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THE COMPARISON OF THERMAL PROPERTIES OF PROTECTIVE CLOTHING USING DRY AND SWEATING MANIKINS

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ABSTRACT

The thermal insulation of clothing is commonly determined by dry thermal manikins either made of plastic or metal. For the determination of evaporative resistance of clothing ensemble, there exist three types of manikin methods: pre-wetted underwear or "skin" covered on dry manikins, the manikin with regulated constant water supply to the "skin" surface and the sweating fabric manikin based on a water filled body covered with waterproof but vapour permeable fabrics. The purpose of this study was to compare thermal insulation and moisture evaporative resistance of a set of protective clothing measured using different type of manikins. The total thermal insulation of seven EU project ensembles (Subzero A and B, Permeable (PERM), Impermeable (IMP), Nomex coverall (with two types of underwear) and Cotton coverall) were measured using the manikin Tore in Sweden, the sweating fabric manikin Walter in Hong Kong, and the manikin Newton in the UK. The results showed that total thermal insulation is reproducible for the seven clothing ensembles measured on the manikins Walter and Tore. The coefficient of variance is less than 8%. Nomex coverall with cotton underwear has 8-16% higher total insulation than that with polypropylene underwear. The apparent evaporative resistance of the impermeable coverall with cotton underwear measured on Newton was 44.5% lower than the evaporative resistance measured on Walter. The effect of condensation and conduction at room temperature environment and measuring time allowing full accumulation of moisture in clothing ensembles might be two important factors affecting the evaporative resistance

1. INTRODUCTION

Thermal properties of clothing such as thermal insulation and evaporative resistance can be determined using manikins (1). However, different types of manikins developed using different designs, constructions, principles, and calculation methods may show different results for the same clothing ensemble. This is in particular the case in the measurement of evaporative resistance of clothing ensembles using sweating manikins as there has been no standard (2). It is therefore necessary to make interlaboratory comparison measurements in order to evaluate and verify results from different manikins and labs in order to assess reproducibility (2, 3).

The coefficient of variation for dry thermal insulation of cold protective clothing in non-walking conditions was reported within 8% measured using dry thermal manikins among eight European thermal laboratories (3). The basic construction of those manikins, heating systems, shell materials, dimensions and the measurement principles are similar to each other. The thermal environment lab at Lund University in Sweden is one of them.

The dry thermal insulation is commonly determined by dry thermal manikins. But it can also determined by a sweating manikin (4, 5). To determine evaporative resistance of clothing ensembles is not as common as determining thermal insulation. There are relatively few sweating manikins available for measuring the evaporative resistance of clothing, and the test procedures have not been standardized (5, 6). Sweating manikins design and test methods vary considerably from lab to lab. The variability among labs was reported relatively high in the interlaboratory evaluation of sweating manikins (2). The sweating manikin methods can be categorized into three types: (a) pre-wetted "skin" (e.g., cotton knit suit) covered on dry manikins, (b) manikin with sweating glands with regulated constant water supply to the "skin" surface (microporous suit). These two types are made of plastic or metal with heating and sweating facilities on the "skin" surface. (c) The sweating fabric manikin. The manikin Walter has been developed at Hong Kong Polytechnic University, which is based on heated water filled body covered with waterproof but vapour permeable fabrics (4). Walter was not used in the above mentioned interlaboratory evaluation of sweating manikins (2).

The purpose of this project was to compare reproducibility between labs with dry and sweating manikins in measuring thermal insulation and evaporative resistance of sets of protective clothing used in the EU-projects.

2. METHODS

Two European research projects have been undertaken with the purpose of investigating thermal properties of protective clothing using thermal manikins and human subject tests, i.e., (a) Assessment of thermal properties of protective clothing and their use (Thermprotect), (b) Thermal insulation measurements of cold protective clothing using thermal manikins (Subzero). In this investigation, two cold protective clothing ensembles and three protective ensembles from Thermprotect were selected out of the above two EU projects (Table 1).

