

Heat Gain From Thermal Radiation Through Protective Clothing With Different Insulation, Reflectivity and Vapour Permeability

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The heat transferred through protective clothing under long wave radiation compared to a reference condition without radiant stress was determined in thermal manikin experiments. The influence of clothing insulation and reflectivity, and the interaction with wind and wet underclothing were considered. Garments with different outer materials and colours and additionally an aluminised reflective suit were combined with different number and types of dry and pre-wetted underwear layers. Under radiant stress, whole body heat loss decreased, i.e., heat gain occurred compared to the reference. This heat gain increased with radiation intensity, and decreased with air velocity and clothing insulation. Except for the reflective outer layer that showed only minimal heat gain over the whole range of radiation intensities, the influence of the outer garments' material and colour was small with dry clothing. Wetting the underclothing for simulating sweat accumulation, however, caused differing effects with higher heat gain in less permeable garments.

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1. INTRODUCTION

Protective clothing, which is worn against thermal, mechanical or chemical hazards, imposes additional thermal stress to the user. This is due to the hampered transport of heat and moisture to the environment and the increased metabolic heat production caused by the clothing's weight, stiffness and bulkiness that subsequently cause higher energy expenditure while executing muscular work [1, 2, 3, 4]. The characteristics of protective clothing are not considered appropriately in currently applied procedures for heat stress assessment [3, 5, 6]. On the one hand, the accumulated sweat in the clothing lowers the thermal insulation and impairs the predictive capacity of the utilised thermoregulatory models [7, 8]; on the other hand, the discrepancies in the predicted heat strain observed under thermal radiation were higher for clothed people compared to seminude persons [9].

Therefore, the main objective of the research project THERMPROTECT funded by the European Union was to provide basic data and models on "Thermal properties of protective clothing and their use" to improve the assessment of thermal stress [10]. Issues related to the increased metabolic rate [4], problems with cold protective clothing [11] and the effects of moisture concerning wet conduction, condensation and evaporative efficiency [12, 13, 14] were addressed.

A further major work item dealt with the effects of both short wave (solar) radiation, which dominates outdoors, and long wave radiation (far infrared radiation, FIR), which is emitted, e.g., by hot walls and surfaces in mining and at industrial workplaces [15]. At these workplaces, the radiant heat transferred to the skin constitutes a major part of the thermal stress experienced by the user. This heat gained from radiation has to be released from the body by increasing the sweat rate [9] and thus imposes additional thermal strain to the user. As all components of human heat exchange with the environment need to be considered properly for an appropriate heat stress assessment based on

the heat balance equation [5, 6], underestimating the heat gain of the body from thermal radiation would reduce the user's protection, whereas overestimating this heat gain would result in too cautious an assessment, which might in turn unnecessarily reduce the worker's efficiency.

In the THERMPROTECT project, a stepwise experimental approach comprising material tests with heated flat plates or cylinders, experiments with thermal manikins and human trials was used [16].

A recent manikin study [17] showed that with protective clothing the body gained the same amount of heat from uniformly or unilaterally applied radiation of equal total intensity, thus confirming the results from human trials that failed to demonstrate a difference in the physiological strain under symmetrical or asymmetrical radiation conditions [9, 18, 19]. Studies on the physiological effects of heat radiation while workwear or protective clothing is worn indicated that the radiant heat transmitted to the body could be attenuated with aluminised or more insulating clothing both under FIR in the laboratory [20], at industrial workplaces [15, 21] and under sun radiation outdoors [22].

Special attention is paid to the impact of high intensity radiation in the presence of moisture inside the protective clothing of firefighters [23, 24]. However, from textile research on drying of wet fabrics by infrared radiation [25, 26] one may also expect that moderate thermal radiation might have an influence on the evaporation of moisture from wet clothing and thus on human heat balance.

To build up a comprehensive database for analysing and modelling the effects of heat radiation, numerous experiments with thermal manikins were performed within the THERMPROTECT project. This article extends earlier presentations at the Third [27] and Fourth European Conferences on Protective Clothing (see foreword on p. 132). The objective was to evaluate the effect of FIR on the heat transferred through protective clothing, considering aspects related to the reflectivity and insulation of the clothing, and the interaction with convection and wet underclothing.

2. METHODS

2.1. Thermal Manikin

The electrically heated thermal manikin TORE [28] was transported from Lund University to the climate simulation laboratory at the Leibniz Research Centre for Working Environment and Human Factors (IfADo). This manikin's surface area is divided into 17 zones: head, chest, back, stomach, buttocks, left and right upper arm, left and right lower arm, left and right hand, left and right thigh, left and right leg, and left and right foot. The manikin is connected to a power supply and a computer-controlled system that regulates each zone's surface temperature individually to a given set-point (34 °C). The computer system also records the surface temperature and the supplied power data for each zone and stores them in 10-s intervals for later evaluation.

The manikin was installed in a standing position into the centre of the climatic chamber and was operated statically, i.e., without movement of the extremities. After installation, the manikin's temperature sensors were calibrated by measuring the temperatures on the nude manikin while the power supply was

not operating, and the air temperature (t_a) was set to 34 °C with mean radiant temperature (t_r) equalling t_a , with air velocity (v_a) of 0.5 m/s and 50% relative humidity (RH). The differences in measured temperatures from 34 °C were entered as offset values for each individual zone into the computer control software.

