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Effects of heat radiation on the heat exchange with protective clothing – a thermal manikin study

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Abstract

Within the scope of the European research initiative THERMPROTECT numerous thermal manikin experiments were performed on the transfer of heat through personal protective clothing (PPC) under far infrared radiation (FIR) stress. The influence of the reflectivity and insulation of the clothing, the radiated body surface area, and the interaction with convection and wet underwear were considered. The data showed a decrease in whole body heat loss, i.e. heat gain under radiant heat stress. This heat gain increased with radiation intensity, the slope depending on air velocity and underwear insulation. Except for an aluminised garment that showed minor effects, the influence of the material and colour of the outer layer was negligible, as was the effect of radiation geometry. However, wetted underwear caused differential effects, with FIR induced heat gain depending on water vapour permeability.

1. Introduction

The work package 'Heat radiation' of the EU funded research project THERMPROTECT ("Thermal properties of protective clothing and their use") studied the effects of long and short wave heat radiation on PPC. A stepwise experimental approach comprising flat plate material tests, manikin experiments and human trials was applied.

Whereas first results of the long wave (1) and solar radiation (2) experiments with thermal manikins have been reported elsewhere and also during this conference (3), this summarising contribution focuses on the effects of far infrared radiation (FIR) that were mainly studied by **CEPA** and *IfADo*.

The **objective** of the manikin experiments was to evaluate the effect of radiation on heat transfer through PPC, considering aspects related to the reflectivity and insulation of the clothing, the radiated body surface area, and the interaction with convection and wet underclothing. Furthermore, the results were to be used as a database for the development of corresponding heat transfer models.

2. Methods

The electrically heated thermal manikins Heatman (**CEPA**) and Tore (Lund University, operated at **IfADo**) were operated with a constant surface temperature of 34 °C standing in climatic chambers (Fig. 1). To ensure proper operation of the manikins' heating mechanism the experiments were carried out at low air temperatures (t_a) of 12 °C (**CEPA**) or 5 °C (**IfADo**) with 50% relative humidity (rh) and air velocities (v_a) of 0.5, 1 and 2 m/s. Infrared radiation was applied by heating up one wall and the ceiling to 60 °C (**CEPA**), resulting in mean radiant temperature (t_r) of 28.8 °C, or by ceramic panels (**IfADo**) that generated FIR with t_r between 41.3 and 88.7 °C, and a condition with $t_r=t_a$ was included as a reference. The geometry of the effective radiant field was varied by rotating the manikin or changing the position of the FIR source.

Garments with different outer materials (cotton, Nomex®) and colours (black, white, orange) as well as an aluminised reflective suit and a black Nomex® with inside lamination were combined with different layers of underwear (Helly Hansen Bodywear Super™ 140 g/m², HHS; Ullfrotté Original™ 400 g/m², ULF). The effect of wet underwear was studied by pre-wetting ULF with 800 g water.

Steady state values were calculated from the final 10 minute recordings of the power supplied to the manikins as area weighted averages of the local heat losses according to the parallel method (4) for the whole body, and separate for radiated and non-radiated body parts. All calculations excluded the head, hands and feet, that were shielded against high intensity FIR with aluminium foil (Fig. 1). As the application of FIR did not cause changes in t_a the results are presented as (changes in) measured heat loss averaged over two replications.