Three thermal manikins were used in this study. Thermal manikin Tore was used for measuring dry insulation. Tore is divided into 17 individually controlled zones. The surface temperatures of all zones were kept at 34 °C, heat losses and ambient temperature were recorded at 10 second intervals. Total insulation values were calculated according to parallel method (ENV 342). The manikin Newton has 32 zones applying the same principle as Tore to measure and calculate the dry thermal resistance. It was also used to measure apparent evaporative resistance of clothing ensembles by covering the manikin with a pre-wetted cotton stretch "skin". A dry and a wet test were carried out separately for the same type of clothing ensembles (Table 2). Apparent Evaporative Heat Loss is calculated as:
The Apparent Evaporative Heat Loss = Total Manikin Heat Loss (measured during wet test) – dry heat loss (measured during dry test).

The apparent evaporative resistance is then calculated as:
R_e= (skin vapour pressure- ambient vapour pressure)/evaporative heat loss
Walter simulates perspiration using a waterproof, but moisture-permeable fabric "skin", which holds the water inside the body, but allows moisture to pass through the "skin". The water supply rate changes automatically by siphon action depending on the amount of clothing worn and perspiration

rate (4). Evaporative heat loss is calculated based on water mass loss (perspiration rate) when a steady state is reached.
Dry heat loss is calculated as:
Dry heat loss (H_d) = total heat loss – evaporative heat loss
Base on H_d the total thermal insulation is then calculated (4).

Table 1. Clothing ensembles and garments

Ensemble	Garment
Subzero A	Underwear (100 % polypropylene): polo shirt, pants. Outer garment: jacket, trousers. Footwear: sport shoes (not worn on Walter). Socks: 65% wool, 35 % polyamide, (not worn on Walter). Handwear: gloves (fleece and Windstopper) (not worn on Walter). Headgear: cap (fleece and Windstopper)
Subzero B	Underwear (100 % polypropylene): polo shirt, pants. Intermediate layer (fibre pile): jacket (80 % polyamide, 20 % polyester), trousers (100 % polyester). Outer garment: jacket, trousers. Footwear: safety boots (not worn on Walter). Socks: 65% wool, 35 % polyamide, (not worn on Walter). Handwear: low temperature mittens (not worn on Walter). Headgear: cap (fleece and Windstopper)
Perm+CO	Permeable coverall (polypropylene layer with inner PTFE membrane), underwear: cotton (CO) shirt and pants
Imperm+CO	Impermeable coverall (polyamide with PVC coating), underwear: cotton shirt (CO) and pants
Nomex+CO	Nomex coverall, underwear: cotton (CO) shirt and pants
Nomex+PP	Nomex coverall, underwear: polypropylene (PP) shirt and pants
Cotton+PP	Cotton coverall, underwear: polypropylene (PP) shirt and pants

Testing environment in the three laboratories was not controlled at the same condition (Table 2).

Table 2. Testing conditions and zone inclusion in the calculation in three labs

	Ta (^oC)	Va (m/s)	R.H. (%)	Zone excluded in calculation
Tore	20	0.2 (0.3 for Subzero A&B)	30	Hands and feet
Walter	21	0.2	70	No hands and feet
Newton (wet)	20	0.5	42	Head, hands and feet
Newton (dry)	5.9	0.5	50	Head, hands and feet

3. RESULTS

The results of dry thermal insulation of the seven clothing ensembles measured on Tore and Walter, four ensembles on Newton are shown in Figure 1. The coefficient of variance (SD/average %, CV) was used to indicate the reproducibility (3). The CV of the seven tested clothing ensembles between Tore and Walter was less than 8% (ranging from 0 to 7.4%). The results obtained on Newton were not included in the calculation of the CV since the testing air velocity and zone inclusion were different (Table 2).