2.2. Climatic Exposure Chamber

The facilities at IfADo make applying high intensities of FIR possible while keeping the other climatic parameters (in particular air and wall temperature) constant. For the simulation of FIR, the chamber uses four radiation towers, each equipped with 30 ceramic panels (FSR 1000, Elstein, Germany), which are electrically heated up to 750 °C and are installed about 3 m above the ceiling. They emit FIR of peak wave lengths between 2 and 10 μm , which is routed into the chamber via reflecting shields. The FIR emitted by all four towers operating simultaneously has a symmetric cylindrical shape, whereas with two active towers the resulting geometry is asymmetric, like a bulged half-cylinder with some radiation from the back, as parts of the

TABLE 1. Inner and Outer Layer Materials' Characteristics: Thermal Insulation (Rct), Vapour Resistance (Ret) and Emissivity (ϵ) in the Far Infrared Spectrum. The Air Permeability (AP) Is Measured According to Standard No. ISO 9237:1995 [33], f_{cl} is the Clothing Surface Area Factor [31] of the Clothed Manikin

Code	Description	Rct (m ² K/W)	Ret (m ² Pa/W)	ϵ (nd)	AP (l/m ² /s)	Thickness (mm)	Weight (g/m ²)	f_{cl} (nd)
Underwear								
HHS	Helly Hansen Bodywear Super™, 100% polypropylene, long-sleeved shirt, longjohns	0.038	4.7	nm	nm	1.43	140 ^a	1.09
ULF	Ullfrotté Original™, wool/polyamide coverall	0.107	9.2	nm	nm	3.01	400 ^a	1.05
Outer layer coveralls								
COB	pure cotton, black	0.012	3.6	0.93	63.5	1.43	382	1.22
COW	pure cotton, white	0.012	3.5	0.93	93.5	1.43	362	1.21
ARO	aramid, Nomex®, orange	0.010	4.7	0.88	44.0	0.60	378	1.21
ARB	aramid, Nomex®, black	0.010	4.7	0.88	74.1	0.63	366	1.23
ARBL	Nomex®, black, laminated on inside	0.012	5.8	0.90	<0.1	0.60	415	1.24
REFL	Nomex®, aluminized on outside	0.045	nm	0.06	<0.1	1.55	509	1.29
PERM	hydrophobic layer with inner PTFE membrane	0.025	5.6	nm	1.0	0.69	268	1.26
IMP	PVC rainwear, impermeable	0.007	∞	nm	0.2	0.35	288	1.26

Notes. PTFE—polytetrafluoroethylene, PVC—polyvinyl chloride, nm—not measured; a—manufacturer's information.

radiant heat are diffusively reflected by the hammered sheet metal walls. Concerning the vertical distribution of radiation intensity, the deviation from the nominal value along the vertical axis is under 3% [17].

Air temperature (t_a) and wet-bulb temperature were controlled with dry- and wet-bulb temperature readings obtained from an Assmann psychrometer (Lambrecht, Germany) with two precision mercury thermometers; air velocity (v_a) was measured with a vane anemometer (Lambrecht) and the radiation intensity was measured with readings of the temperature of a standard black globe (t_g , Lambrecht), which was positioned 1.35 m above the floor corresponding to 1.1 m above the level of the manikin's feet. These black globe measurements were executed in the absence of the manikin. Globe temperature was used in combination with t_a and v_a to calculate mean radiant temperature (t_r) [29] and radiation intensity (I_r) [30]. Frontal, lateral and vertical radiant temperature asymmetries (Δt_{pr}) were calculated from plane radiant temperatures measured in six directions with a Brüel & Kjær (Denmark) climate analyser 1213 with MM0036 radiant temperature asymmetry transducer (Brüel & Kjær).

2.3. Clothing

One-, two- and three-layer ensembles were studied with different types of outer layers made of cotton, aramid (Nomex®) or aluminised materials combined with polypropylene underwear (Helly Hansen Super™ Bodywear 140 g/m², HHS) and/or a wool/polyamide coverall undergarment (Ullfrotté Original™ 400 g/m², ULF). Also permeable (PERM) and impermeable (IMP) outer materials that had been used in earlier studies [12, 13] were included. Table 1 provides the characteristics of the fabrics such as the material thickness and weight, and the clothing surface area factor (f_{cl}) of the clothed manikin [31]. The thermal insulation (R_{ct}) and water vapour resistance (R_{et}) values were determined according to Standard No. ISO 11092:1993 [32]. The air permeability (AP) was measured according to [33]. The emissivity (ϵ) in the far infrared spectrum (10 µm) was determined

with tests with a guarded hot plate controlled at 35 °C, where the textile samples were irradiated with a ceramic heat source (Epiradiateur, cf. [34]). As the radiation transmissivity was negligible, the reflectivity could be calculated as $1 - \epsilon$. The emissivity values for the underwear and the nonreflective PERM and IMP outer layers were not measured, but may be assumed to resemble the emissivity of the other nonreflective materials, i.e., estimated for the purpose of this study to be 0.9 in the far infrared spectrum.

As outer layers, equally sized, uniformly designed no-pocket coveralls were purpose-built and possessed a waist band, which was tightened, and were sealed with a zipper at the front and Velcro® fasteners at ankles, wrists and along the front up to the collar.

The manikin wore socks and gloves, and the head, hands and feet were shielded against FIR with aluminium foil [17, 27]. With ULF underwear, experiments were performed with the underwear being either dry or pre-wetted. The latter was intended to simulate the accumulation of sweat in the clothing in heavy work and/or hot environments. For the purpose of protecting the manikin's electrical system from moisture in these experiments, its surface was covered with a polyethylene film.

2.4. Climatic Conditions

To ensure the reliable operation of the manikin's heating mechanism under radiant heat load, i.e., to avoid passive overheating of the radiated zones above the set-point, the experiments were carried out at a low t_a of 5 °C, with 50% RH and v_a set to 0.5, 1.0 or 2.0 m/s. Pre-tests with the manikin wearing the polypropylene underwear and black Nomex® coverall had shown that with semicylindrical frontal radiation with $t_r = 50$ °C the mainly radiated body areas at chest and abdomen were still heated by 7–10% of the maximum heating capacity.