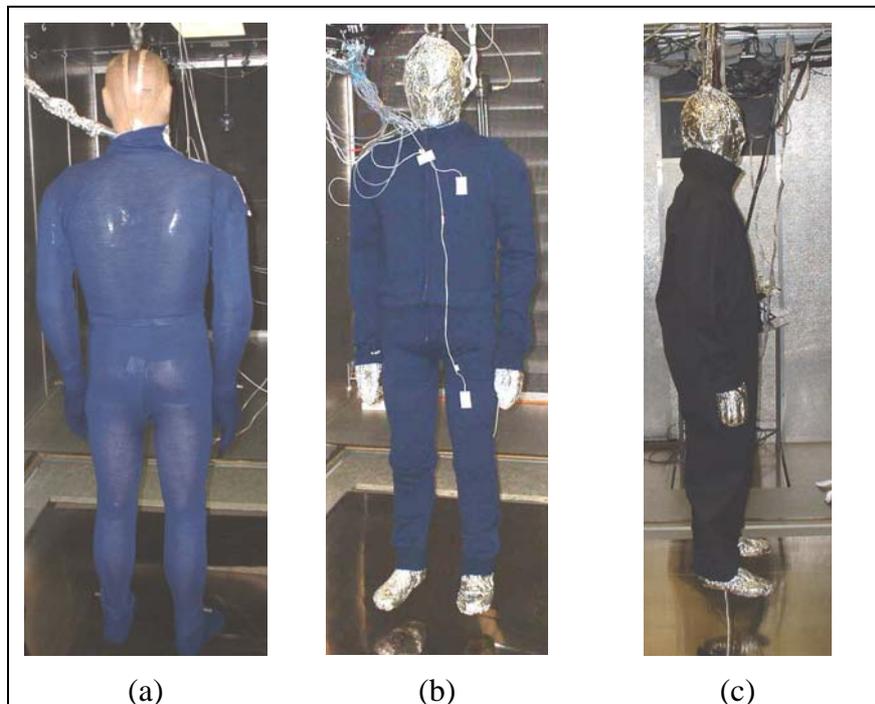


Figure 1. Experimental set-up of the thermal manikin Tore from Lund University inside the **IfADo** climatic chamber (a) with HHS underwear, gloves and socks, (b) with ULF coverall and head, hands and feet covered with aluminium foil, and (c) with the black Nomex® outer layer.

3. Results and discussion

3.1. FIR effects related to reflectivity and insulation

The results showed a decrease in whole body heat loss (Fig. 2a), i.e. heat gain for the conditions with radiant heat stress compared to the reference, as shown in Fig. 2b). Except for the reflective suit that demonstrated no effects at **CEPA** and only minor effects with the higher intensity FIR at *IfADo*, the other outer garments revealed only a negligible influence of colour and material on this heat gain. This was in contrast to experiments with short wave radiation (2;3;5) showing definite colour effects.

The FIR induced heat gain appeared to be linearly related to radiation intensity expressed as $t_r - t_a$ (Fig. 2a) and showed a flatter slope for a 3 layer clothing compared to a 2 layer combination (Fig. 3).

Extrapolation of these curves suggest that at higher radiation intensities heat gain may be smaller for the 3 layer system with higher insulation, which would be beneficial to the user.

3.2. FIR effects related to radiated surface area

The comparison of the heat losses between three positions of the manikin in the **CEPA** chamber are illustrated in Fig. 4. The whole body heat loss was very similar between the various conditions, but local differences were observable. Note that even when facing the air (middle part of the figure) one side of the manikin had larger heat losses because a warm wall was still present on the other side. The rotation of the manikin had exactly the same consequences on any side (left and right parts of Fig. 4). An interesting observation concerns the wind effect, clearly visible as a higher heat loss on the side of the manikin which was directly exposed after rotation.

