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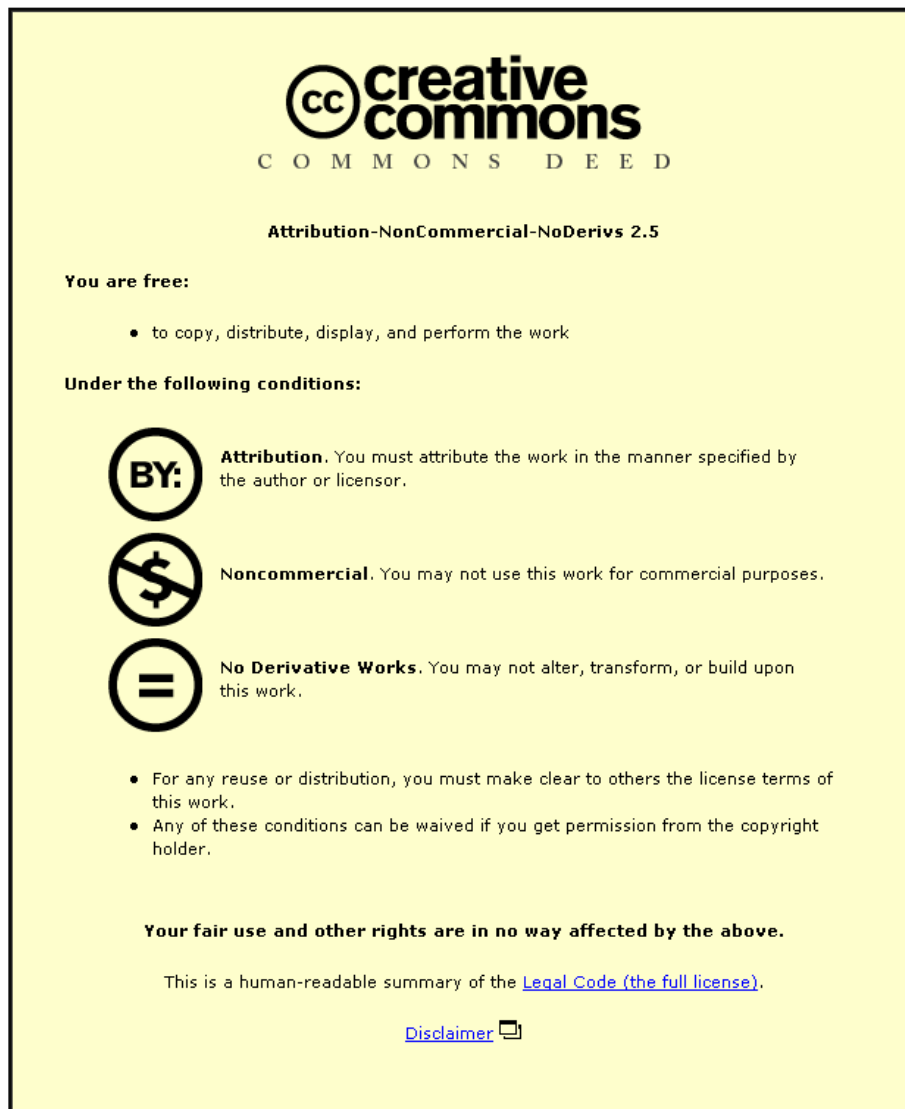
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## **Radiant Heat Transfer Network in the Simulated Protective Clothing System under High Heat Flux**

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### **ABSTRACT**

A radiant network model was developed for design of the protective clothing system against solar and infrared radiative heat flux. A one-dimensional model was employed in the present study, because the aim of this study was to obtain precise temperature distribution through the system with use of a rather simple geometry. The model consists of a hot plate simulating the skin, layered underwear, an air gap of 8 mm thick, and a protective clothing layer. In the present study, several protective clothing materials made of para-polyamide fibre were used. Materials were identical, but had different colours. A series of experiments simulating the human wearing clothes has also been performed. One of the peculiar observations in the present experiment was that temperature on the protective clothing surface exposed to the radiation was often lower than the one on the inside of the outer fabric facing to the layered underwear; that is, the highest temperature arises inside the clothing and not on the clothing surface itself. Through an analytical solution of the heat conduction in the clothing with consideration of radiation heat transfer, it has been indicated that the point of the highest temperature appears in a depth about 0.3 mm from the surface in case of the IR heat flux, while 0.2 mm in case of the solar. This small but noticeable difference in the depth of the highest temperature between the two radiation types is due to the difference in the wavelength of the radiation. The position of the highest temperature has been revealed to be dependent upon properties of the material, the wavelength of the radiation and the heat transfer coefficient from the surface to the environment.