Thus, $t_r = 50$ °C was chosen as an upper limit for frontally applied FIR with the manikin's heating system still operating reliably. For uniform, cylindrical all-side radiation t_r could be increased to 62.4 °C, and a homogeneous

TABLE 2. Climatic Conditions With Air (t_a), Globe (t_g) and Mean Radiant (t_r) Temperatures as Well as Radiation Intensity (I_r) and Radiant Temperature Asymmetries (Δt_{pr}) for the Applied Air Velocities (v_a)

Radiation Level, Direction	t_a (°C)	v_a (m/s)	t_g (°C)	t_r (°C)	I_r (W/m ²)	Δt_{pr} (°C) Front-Back	Δt_{pr} (°C) Right-Left	Δt_{pr} (°C) Top-Down
Reference	5.0	0.5	5.0	5.0	0	0	0	0
		1.0	5.0					
		2.0	5.0					
Medium, frontal	5.0	0.5	19.7	41.3	215	28.2	-2.2	-3.0
		1.0	16.1					
		2.0	13.1					
High, frontal	5.0	0.5	23.9	50.0	279	29.6	-1.9	-1.7
		1.0	19.3					
		2.0	15.5					
High, all-side	5.0	0.5	23.9	50.0	279	2.4	-2.8	-0.8
Extra high, all-side	5.0	0.5	30.4	62.4	380	3.4	-3.8	-3.1
		1.0	24.4					
		2.0	19.2					

Notes. High all-side radiation was only studied at $v_a = 0.5$ m/s.

condition with $t_r = t_a = 5$ °C was included as a reference.

2.5. Study Design, Procedure and Measurements

Table 3 summarises the combinations of the climatic and clothing conditions as they were applied under the different research questions of this study. With dry clothing, all climatic conditions were studied after dressing the manikin without changing the configuration of the manikin, then the same procedure was used to the next clothing combination. To attenuate the influence of dressing and variability in clothing fit on the results, the whole procedure was carried out twice for each clothing condition.

For the experiments with wet ULF, wetting of the underwear was performed by soaking the clothing using the rinse cycle (5 min, water temperature ~10 °C) followed by a short (7-s) spin-drying programme of a washing machine. If the amount of water stored in ULF after this procedure was below 750 g, extra water was sprayed onto the underwear to approach 800 g. Averaged over all experiments the amount of water stored in ULF was 844.4 ± 31.3 g ($M \pm SD$). The ULF coverall with a dry weight of 804 g could store 1200 g water without any dripping. Pre-tests with wet ULF had shown that

it took 15 min for the local heat losses to stabilise after the initial regulating of the system and that a decrease in the local heat losses resulting from the clothes drying did not occur until 80 min after the start of the test. So the duration of the measurements with wet ULF was fixed to 70 min, which ensured a stable distribution of the moisture in the clothing system for a sufficient time when measuring the heat loss and the rate of evaporation.

Measurements with dry ULF were continued until a steady state of local heat losses was obtained for at least 20 min with total measuring duration varying between 40 and 60 min. During the measurements with wet ULF, the manikin was mounted inside a frame that was put on a balance. This made continuous recordings of both the heat loss and the amount of vapour evaporating to the environment possible. The rate of evaporation (grams per hour) was calculated from the slope of the recorded mass loss over the final 20 min of exposition time. Steady-state values were calculated from the final 10-min recordings of the power supplied to the manikin as area weighted averages of the local heat losses according to the parallel method for the whole body, from which the clothing insulation was computed [35]. All calculations excluded the head, hands and feet, as they were not covered

TABLE 3. Summary of the Study Conditions and of the Results on the Heat Loss Measured With the Manikin and on the Heat Gain From Far Infrared Radiation (FIR) Calculated With Equation 1

Research Question	FIR Conditions	Clothing Conditions	Effect on Heat Loss	Effect on Heat Gain From FIR
What is the influence of				
increased radiation intensity?	reference, medium and high frontal radiation at $v_a = 0.5$ m/s	COB, COW, ARO, ARB, ARBL, REFL outer layers combined with dry HHS underwear	↓	↑ (linearly with FIR intensity)
increased reflectivity of outer layers?	reference, medium and high frontal radiation at $v_a = 0.5$ m/s	COB, COW, ARO, ARB, ARBL, REFL outer layers combined with dry HHS underwear	↑ (under FIR for REFL compared to other outer layers)	↓ (for REFL compared to other outer layers)
adding inner clothing layers?	reference and high frontal radiation at $v_a = 0.5$ m/s	COB, COW, ARO, ARB, ARBL, REFL outer layers configured as 1 layer (no underwear) 2 layers (with HHS and ULF underwear, respectively) 3 layers (with ULF midlayer on top of HHS)	↓	↓
increased wind speed?	every condition in Table 2	ARB, REFL outer layers combined with dry HHS underwear	↑	↓
moisture in the underwear?	reference and high all-side radiation at $v_a = 0.5$ m/s	dry and pre-wetted ULF underwear combined with COB, ARB, ARBL, PERM, IMP outer layers	↑	↓ for permeable ↑ for impermeable

Notes. For clothing codes see Table 1; ↑—increase, ↓—decrease.

with the clothing but were shielded against high intensity FIR with aluminium foil.

To describe the extra amount of heat transferred to the skin under radiant load, the heat gain from FIR for each radiation condition (Table 2) was calculated by subtracting the heat loss measured under radiant load from the heat loss obtained under the corresponding reference condition with the same wind speed as

$$\text{heat gain} = \text{heat loss}_{\text{reference}} - \text{heat loss}_{\text{radiation}} \quad (1)$$

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.

3. RESULTS

With radiant heat load, a decrease in whole body heat loss, i.e., heat gain compared to the

reference for all clothing configurations was observed (Figure 1).

3.1. FIR Effects Related to Reflectivity and Insulation

With the exception of the reflective suit, a negligible influence of colour and material on FIR heat gain was observed in the tests with the HHS underwear (Figure 1). The heat loss in the reflective suit was much less affected by radiation levels than in the other suits. A small colour effect on the heat gain as calculated with Equation 1 was observed only in the one-layer configuration without any underwear, where the heat gain with the black cotton and Nomex® coveralls was higher than with the white cotton and orange Nomex® material, respectively (Figure 2).