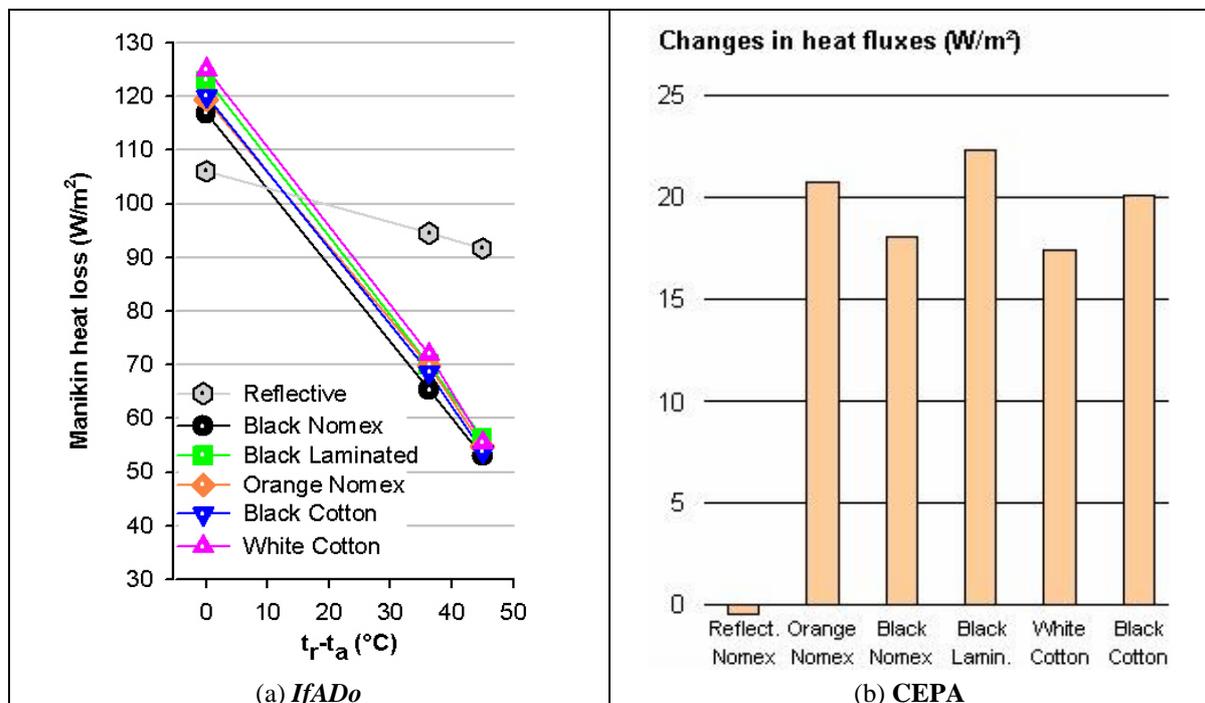


Figure 2. a) Manikin heat losses at *IfADo* measured with HHS underwear at $t_a=5$ °C, $v_a=0.5$ m/s, $rh=50\%$, and b) Changes in heat loss to the condition with $t_r=t_a$, i.e. **heat gain** as measured at **CEPA** without underwear at $t_a=12$ °C, $v_a=0.5$ m/s, $rh=50\%$ (radiation via 2 surfaces at 60°C), for the whole covered body area (head, hands, feet excluded) related to the different outerwear.

Also experiments at *IfADo* showed (1) that whole body heat gain under radiant heat load ($t_r=50\text{ }^\circ\text{C}$) was similar for frontal, lateral and all-side radiation, but that one-sided radiation affected differently radiated and non-radiated body parts, thus causing an inhomogeneous spatial distribution of heat gain.

These results are concordant with human wear trials showing no effect of radiation direction on the physiological heat strain with light clothing, cf. (1), or PPC (6).

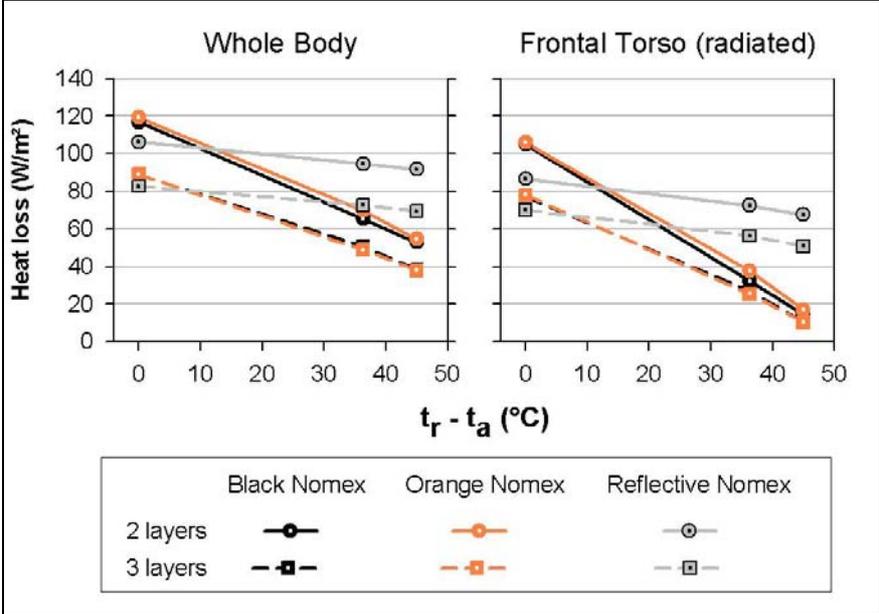


Figure 3. Manikin heat loss connected by straight lines as measured at *IfADo* for the whole body (left panel) and frontal torso area (right panel) at $t_a=5\text{ }^\circ\text{C}$, $v_a=0.5\text{ m/s}$, $rh=50\%$ in relation to $t_r - t_a$ for ensembles with 2 layers (depicted from Figure 2a) and with an additional layer (ULF).

