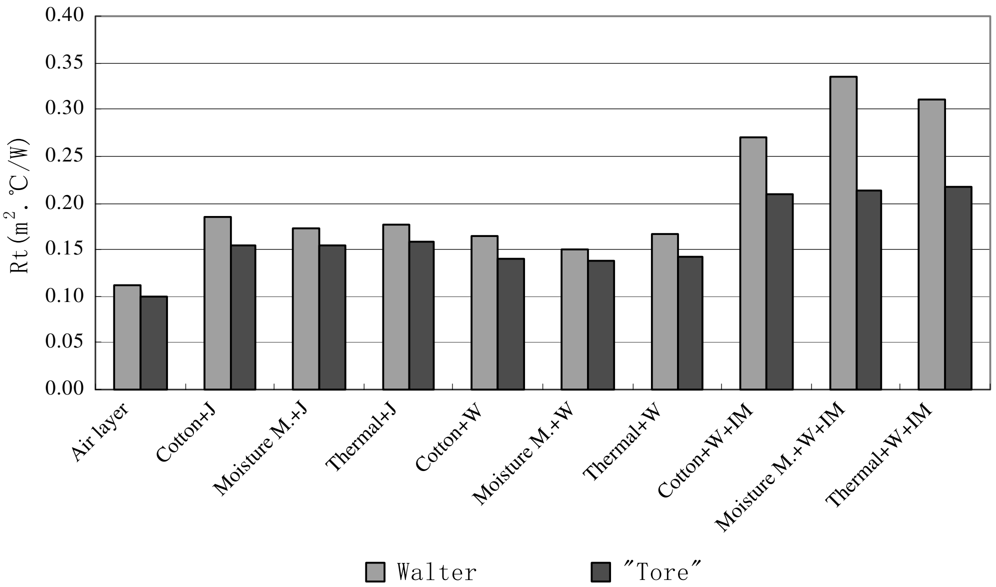

Figure 2. The thermal insulations measured on two manikins.

Table 1. The experimental data on the manikins.

Manikin	Cover on skin	Air velocity (m s^{-1})	T_i (°C)	T_c (°C)	T_s (°C)	T_a (°C)	RH$_e$ (%)	H (W)	Q (g h^{-1})	R_t (K m^2 W^{-1})	H_e (W)	H_d (W)	H_d/H (%)	Q_c (g h^{-1})
Tore	Air layer	0.16	–	–	34	19.9	65	250.5	–	0.101	–	250.5	100	–
	Cotton+J	0.16	–	-	34	20.2	65	160	–	0.154	–	160	100	–
	Moisture M.+J	0.16	–	–	34	20.3	65	158.5	–	0.154	–	158.5	100	–
	Thermal+J	0.16	–	–	34	20.2	65	154.5	–	0.158	–	154.5	100	–
	Cotton+W	0.16	–	–	34	19.9	65	178.0	–	0.141	–	178.0	100	–
	Moisture M.+W	0.16	–	–	34	19.9	65	179.0	–	0.139	–	179.00	100	–
	Thermal+W	0.16	–	–	34	20.0	65	175.5	–	0.142	–	175.50	100	–
	Cotton+IM	0.16	–	–	34	20.1	65	117.0	–	0.210	–	117.00	100	–
	Moisture M.+IM	0.16	–	–	34	20.0	65	115.5	–	0.214	–	115.50	100	–
	Thermal+IM	0.16	–	–	34	20.2	65	113.0	–	0.217	–	113.00	100	–
Walter	Air layer	0.13	37	37.0	33.2	20.4	67.5	490.9	413.5	0.111	277.8	213.0	43.4	–
	Cotton+J	0.13	37	37.0	34.4	20.1	66.9	342.3	296.3	0.186	199.1	143.2	41.8	3.2
	Moisture M.+J	0.13	37	37.0	34.2	20.2	66.7	347.4	295.0	0.174	198.2	149.2	42.9	2.6
	Thermal+J	0.13	37	37.0	34.4	20.2	66.3	345.5	292.0	0.176	196.2	149.3	43.2	2.5
	Cotton+W	0.13	37	37.0	34.2	20.4	66.3	383.4	338.5	0.165	227.5	155.9	40.7	2.6
	Moisture M.+W	0.13	37	37.0	34.0	20.4	67.3	392.5	333.1	0.150	223.9	168.7	43.0	1.9
	Thermal+W	0.13	37	37.0	34.1	20.3	66.3	372.3	323.1	0.166	217.1	155.1	41.7	1.8
	Cotton+W +IM	0.13	37	37.0	34.9	20.0	70.0	224.9	192.5	0.290	129.4	95.5	42.7	70.5
	Moisture M+W+IM	0.13	37	37.0	35.4	20.1	67.7	212.2	188.8	0.335	126.9	85.3	40.2	75.4
	Thermal+W +IM	0.13	37	37.0	35.7	20.1	69.5	216.6	184.0	0.310	123.6	92.9	42.9	71.1