Figure 2 illustrates how the heat gain from frontal high intensity radiation decreased when

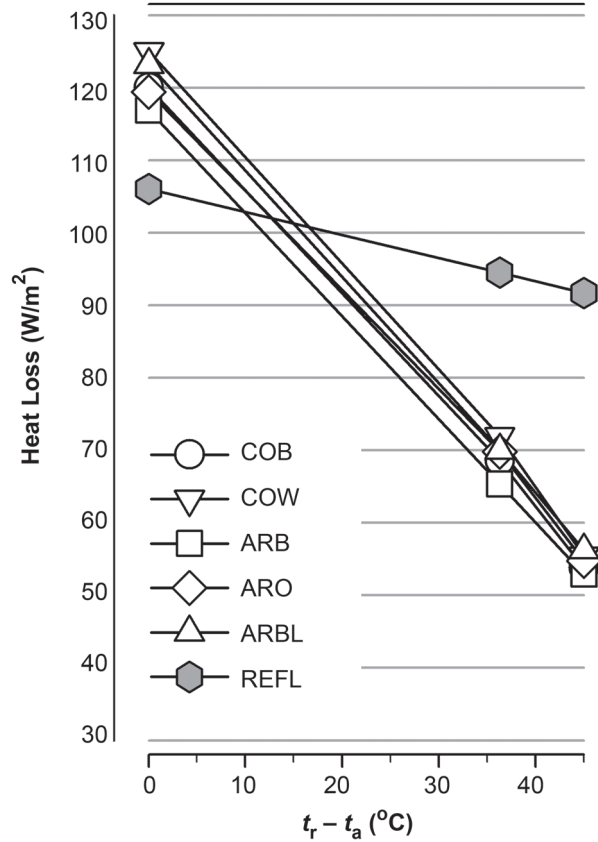


Figure 1. Heat loss related to radiation intensity measured at $t_a = 5\text{ °C}$, $v_a = 0.5\text{ m/s}$, $RH = 50\%$ with HHS underwear combined with different outer layers. Notes. t_a —air temperature, v_a —air velocity, RH—relative humidity; for clothing codes see Table 1.

the HHS underwear was added, and further decreased with the woollen ULF underwear. However, the three-layer clothing with the HHS and ULF as inner and mid layers, respectively, did not further reduce the heat gain. There was a strong negative correlation of heat gain with clothing insulation, which was slightly better approximated by a reciprocal ($R^2 = .97$) compared to a linear ($R^2 = .94$) regression function.

The heat gain with the reflective coverall was much lower, but it also decreased when the underwear insulation increased (Figure 3). The parallel shift of the curve on a log-scale compared to the values averaged over the nonreflective outer materials indicates that the relative attenuating effects of decreased emissivity on the one hand and increased insulation on the other may be represented by a multiplying term in a modelling approach.

3.2. Interaction of FIR Effects With Wind Speed

As expected, with increasing wind speed the heat loss also increased [27]. However, the FIR induced heat gain appeared to be linearly related to radiation intensity (expressed as $t_r - t_a$) for all wind speeds. Figure 4 illustrates the interaction effect of FIR and increased convection on the heat gain observed with the HHS underwear combined with the black Nomex® representing the nonreflective materials and with the reflective outer layer. With both outer layers, increasing wind speed lowered the level and the steepness of the effect of FIR. These conditions had also been studied with the orange and laminated black Nomex® suits, but as their results were nearly identical to the results of the black Nomex® [27], only the latter are shown in Figure 4. Similar

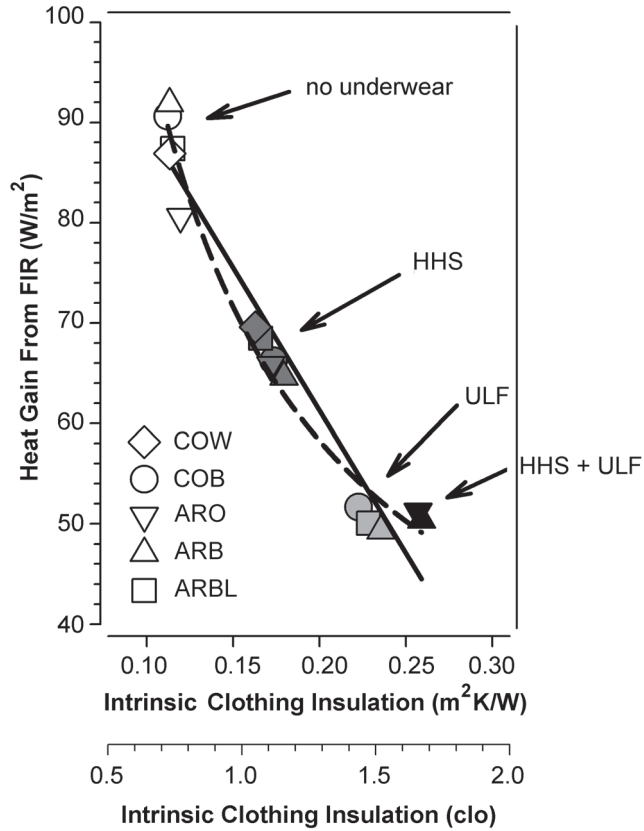


Figure 2. Heat gain from frontally applied radiation ($t_r = 50\text{ }^\circ\text{C}$) as calculated with Equation 1 in 1-, 2- and 3-layer combinations at $t_a = 5\text{ }^\circ\text{C}$, $v_a = 0.5\text{ m/s}$, $\text{RH} = 50\%$, in relation to clothing insulation with linear (solid line, $R^2 = .94$) and reciprocal (dashed line, $R^2 = .97$) regression functions. Notes. t_r —mean radiant temperature, t_a —air temperature, v_a —air velocity, RH —relative humidity, R^2 —proportion of variance explained by regression function, FIR—far infrared radiation; for clothing codes see Table 1.