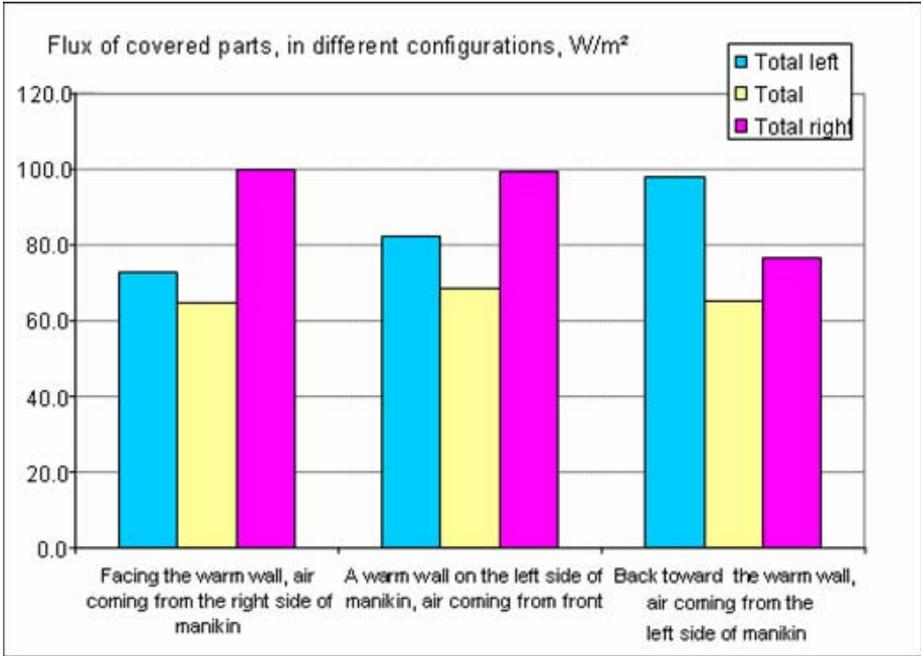


Figure 4. Manikin heat loss under the radiation effect as measured at *CEPA* for the whole covered body area (Total) and for the left and right specific area exposed to the radiation field (head, hands, feet excluded). The manikin wore the black Nomex® coverall without any underwear.

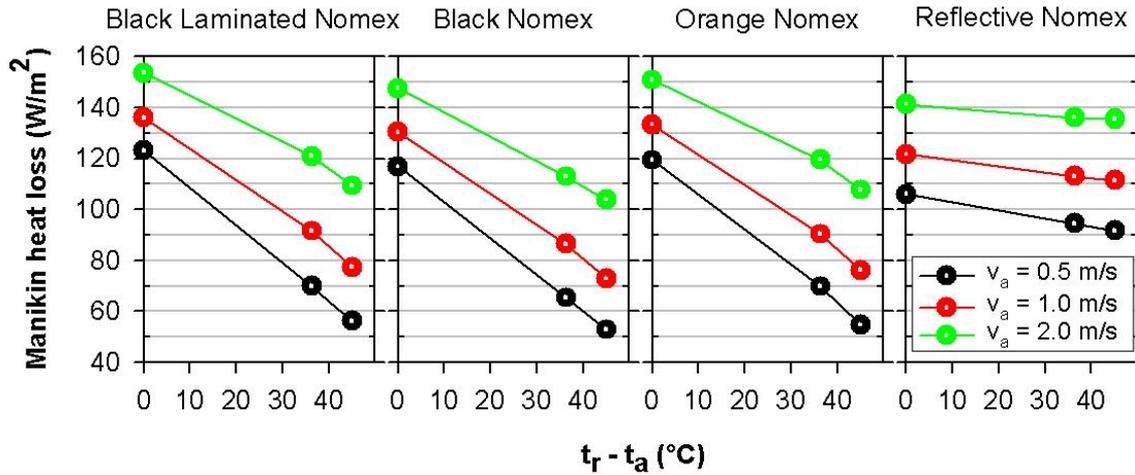


Figure 5. Manikin heat loss as measured at *IfADo* for the whole covered body area (head, hands, feet excluded) vs. FIR intensity expressed as $t_r - t_a$ for different air velocities and outerwear materials. Filled circles represent averages of replicated measurements obtained with HHS underwear at $t_a=5$ °C, $rh=50\%$.

