A THERMAL MANIKIN STUDY ON THE HEAT GAIN FROM INFRARED RADIATION WITH WET CLOTHING.

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INTRODUCTION

Work in protective clothing often causes wetting of the inner layers due to accumulated sweat, especially when impermeable garments are worn against biological and chemical hazards (Havenith, 2002; Holmér, 2006) or when the user is exposed to radiant heat load outdoors and at industrial workplaces (Müller & Hettinger, 1995).

The transfer of heat radiation through clothing (Bröde et al., 2005; Clark & Cena, 1978; Lotens & Pieters, 1995) and the effects of moisture in different clothing layers (Bröde et al., 2008a; Havenith et al., 2008; Richards et al., 2008) have been studied separately. Also models predicting the heat gain from radiation (den Hartog et al., 2007; Lotens & Pieters, 1995) or the heat loss with wet clothing (Wissler & Havenith, 2009) have been formulated.

The drying of clothing materials by infrared radiation was studied in textile research (McFarland et al., 1999; Paul & Wilhelm, 1948) and changes in heat loss during the drying of wet clothing have been reported occasionally (Nielsen et al., 1992). Though fire-fighting scenarios have been tested with wet materials irradiated at several kW/m^2 (Keiser & Rossi, 2008), less is known on the interaction of heat radiation with wet clothing on the human heat exchange.

This paper presents a thermal manikin study which aimed at the interaction of wet inner clothing layers with long wave thermal radiation on the heat transfer through protective clothing in relation to the vapour permeability of the outer garment.

METHODS

The electrically heated thermal manikin TORE (Kuklane et al., 2006) was operated with its surface temperature controlled at 34 °C inside a climatic chamber at *IfADo* (Bröde et al., 2008b). The manikin was mounted in a standing position statically, i.e. without movement of the extremities inside a frame that was put onto a balance. This allowed for continuous recordings of the heat loss and the amount of vapour evaporating to the environment.

To ensure proper operation of the manikins' heating mechanism under radiant load the tests were carried out at a low air temperature (ta) of 5 °C with 50% relative humidity and air velocity of

0.5 m/s. Two conditions of frontally applied infrared radiation (IR) with incident powers of 626 and 693 W/m^2, corresponding to mean radiant temperatures (tr) of 41.3 °C (MEDIUM) and 50.0 °C (HIGH), respectively, were compared to a reference condition with tr=ta (NoRad).

Equally sized, uniformly designed no-pocket coveralls were purpose-built and possessed a waist band, which was tightened, and were sealed by a zipper at the front and Velcro® fasteners at ankles, wrists and along the front up to the collar. The following outer materials were used: black cotton (COT), a dark-blue coloured hydrophobic layer with inner PTFE membrane (PERM), black aramid (Nomex®, NOM), NOM with inside laminate (LAM) and a PVC rainwear (IMP). Water vapour resistance values varied between infinity (IMP) and 3.6 m^2Pa/W (COT), further details of the garments' characteristics are provided elsewhere (Bröde et al., 2008b).

Experiments were carried out with the exposure period fixed to 70 min using as underwear a woollen coverall (Ullfrotté Orginal overall 400 g/m^2) in either DRY condition or pre-wetted by 800 g water (WET).

The heat loss (HL, W/m^2) of the covered body area, i.e. excluding head, hands and feet, was determined as area weighted average from the recordings of the individual body zones according to the parallel method (ISO 15831, 2004) averaged over the final 10 min of exposure. The rate of evaporation (EVAP, g/h) was calculated from the continuously recorded mass loss over the final 20 min of exposure. For the WET condition, the amount of water released from the underwear, as well as that absorbed by the outer layer and that transferred to the environment, respectively, were obtained by weighing the single pieces of clothing before and after the experiment. Results for each condition are presented as averages from two replicated measurements.