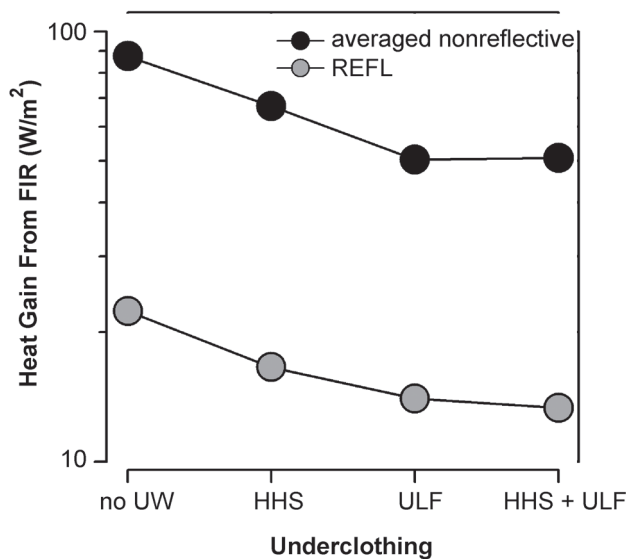


Figure 3. Heat gain as calculated by Equation 1 on a log-scale from frontally applied radiation ($t_r = 50\text{ }^\circ\text{C}$) comparing the reflective outer layer (REFL) combined with different underwear (UW) to the averaged values with the nonreflective materials from Figure 2. Notes. t_r —mean radiant temperature FIR—far infrared radiation; for clothing codes see Table 1.

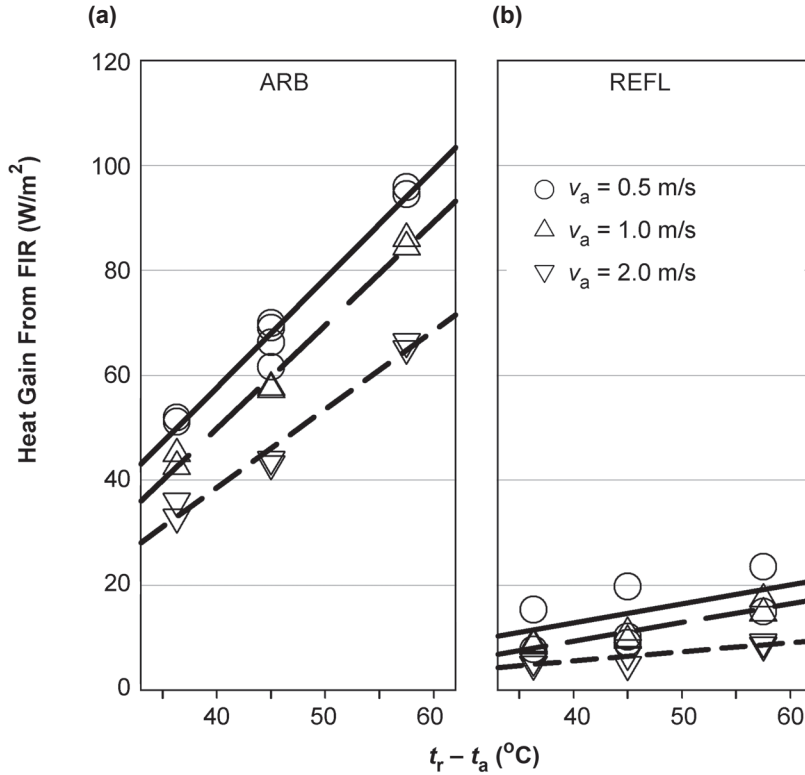


Figure 4. Heat gain from different levels of frontal and all-side FIR as calculated with Equation 1 with linear regression function for $v_a = 0.5$ (solid line), 1.0 (long dashes) and 2.0 m/s (short dashes) observed with (a) the black Nomex® and (b) reflective outer layer. Measurements were performed at $t_a = 5$ °C, RH = 50% with HHS underwear. Notes. FIR—far infrared radiation, v_a —air velocity, t_a —air temperature, RH—relative humidity; for clothing codes see Table 1.

relations had been reported from experiments with short wave radiation [36].

3.3. Interaction of FIR Effects With Wet Underwear

Figure 5 shows the heat losses with dry and wet ULF underwear as well as the rate of evaporation measured with different outer layers for the reference condition ($t_r = t_a$) compared to high intensity all-side radiation ($t_r = 50$ °C). With dry ULF underwear the reduction in heat loss under radiant load, i.e., the heat gain from FIR was again similar for the nonreflecting materials (Figure 5a), confirming the results obtained with HHS underwear (Figure 1). Wetting the underwear increased the heat loss in all conditions (Figure 5b), but more for permeable, cotton and Nomex® compared to the impermeable suit, which also showed a lower rate of evaporation (Figure 5c).

However, wetted underclothing caused differing outcomes with respect to the radiation effect. For the impermeable PVC-coated garment, the decrease in heat loss under radiant stress, i.e., heat gain (cf. Equation 1), appeared to be steeper with wet than with dry ULF, and the heat gain for the laminated Nomex® was higher than with the cotton, PERM and black Nomex® material.

Figure 5d presents the change in heat gain in wet versus in dry ULF. For PERM, cotton and the black Nomex® outer layers, the heat gain from FIR as calculated with Equation 1 was lower in wet ULF. For the laminated Nomex® suit a slight increase in heat gain was observed in wet ULF, whereas this increase was considerably greater in the impermeable outer layer (Figure 5d).