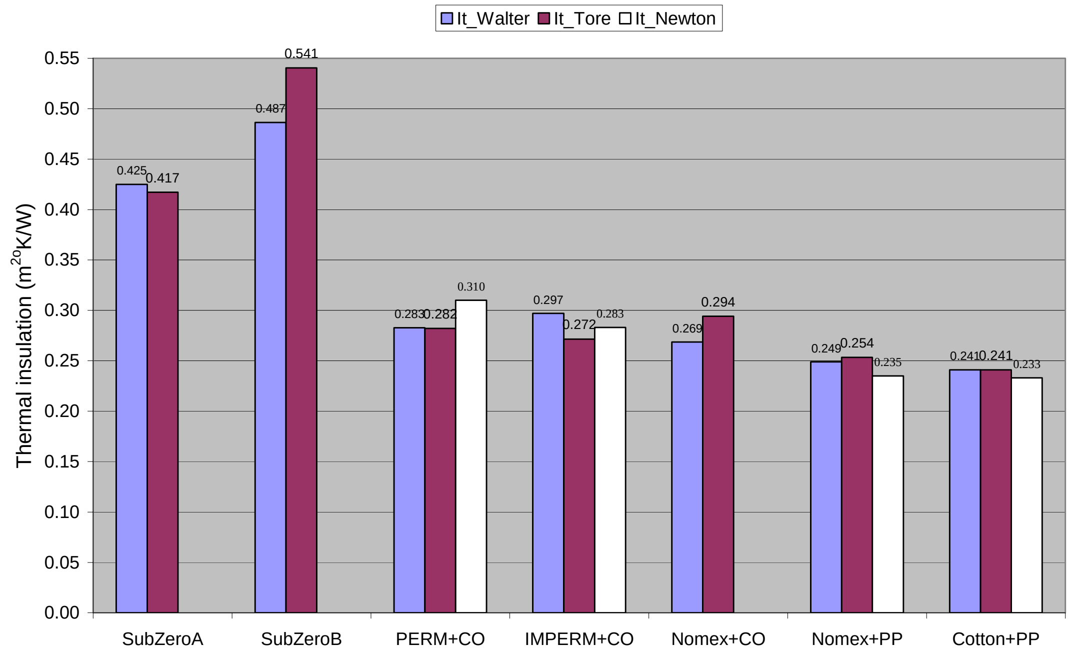

Figure 1. The thermal insulation of seven clothing ensembles measured on Walter, Tore and Newton (CV between Walter and Tore: 0-7.4%)

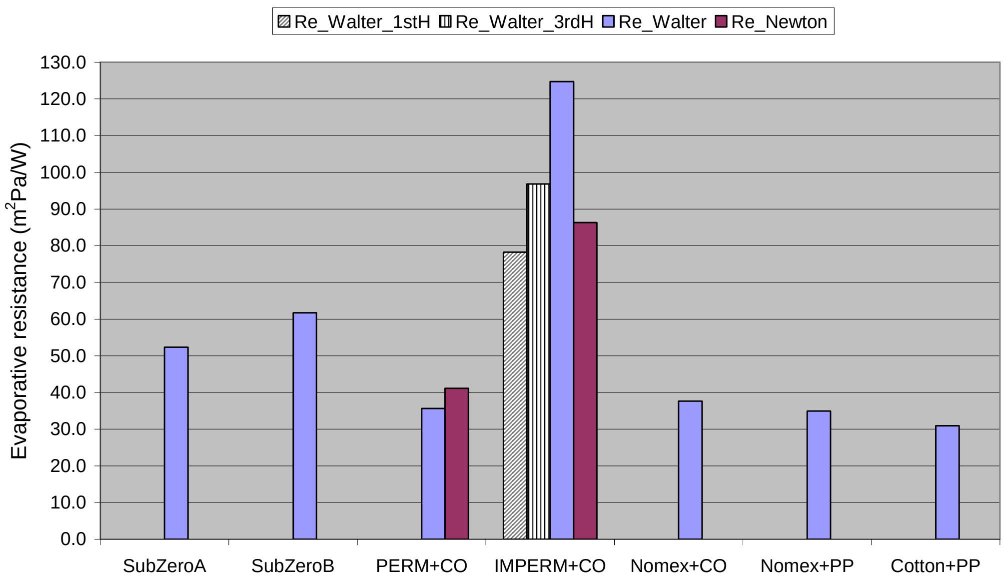

Figure 2. Evaporative resistance of clothing ensembles measured on Walther and apparent evaporative resistance measured on Newton