**Key words:** protective clothing, heat transfer, solar and infrared waves, high heat flux

### **INTRODUCTION**

A research project of THERMPROTECT is being conducted to provide data and models in order to improve standards for the use of the personal protective clothing (PPC) and equipment (PPE). One of the objectives in the project is to describe mechanism of heat transfer through the protective clothing system during exposure to various radiant environments such as solar and long waves in terms of the interaction between the heat transfer and properties of the PPC. In the present study, the radiant heat transfer in the protective clothing system

is discussed numerically using a simulated clothing system and a developed model in terms of obtaining precise temperature distribution in the system.

### **HEAT TRANSFER MODEL**

The radiant heat transfer model with/without radiation source is drawn in Figure 1. In the model, the simulated skin surface was controlled at 35 °C and the environmental temperature was maintained at 20 °C. Upper and bottom lines indicate temperature distribution in the system with/without the radiation, respectively.

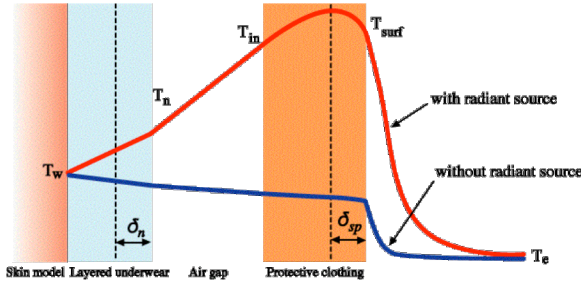


Figure 1 Theoretical model of the heat transfer with/without exposure to the radiant heat source.

According to results of the preliminary test, surface temperature of the protective clothing  $T_{surf}$  was somewhat lower than that of its inner surface during exposure to the radiant heat flux. We will analyse this temperature distribution with use of a heat transfer model depicted in Figure 2. A simple one-dimensional model is employed. We assume that the radiant heat flux is attenuated in the test protective clothing (henceforth, PC) according to the following equation,

$$q(x) = q_0 e^{(x \square d_{sp}) / \square_{sp}} \quad (1)$$

where  $q$  is the heat flux ( $\text{W} \cdot \text{m}^{-2}$ ),  $x$  the distance from the reverse side of the PC (m),  $d_{sp}$  the thickness of the PC (m),  $\square_{sp}$  the radiation permeation depth of the PC (m). Then the heat release  $Q_{sp}^*$  ( $\text{W} \cdot \text{m}^{-3}$ ) in the PC becomes

$$Q_{sp}^{\square} = \frac{q_0}{\square_{sp}} e^{(x \square d_{sp}) / \square_{sp}} \quad (2)$$

Similarly, the heat flux attenuation and the heat release in the layered underwear can be given as

$$q(x) = q_{0,n} e^{(x \square d_n) / \square_n}, \quad (3)$$

$$Q_n^{\square} = \frac{q_{0,n}}{\square_n} e^{(x \square d_n) / \square_n} \quad (4)$$

where  $x$  in Eqs. (3) and (4) is the distance from the skin model (m),  $d_n$  the thickness of the layered underwear (m),  $\square_n$  the permeation depth of the layered underwear and  $q_{0,n}$  is the incident radiant heat flux to the layered underwear which will be determined later ( $\text{W} \cdot \text{m}^{-2}$ ).

Note that, according to Eq. (1), the radiation heat flux over the reverse side of the PC is not zero; that is,

$$q_{through} = q_0 e^{\square d_{sp} / \square_{sp}}, \quad (5)$$

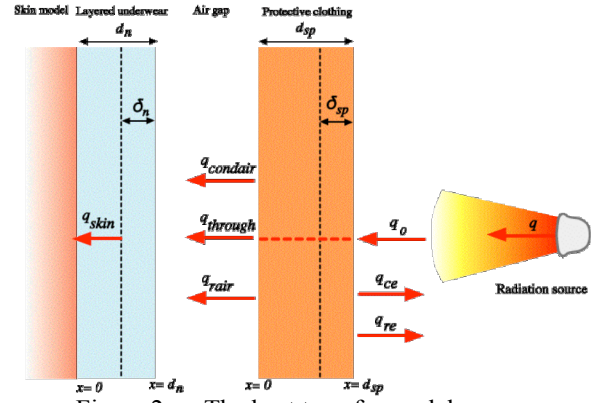


Figure 2 The heat transfer model.