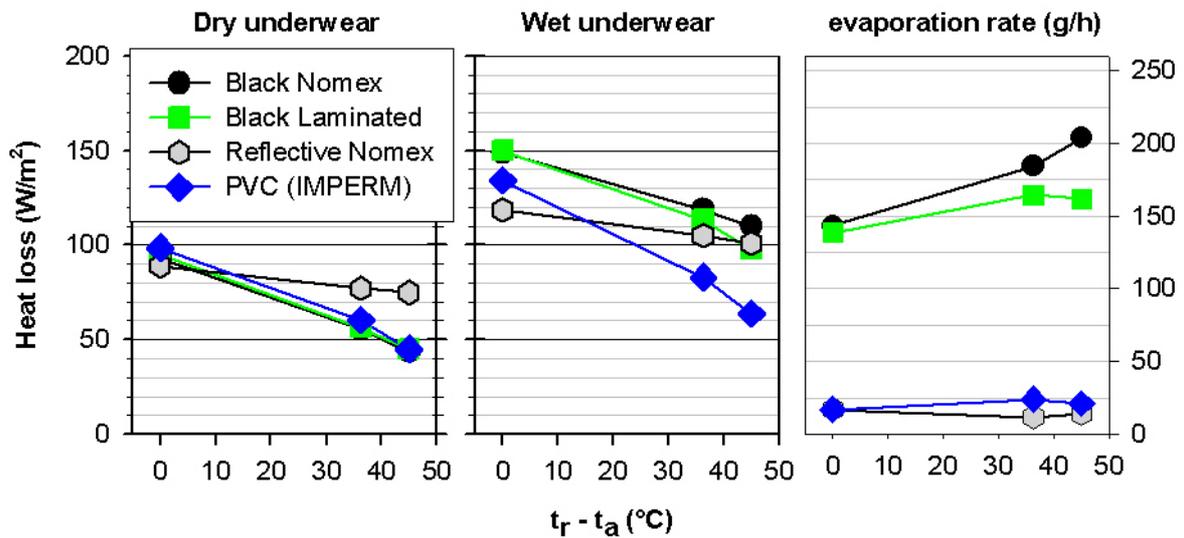


Figure 6. Manikin heat loss as measured at *IfADo* for the whole covered body area (head, hands, feet excluded) vs. FIR intensity expressed as $t_r - t_a$ for different outerwear materials at $t_a=5$ °C, $v_a=0.5$ m/s, $rh=50\%$ with dry ULF underwear (left panel) and wet ULF (mid panel). The right panel shows the evaporation rate with wet ULF.

3.3. Interaction of FIR effects with wind speed

Fig. 5 illustrates for the *IfADo* experiments, that increasing wind speed also increased heat loss as expected with the adjusted air temperature of 5 °C. An interaction effect of FIR and convection appeared insofar, as the steepness of the effect of FIR was modified by wind speed. Apparently, the FIR related reduction in heat loss (i.e. heat gain) was flatter at higher wind speed. Similar relations were also found in experiments with short wave radiation (2).

3.4. Interaction of FIR effects with wet underwear

With dry ULF underwear the change in heat loss, i.e. heat gain was again similar for the non-reflecting materials (Fig. 6, left). However, wetted underclothing caused differential effects (Fig. 6, mid), with FIR induced heat gain depending on water vapour permeability, as indicated by evaporation rate that increased with radiation intensity only for the more permeable black materials (Fig. 6, right).

For an impermeable PVC coated garment, heat gain increase appeared to be steeper with wet than with dry ULF (Fig. 6, blue lines). The reflecting property of the aluminised suit was outweighed by its low vapour permeability, so that with wet ULF its heat loss was nearly identical to that of the black suits, which showed its consequences in wear trials (6).

4. Conclusion

The results show that thermal radiation transferred through PPC causes **heat gain** at the skin surface that **(i)** increases linearly with radiation intensity ($t_r - t_a$), **(ii)** depends on the reflecting properties of the clothing with an colour effect evident only in the solar (2;3), but not in the infrared spectrum, **(iii)** is attenuated by adding clothing layers, **(iv)** is attenuated with increasing wind speed.

During THERMPROTECT an appropriate model for the effect of radiation on **dry** heat loss had been developed under the lead of E. den Hartog (TNO), that provided good predictions of the effects of short and long wave radiation measured with the manikins under different conditions in different laboratories.

However, the manikin experiments with wet underwear, as well as wear trials (6) indicate that such models need to be expanded by the modifying effects of (sweat) evaporation, that may outweigh the benefits of reflective, but vapour resistant clothing at low to moderate radiation intensities.

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5. References

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