T_i = setting of internal temperature of the manikin (°C); T_i' = instant internal temperature of the manikin (°C); T_s = the mean skin temperature (°C); T_a = the mean air temperature of the environment (°C); H = the total heat loss (W); Q = the 'perspiration' rate or water loss per unit time (g h^{-1}); R_t = the total thermal insulation value (m^2 K W^{-1}); H_e = the evaporative heat loss from the water evaporation from the 'Walter' manikin (W, the heat of evaporation of water (E) at the skin temperature of 35 °C was taken equal to 0.672 W h g^{-1}); H_d = the dry heat loss (W); Q_c = the weight of condensed water in the clothes on the 'Walter' manikin (g h^{-1}).

3. Results and discussion

The total thermal insulation values R_t, obtained from the 'Walter' manikin, are higher than those acquired with the 'Tore' manikin. It is known that condensation occurs on clothes during heat and water moisture transfer on the 'Walter' manikin. The diversity in condensation between dress styles is rather large. When heavy condensation appears on the impermeable coverall, the differences in the thermal insulation values are greater between the manikins (figure 2).

First, the temperature gradient between the skin and environment was about 15 °C when the 'Walter' manikin

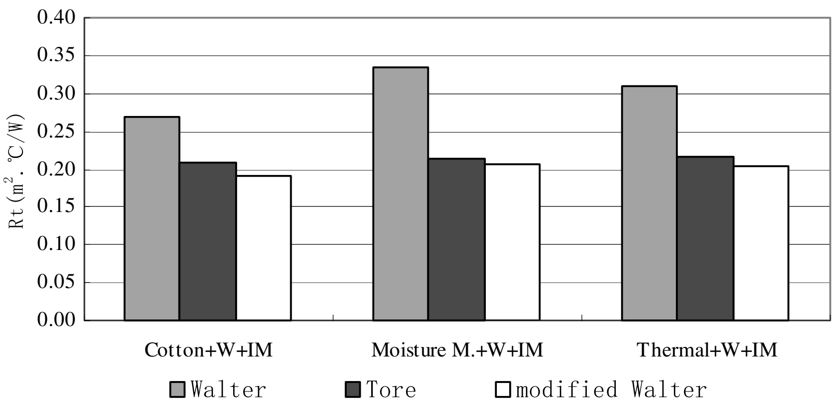

Figure 3. Comparison of thermal insulation calculated according to formulas (1) and (2), and the modified formula (3).

was covered by the impermeable coverall. It resulted in the increase of the total thermal insulation measured by the 'Walter' manikin according to formula (2). However, the 'Tore' skin temperature was always maintained at 34 °C. When the temperature gradient increased, the heat loss also increased. The higher total thermal insulation measured on Walter was due to condensation.

Secondly, the total heat loss consists of the dry heat loss and the evaporative heat loss from evaporation of water from the 'Walter' manikin. The evaporation from the 'Walter' manikin can be divided into evaporation through the clothes and condensation on the clothes. It is necessary to modify formula (2) as

$$R_t = \frac{(T_s - T_e) \times A}{H - E \times Q_p}, \tag{3}$$

where Q_p is the moisture transfer rate through the cloth (g h^{-1}), $Q_p = Q - Q_c$.

The comparison of thermal insulation of the impermeable clothes calculated according to the original formula (2) for 'Walter', formula (1) for 'Tore' and the modified formula (3) for 'Walter' can be seen in figure 3. It is found that the difference in thermal insulation between 'Tore' and 'Walter' disappeared. These results demonstrate that condensation in the clothing ensembles on the 'Walter' manikin influences heat transfer and thereby calculation of insulation. The thermal insulation obtained from the 'Walter' manikin has to be modified when heavy condensation occurs. The modified equation was obtained in this study.

4. Conclusions

Thermal manikins are used to evaluate clothing thermal comfort. The 'Walter' manikin is made of water and waterproof breathable fabric 'skin'. It can measure clothing thermal insulation and moisture vapour resistance simultaneously. It is known that evaporation, condensation or sorption and desorption are always accompanied by heat transfer. If heavy condensation occurs on clothing, the thermal insulation obtained from the 'Walter' manikin has to be modified.

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