where  $q_{through}$  means the heat flux which penetrates through the PC without being absorbed and attains to the air gap directly. The incident radiant heat flux to the layered underwear ( $q_{0,n}$ ) is given by

$$q_{0,n} = q_{through} + q_{r,air} \quad (6)$$

where  $q_{r,air}$  is the radiant heat flux from the reverse side of the PC. The  $q_{cond,air}$  in Figure 2 is the heat flux due to the heat conduction through the air gap, which is obtained from the temperature difference across the air gap. Finally  $q_{skin}$  is the heat flux through the layered underwear ( $\text{W} \cdot \text{m}^{-2}$ ) and can be calculated using the measured temperature gradient in the layered underwear. Note that

$$q_{skin} = q_{cond,air} + q_{through} + q_{r,air} \quad (7)$$

from which we can estimate the  $q_{through}$ . Then finally, we can calculate the radiation permeation depth with use of Eq. (5).

In Figure 2,  $q_{re}$  is the radiant heat flux from the PC surface to the environment ( $\text{W} \cdot \text{m}^{-2}$ ). Note that the direct reflection of the radiation from the lamp is not induced in  $q_{re}$ , because it doesn't affect the heat balance inside the PC. The convective heat flux from the surface of the PC to the environment ( $q_{ce}$ ,  $\text{W} \cdot \text{m}^{-2}$ ) can be given by

$$q_{ce} = h_{ce} (T_{surf} \square T_e). \quad (8)$$

The heat transfer coefficient  $h_{ce}$  ( $\text{W} \cdot \text{m}^{-2} \text{K}^{-1}$ ) can be obtained from the Nusselt number for the laminar boundary layer given by Kakaç and Yener [1995]. Without the radiant source, the surface temperature of the PC is isothermal. On the other hand, during the exposure to the radiant source, the radial non-uniformity of the incident radiant heat flux causes the radial distribution also in the surface temperature, which results in the streamwise development of the

Table 1 Properties of the protective and the underwear clothings.

	Thickness (mm)	Weight (g·m <sup>-2</sup> )	Thermal conductivity (W·m <sup>-1</sup> ·K <sup>-1</sup> )	Emissivity at IR (-)	Emissivity at Solar (-)
<b>Protective clothing</b>					
Orange	0.55	265	0.037	0.72	0.74
Black	0.55	265	0.029	0.90	0.77
Navy	0.55	265	0.035	0.98	0.73
Reflective mesh	0.22	106	0.034	0.32/0.86*	0.17/0.75*
<b>Underwear</b>					
PP1	1.40	140	0.044	0.90	0.90
PP2	1.13	176	0.038	0.90	0.90

\* back face

heat transfer coefficient in the boundary layer flow. This effect is taken account in the calculation of  $h_{ce}$  referring to Kakaç and Yener [1995].

## EXPERIMENT

### Materials

In the study, three materials for the protective clothing made of para-polyamide fibre (trademarked Nomex) were selected because of their wide practical use for the PPC. Characteristics of the selected materials are summarised in Table 1. The properties of the selected materials are identical except the colour and the thermal conductivity. A material whose surface side is reflective but not on the reverse side was also employed as the test material. The three Nomexes are tightly woven while the rest of the material is extremely rough-woven.

In order to a simulate practical clothing system, two types (PP1 and PP2, henceforth) of materials were also selected for underwear. The PP1 and PP2 were employed for the tests of long wave and solar, respectively.

### Setup

Figure 3 shows the employed apparatus for the long wave and solar radiation tests. The temperature of the base plate was regulated to be constant at 35 °C to simulate the skin surface condition. Five-layered underwear material was directly placed on the simulated skin surface. The test protective clothing material was mounted over the layered underwear with an air gap of 8 mm thick. Fine thermocouples were put on the surface of each layer of the underwear and on both sides of the test material.