Correspondingly, the effect of FIR on the rate of evaporation (Figure 5c) differed between the outer layers. Whereas the impermeable

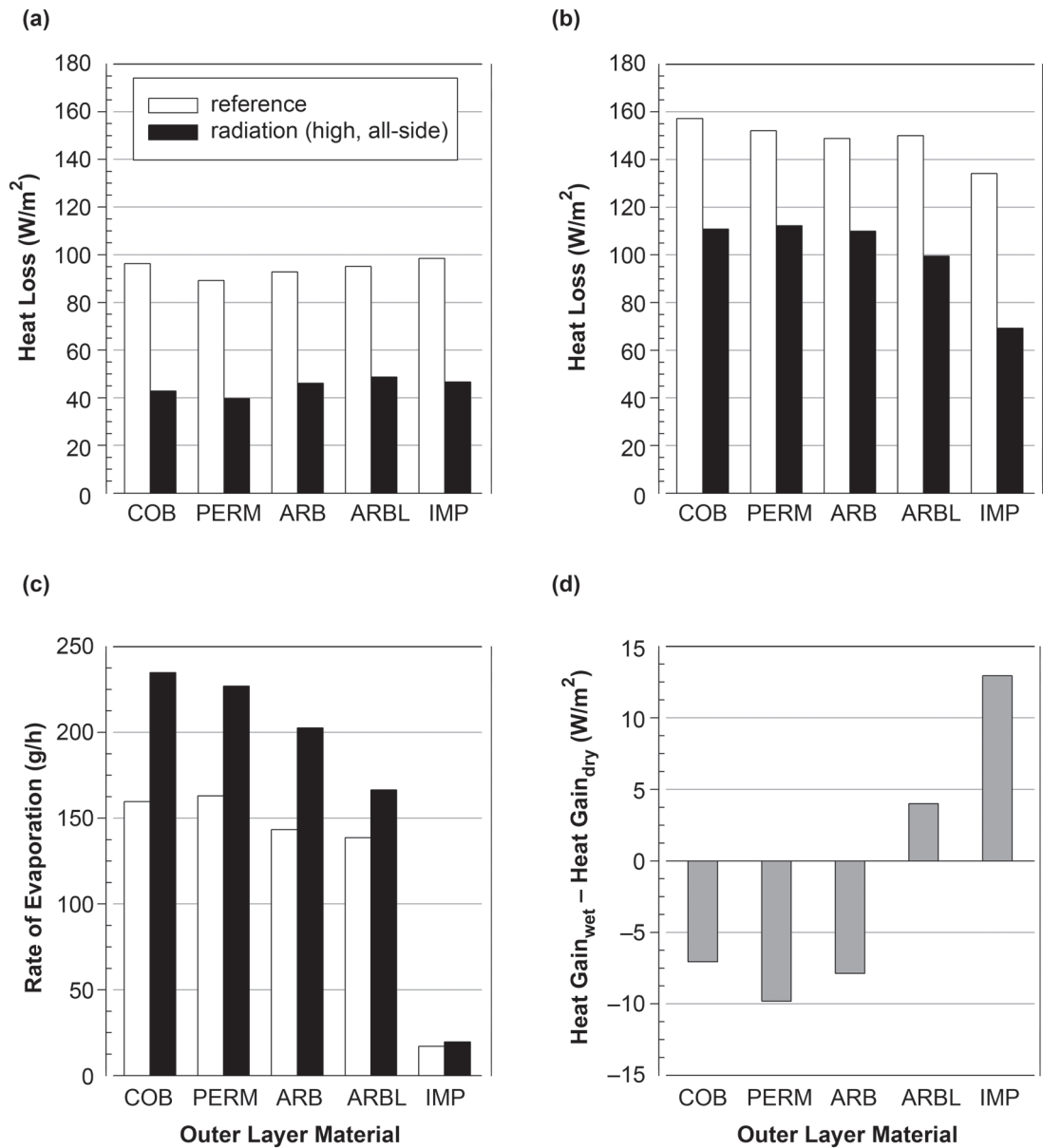


Figure 5. Heat loss with (a) dry and (b) wet ULF underwear as well as evaporation rate (c) with wet ULF measured at $t_a = 5\text{ }^\circ\text{C}$, $v_a = 0.5\text{ m/s}$, $\text{RH} = 50\%$ under reference ($t_r = t_a$) and all-side FIR ($t_r = 50\text{ }^\circ\text{C}$) conditions with different outer layers. Panel (d) depicts the effect of wetting the underwear on the heat gain from FIR as calculated from the heat loss data in (a) and (b) with Equation 1. *Notes.* t_a —air temperature, v_a —air velocity, RH —relative humidity, t_r —mean radiant temperature, FIR—far infrared radiation; for clothing codes see Table 1.

layer only showed a negligible effect of FIR on evaporation, the increase in evaporation rate with FIR observed with the laminated Nomex® was smaller than with the other permeable materials.

4. DISCUSSION

This study used a thermal manikin to determine the heat gain from long wave radiation through

protective clothing by subtracting the decreased heat loss measured under radiation stress from the heat loss obtained in a reference condition without radiant load. Table 3 summarises the principal results of both the measured heat loss and the heat gain from FIR as calculated with Equation 1 for the different research questions.

In the range of the applied conditions, the increase in this heat gain with radiation intensity

was well approximated with a linear function of $(t_r - t_a)$, thus confirming this simplified approach used in some models and assessment procedures [5, 20, 37].

Heat gain in relation to radiation intensity for the reflective suit showed only minimal increase compared to all other materials. In the latter group, the influence of the material and colour of outer garments on heat gain was small especially with two- or three-layer systems. This was in contrast to experiments with short wave radiation [28, 36, 38] showing definite colour effects with one- and two-layer clothing, but might be explained with the similar emissivity values of ~ 0.9 in the far infrared range.

It is well known that wind lowers the effective clothing insulation, i.e., that the heat loss increases with wind speed [39]. The observed attenuating effect of wind speed on the heat gain calculated from the heat losses with Equation 1 and its interaction with FIR intensity had also been reported from experiments with short wave radiation [36] and could be expected from physical considerations [29].

Adding inner layers also attenuated the heat gain from FIR; however, our results did not support a reduction proportional to the number of inner layers as postulated by Lotens and Pieters [20] and Lotens [40], as the three-layer systems with HHS and ULF showed effects similar to ULF alone combined with the outer layers. Instead, the influence of fabric density and material thickness, as evident by the reduced heat gain with ULF compared to HHS underwear, seems important. The highly significant negative correlation of heat gain with clothing insulation was well fitted by a reciprocal regression function thus confirming existing prediction formulas [22, 37]. Because clothing insulation also depends on the number of inner layers as well as on fabric density and thickness [1], it might be a suitable surrogate measure for capturing these influences on the heat gained from FIR in heat stress assessment procedures, especially when considering the information on clothing insulation already available in international standards [5, 31].