The heat gain (HG, W/m^2) from MEDIUM and HIGH radiation for the DRY and WET conditions, respectively, was computed as heat loss difference to the NoRad condition:

$$HG_{ir,u} = HL_{NoRad,u} - HL_{ir,u}\text{ , with } ir = (\text{MEDIUM, HIGH}) \text{ and } u = (\text{DRY, WET}).$$

For the WET conditions, the change in the rate of evaporation due to radiation was calculated in a similar way as:

$$\Delta EVAP_{ir} = EVAP_{ir} - EVAP_{NoRad}.$$

For expressing the modifying influence of WET underwear on the effect of IR, the change in heat gain from IR for the WET compared to the DRY condition was computed as:

$$\Delta HG_{ir} = HG_{ir,WET} - HG_{ir,DRY}.$$

RESULTS AND DISCUSSION

A decrease in whole body heat loss, i.e. heat gain for the conditions with radiant heat stress compared to the reference was observed (Figure 1). This heat gain increased with radiation intensity and was very similar for the different outer garments when the underwear was dry. This confirms earlier results obtained with different inner layers (Bröde et al., 2005) and can be attributed to the similar emissivity values varying between 0.88 and 0.93 for the different coveralls in the long wave range of the spectrum (Bröde et al., 2008b).

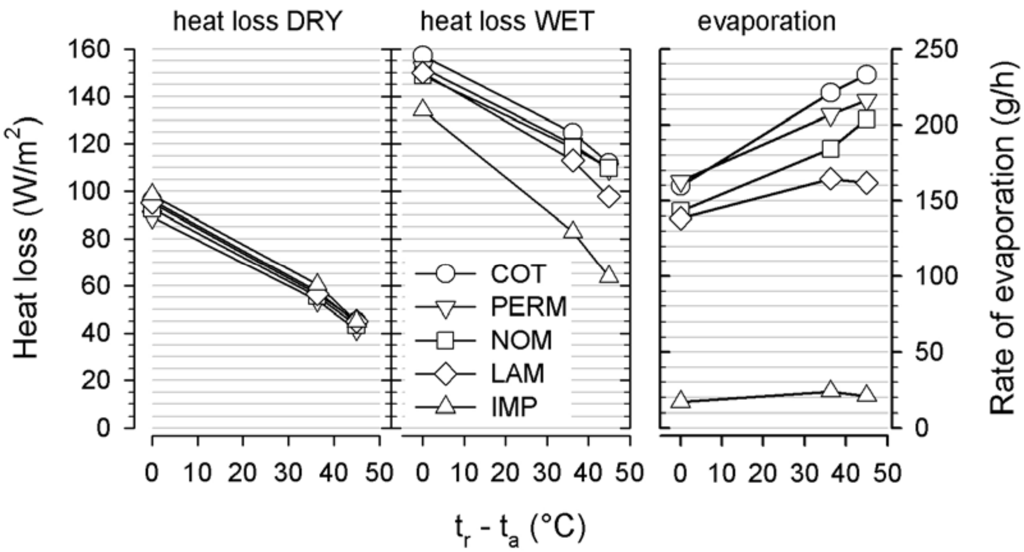

Figure 1: Heat loss under DRY and WET conditions and rate of evaporation for different outer layers related to the intensity of IR expressed as tr-ta.

Heat loss always increased with WET underwear compared to DRY clothing for all IR levels and outer materials (Figure 1), and the rate of evaporation was always higher with radiant load than under NoRad. However, wetting the underclothing caused differential effects with respect to the outer material.

With IMP the heat loss increased less with WET clothing than for the other materials. As the increase in conductive heat loss is expected to be less than 10%, this may be mainly determined by the reduced evaporation particularly with regard to the extra heat loss occurring due to cycles of evaporation and condensation inside the clothing (Bröde et al., 2008a; Havenith et al., 2008).