The evaporative resistance measured on Walter (seven ensembles) and the apparent evaporative resistance measured on Newton (two ensembles) of the clothing are in Figure 2. The evaporative resistance of the ensemble "IMPERM+CO" measured on Walter was calculated after several hours when it had reached stable state. The transient values at the 1st, and 3rd hours were 78.3 and 96.8 m^2Pa/W respectively (Figure 2).

4. DISCUSSION AND CONCLUSIONS

Seven ensembles were measured with Walter in Hong Kong with the procedures developed in house. The total thermal insulation is reproducible for the seven clothing ensembles measured on Walter and on Tore even though the constructions, measurements and calculation principles are quite different. The reproducibility for the total insulation measurements are in good agreement with previous European interlaboratory tests with different types of manikins (3). The differences of the total insulations measured on Newton compared to those on Tore and Walter are less than 10% despite of different testing air velocity and zone inclusion in the calculation (Table 2).

The results from Tore and Walter showed that Nomex coverall with cotton underwear has 8-16% higher dry insulation than that with polypropylene underwear. This is consistent with Thermprotect findings (7). The thermal insulation of Nomex coverall with PP underwear showed slightly higher values than that of cotton coverall with PP underwear. The difference is marginal. This difference could be due to the accuracy or repeatability within a laboratory.

The evaporative resistance measured on Walter and the apparent evaporative resistance on Newton varied between permeable and impermeable coveralls. The apparent evaporative resistance of permeable coverall measured on Newton based on total heat loss subtracted by dry heat loss was 15% higher than the evaporative resistance measured on Walter (based on mass loss), whereas the apparent evaporative resistance of the impermeable coverall measured on Newton was 44.5% lower. This is mainly due to the fact that measurement and calculation principles are different between Walter and Newton. The value measured on Newton is apparent evaporative resistance. “Apparent” indicates that it is not only due to actual evaporation (water mass loss), but also includes other heat loss compared to dry such as condensation and conduction, in which the heat loss increases with lowering ambient temperature and reducing clothing vapour permeability (7). The condensation and conduction during test at room temperature environment causes extra heat loss besides heat loss from mass. This is discussed in detail in the report of the latest EU Thermprotect project (7).

Other factors affecting the evaporative resistance could be the measuring time. It took about several hours for Walter to stabilize for the impermeable coverall with cotton underwear. The transient values at the 1st and 3rd hours increase with measuring time (Figure 2). This implies that the perspiration rate (water loss) decreases with time before the accumulation of moisture in the cotton underwear and impermeable coverall reached its maximum. Walter took more than 1 hour to stabilize for the permeable coverall with cotton underwear. The measurement on Newton lasted 40 minutes. The steady-state might have not completely reached (2). The accumulation of moisture in the cotton underwear and the coverall might have not been stabilized. On the other hand, it is not surprising that the evaporative resistance of the permeable coverall between Newton and Walther is about 15% different although there is no or very small condensation and conduction heat loss, as the variability of evaporative resistance among labs has been reported relatively high. The mean evaporative resistance values of chemical protective clothing between labs could differ three times (2).

In conclusion, the total thermal insulation is reproducible for the seven clothing ensembles measured on the manikins Walter and Tore. The coefficient of variance is less than 8%. Nomex coverall with cotton underwear has 8-16% higher total insulation than that with polypropylene underwear. The apparent evaporative resistance of the impermeable coverall with cotton underwear measured on Newton was 44.5% lower than the evaporative resistance measured on Walter. The effect of condensation and conduction at room temperature environment and measuring time allowing full accumulation of moisture in clothing ensembles might be two important factors affecting the evaporative resistance.

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