Wetting the inner layer, which might occur in real working conditions when sweat is accumulated, caused differing effects in relation to the outer layer material. The FIR induced heat gain appeared to be lower for permeable fabrics with a more elevated rate of evaporation under radiant load. In contrast, with an impermeable outer layer, the heat gain from FIR was higher with wet than with dry underwear, though overall heat loss was higher in the wet condition.

This dependency on water vapour permeability may result from an interaction of several pathways of heat exchange in wet clothing [12, 13, 14]. The increased evaporation under FIR [25, 26] dominates with permeable clothing and may outweigh the increased heat absorbed by wet clothing [26]. With impermeable clothing, another avenue of heat exchange with moisture evaporating near the skin followed by condensation in the outer clothing layers and thus increasing heat loss, similar to a heat pipe effect became apparent [12]. As this avenue turned out to be less effective at higher temperatures [12, 13], the increased heat gain from FIR with wet impermeable clothing may be explained, because FIR will increase the temperature of the outer layer and thus reduce the re-condensation of moisture. In addition, transport of water vapour from the outer layers to the skin contributing to heat gain was observed in studies with higher radiant load [23, 24].

5. CONCLUSIONS

Concerning the prediction of the heat transferred through protective clothing by heat budget models applied in assessment procedures, it may be concluded from the results obtained within the THERMPROTECT project that thermal radiation causes heat gain on the surface of the skin, which

- increases approximately linearly with radiation intensity $(t_r - t_a)$;
- depends on the different reflecting/emitting properties of the clothing in the long (and short) wave spectrum with FIR showing no evident colour effect as it was the case with solar (short wave) radiation [28, 36, 38];

- is attenuated with increasing insulation provided by additional layers of clothing;
- is attenuated with increasing wind speed.

The horizontal distribution of the radiation appears to be less important if the fraction of the exposed skin area remains unchanged [17, 18]. Differences in the viewing angle factors were not considered in this study.

The effects of short and long wave radiation on the dry heat loss measured with different manikins under various conditions in different laboratories during the THERMPROTECT project [27, 36] were well-predicted by models considering the aforementioned influences [20, 37]. However, the manikin experiments with wet underwear, as well as wear trials [16, 18] indicate that such models need to be expanded by considering the effects of sweat evaporation, absorption and condensation on the heat gain under thermal radiation, which may be especially relevant for impermeable garments and may also outweigh the benefits of reflective but vapour resistant clothing at low to moderate radiation intensities.

Further research, which should aim at the quantification of the moderating influence of moisture on the heat gain from thermal radiation, and which might also consider the potentially interacting effects of wind and body movements with wet clothing under radiant load, might improve existing standardised assessment procedures [5, 6] and contribute to an appropriate evaluation of the thermal stress resulting from work in protective clothing under heat radiation.

REFERENCES

1. Havenith G. Interaction of clothing and thermoregulation. *Exogenous Dermatology*. 2002;1(5):221–30.
2. Holmér I. Protective clothing in hot environments. *Ind Health*. 2006;44(3):404–13.
3. Parsons K. Heat stress standard ISO 7243 and its global application. *Ind Health*. 2006;44(3):368–79.
4. Dorman L, Havenith G. The effects of protective clothing on energy consumption during different activities. *Eur J Appl Physiol*. 2009;105(3):463–70.
5. International Organization for Standardization (ISO). Ergonomics of the thermal environment—analytical determination and interpretation of heat stress using calculation of the predicted heat strain (Standard No. ISO 7933:2004). Geneva, Switzerland: ISO; 2004.
6. Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, et al. Development and validation of the predicted heat strain model. *Ann Occup Hyg*. 2001;45(2):123–35.
7. Cheuvront S, Montain S, Goodman D, Blanchard L, Sawka M. Evaluation of the limits to accurate sweat loss prediction during prolonged exercise. *Eur J Appl Physiol*. 2007;101(2):215–24.
8. Gebhardt H, Kampmann B, Müller BH. Arbeits- und Entwärmungsphasen in wärmebelasteten Arbeitsbereichen [Work-rest cycles during work in the heat]. Dortmund, Germany: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin; 2007.
9. Forsthoff A, Mehnert P, Neffgen H. Comparison of laboratory studies with predictions of the required sweat rate index (ISO 7933) for climates with moderate to high thermal radiation. *Appl Ergon*. 2001;32(3):299–303.
10. Havenith G, Holmér I, Meinander H, den Hartog EA, Richards M, Bröde P, et al. THERMPROTECT. Assessment of thermal properties of protective clothing and their use. Summary Technical Report, European Union Contract No. G6RD-CT-2002-00846. 2005. Retrieved March 18, 2010, from: <http://www.lboro.ac.uk/departments/hu/groups/htel/THERMPROTECT/THERMPROTECT%20report%201.htm>
11. Kuklane K, Gao C, Holmér I, Giedraityte L, Bröde P, Candas V, et al. Calculation of clothing insulation by serial and parallel methods: effects on clothing choice by IREQ and thermal responses in the cold. *International Journal of Occupational Safety and Ergonomics (JOSE)*. 2007;13(2):103–16.
12. Havenith G, Richards MG, Wang X, Bröde P, Candas V, den Hartog E, et