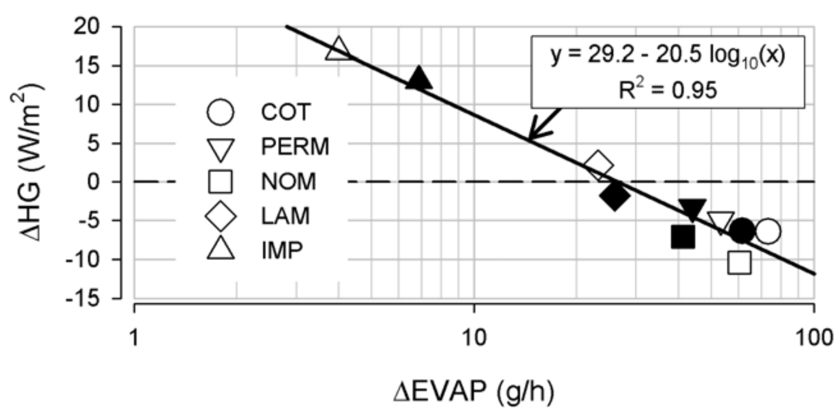

Figure 2: The effect of wet underwear on the heat gain from IR (ΔHG) related to the effect of IR on evaporation (ΔEVAP) on a log scale. Open and closed symbols mark HIGH and MEDIUM radiant load, respectively.

Figure 1 also shows that the decrease in heat loss, i.e. heat gain from IR with WET underwear was steeper for IMP compared to the other materials, and also for LAM compared to COT, PERM and NOM. These observations corresponded to a limited increase in the rate of evaporation with the intensity of IR for IMP and LAM.

This aspect is further developed in Figure 2, which illustrates that the effect of WET clothing on the heat gain from IR (ΔHG) was highly correlated with the impact of IR on evaporation (ΔEVAP) plotted on a logarithmic scale. For the highly permeable outer materials the increased rate of evaporation was associated with a decreased heat gain from IR compared to DRY. For IMP the heat gain increased with WET underwear whereas LAM showed similar heat gain from IR in DRY and WET conditions with a moderately increased rate of evaporation.

Figure 3 presents the change in clothing weight after the WET experiments. Interestingly, IMP showed a decrease in underwear weight loss with increasing IR intensity, although evaporation slightly increased, whereas with all other materials the underwear released more water under radiant load. This suggests the occurrence of vapour recondensation at the underwear surface.

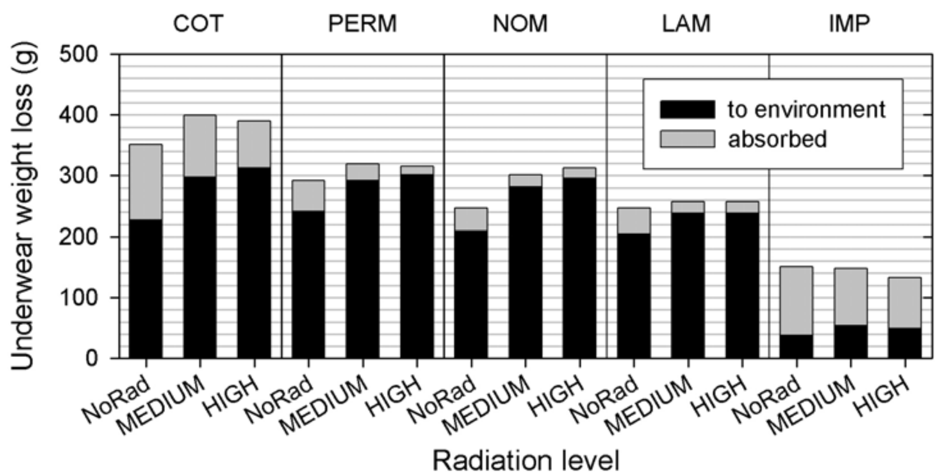

Figure 3: Amount of water released from the underwear, and the fractions absorbed by the different coveralls and lost to the environment after 70 min of exposure to different levels of IR.

CONCLUSIONS

The results point to distinct avenues of heat exchange acting in opposite directions with wet underwear under radiant heat load. On the one hand an increased evaporative heat loss dominates with permeable clothing. On the other hand more heat from IR might be absorbed by the wet material, especially when it is hydrophobic (McFarland et al., 1999), and processes transferring heat to the body by the recondensation of moisture at inner layers of the clothing become apparent with impermeable garments.

The noticeable spread in the observed responses to radiant heat with wet clothing suggests that these effects should be considered when modelling the heat exchange in protective clothing.

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