- al. Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects. *J Appl Physiol*. 2008;104(1):142–9.
13. Richards MGM, Rossi RM, Meinander H, Bröde P, Candas V, den Hartog E, et al. Dry and wet heat transfer through clothing dependent on the clothing properties under cold conditions. *International Journal of Occupational Safety and Ergonomics (JOSE)*. 2008;14(1):69–76.
 14. Bröde P, Havenith G, Wang X, Candas V, den Hartog E, Griefahn B, et al. Non-evaporative effects of a wet mid layer on heat transfer through protective clothing. *Eur J Appl Physiol*. 2008;104(2):341–9.
 15. Meyer JP, Rapp R. Survey of heat stress in industry. *Ergonomics*. 1995;38(1):36–46.
 16. Meinander H, Bröde P, THERMPROTECT network. Effect of long wave radiation on heat loss through protective clothing ensembles—material, manikin and human subject evaluation. In: 6th International Thermal Manikin and Modeling Meeting (6I3M): Thermal Manikins and Modelling. Hong Kong: The Hong Kong Polytechnic University; 2006. p. 29–40.
 17. Bröde P, Kuklane K, Candas V, den Hartog E, Griefahn B, Holmér I, et al. Heat transfer through protective clothing under symmetric and asymmetric long wave thermal radiation. *Z Arb Wiss*. 2008;62(4):267–76.
 18. van Es EM, den Hartog EA, Bröde P, Candas V, Heus R, Havenith G et al. Effects of short wave radiation and radiation area on human heat strain in reflective and non-reflective protective clothing. In: 3rd European Conference on Protective Clothing (ECPC) and NOKOBETEF 8. Protective Clothing Towards Balanced Protection [CD-ROM]. Warszawa, Poland: CIOP-PIB; 2006.
 19. Neuschulz H. Thermophysiologische Beanspruchung des menschlichen Organismus durch anisotrope Infrarotstrahlung [Thermal strain of the human organism by anisotropic infrared radiation]. Bremerhaven, Germany: Wirtschaftsverlag N. W. Verlag für neue Wissenschaft; 2003.
 20. Lotens WA, Pieters AM. Transfer of radiative heat through clothing ensembles. *Ergonomics*. 1995;38(6):1132–55.
 21. Müller BH, Hettinger T. Influence and assessment of heat radiation. *Ergonomics*. 1995;38(1):128–37.
 22. Shapiro Y, Moran D, Epstein Y, Stroschein L, Pandolf KB. Validation and adjustment of the mathematical prediction model for human sweat rate responses to outdoor environmental conditions. *Ergonomics*. 1995;38(5):981–6.
 23. Keiser C, Rossi RM. Temperature analysis for the prediction of steam formation and transfer in multilayer thermal protective clothing at low level thermal radiation. *Text Res J*. 2008;78(11):1025–35.
 24. Barker RL, Guerth-Schacher C, Grimes RV, Hamouda H. Effects of moisture on the thermal protective performance of firefighter protective clothing in low-level radiant heat exposures. *Text Res J*. 2006;76(1):27–31.
 25. Paul GT, Wilhelm RH. Radiation drying of textiles. *Text Res J*. 1948;18(10):573–97.
 26. McFarland EG, Carr WW, Sarma DS, Dorrity JL. Effects of moisture and fibre type on infrared absorption of fabrics. *Text Res J*. 1999;69(8):607–15.
 27. Bröde P, Candas V, Kuklane K, den Hartog EA, Havenith G, Griefahn B et al. Effects of heat radiation on the heat exchange with protective clothing—a thermal manikin study. In: 3rd European Conference on Protective Clothing and NOKOBETEF 8: Protective Clothing—Towards Balanced Protection [CD-ROM]. Warszawa: CIOP-PIB; 2006.
 28. Kuklane K, Gao C, Holmér I, THERMPROTECT network. Effects of natural solar radiation on manikin heat exchange. In: 3rd European Conference on Protective Clothing and NOKOBETEF 8: Protective Clothing—Towards Balanced Protection [CD-ROM]. Warszawa: CIOP-PIB; 2006.
 29. International Organization for Standardization (ISO). Ergonomics of the thermal environment—instruments for measuring physical quantities (Standard No. ISO 7726:1998). Geneva, Switzerland: ISO; 1998.
 30. Gebhardt H, Müller BH, Hettinger T, Pause B. Physiologische Bewertung von Strahlungsheizungen [Physiological assessment of infrared radiators].

- Bremerhaven, Germany: Wirtschaftsverlag N. W. Verlag für neue Wissenschaft; 1995.
31. International Organization for Standardization (ISO). Ergonomics of the thermal environment—estimation of thermal insulation and water vapour resistance of a clothing ensemble (Standard No. ISO 9920:2007). Geneva, Switzerland: ISO; 2007.
 32. International Organization for Standardization (ISO). Textiles—physiological effects—measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test) (Standard No. ISO 11092:1993). Geneva, Switzerland: ISO; 1993.
 33. International Organization for Standardization (ISO). Textiles—determination of the permeability of fabrics to air (Standard No. ISO 9237:1995). Geneva, Switzerland: ISO; 1995.
 34. Bonnaire T, Touchais G. NF P 92-501. Epiradiateur test. In: Troitzsch J, editor. *Plastics flammability handbook. Principles, regulations, testing, and approval.* Munich, Germany: Hanser; 2004. p. 298–9
 35. International Organization for Standardization (ISO). Clothing. Physiological effects. Measurement of thermal insulation by means of a thermal manikin (Standard No. ISO 15831:2004). Geneva, Switzerland: ISO; 2004.
 36. Havenith G, Wang X, THERMPROTECT network. Interaction effects of radiation and convection measured by a thermal manikin wearing protective clothing with different radiant properties. In: *The Third International Conference on Human–Environment System: ICHES '05.* Tokyo, Japan: Bunka Women's University; 2005. p. 47–50.
 37. den Hartog EA, Bröde P, Candas V, Havenith G. Effect of clothing insulation on attenuation of radiative heat gain. In: *12th International Conference on Environmental Ergonomics: Environmental ergonomics XII.* Ljubljana, Slovenia: Biomed; 2007. p. 157–8.
 38. Clark JA, Cena K. Net radiation and heat transfer through clothing: the effects of insulation and colour. *Ergonomics.* 1978;21(9):691–6.
 39. Havenith G, Nilsson HO. Correction of clothing insulation for movement and wind effects, a meta-analysis. *Eur J Appl Physiol.* 2004;92(6):636–40.
 40. Lotens WA. Heat exchange in clothing. In: *Stellman JM, editor. Encyclopaedia of occupational health and safety.* 4th ed. Geneva, Switzerland: International Labour Organization; 1998. p. 42.23–9.