Epiradiateur and Thorn-CSI lamps were used to provide the long wave and the solar radiation heat fluxes of 700 W·m<sup>-2</sup> to 1,000 W·m<sup>-2</sup> at the level of the PC, respectively.

Air flow of 1 m·s<sup>-1</sup> was provided by an air blower to keep surrounding of the apparatus at a constant

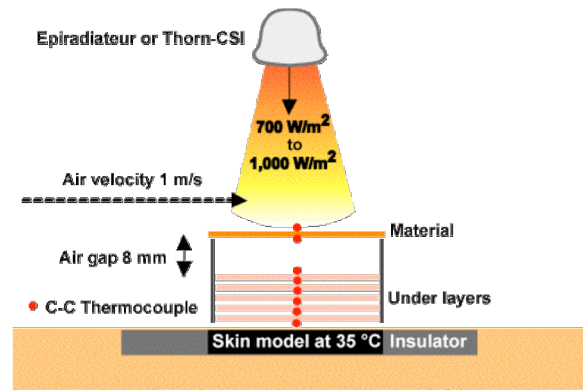


Figure 3 Experimental setup to simulate the clothing system.

condition.

### Procedure

All measurements were conducted in two climate chambers in which temperature was maintained at 20 °C and relative humidity was at 40 % in the one chamber and at 60 % in the other one.

Measurement was conducted firstly without radiation exposure until temperature distribution in the clothing system became steady. Then the irradiation was switched on and the measurement was continued till the temperature became stabilized again.

## RESULTS AND DISCUSSION

We compare our analytical method for estimating the temperature distribution in the protective clothing system with the experimental results. Results obtained from the experiment and the calculation are plotted for the long wave and solar in Figures 4 and 5, respectively. The experimental and the calculated values agree well with each other except for the surface temperature of the PC during the exposure. The experimental temperatures of the outer surface of the test material are lower than the calculated ones as seen in both the figures. This is probably because the surface sensors indicated average temperature of the surface and the environment, even though fine thermocouples were employed.

This model provides us with a good explanation why the highest temperature arises not over the surface but inside the PC; that is, the radiant heat is converted to the sensible heat inside the PC (according to Eq. (2)) and flows either towards the surface or towards the air gap. This causes the highest point of temperature inside the PC.

The estimated incident radiant heat flux ( $q_0$ ) and

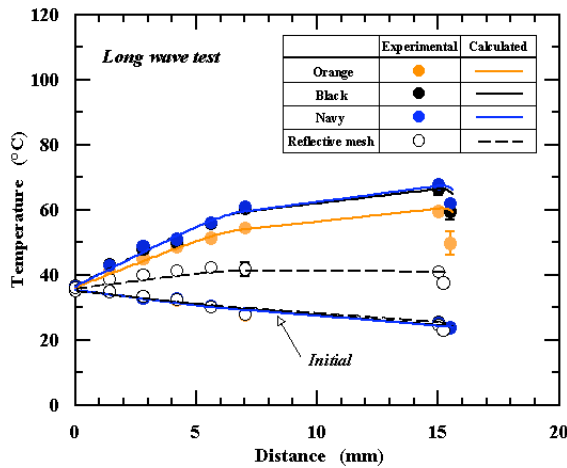


Figure 4 Experimental and calculated temperature distributions in the clothing system during exposure to the long wave are plotted against the distance from the simulated skin. Initial distributions are also given.

Table 2 Calculated permeation depth of radiation into the material and the given radiant heat flux to the material during exposed to the radiations.

Exposed to	Material	$\delta_{sp}$ (mm)	$q_0$ (W·m <sup>-2</sup> )
Long wave	Nomex Orange	0.26	633
	Nomex Black	0.29	740
	Nomex Navy	0.26	795
	Reflective mesh	0.19	214
Solar	Nomex Orange	0.37	1,042
	Nomex Black	0.24	1,524
	Nomex Navy	0.21	1,664
	Reflective mesh	0.11	671

the permeation depth ( $\bar{\Delta}_{sp}$ ) are listed in Table 2. The radiant heat flux  $q_0$  is the sum of the convective heat flux ( $q_{ce}$ ), the radiant heat loss from the surface to the environment ( $q_{re}$ ) and the passing through heat flux ( $q_{through}$ ). The permeation depth  $\bar{\Delta}_{sp}$  is calculated from  $q_0$  and  $q_{through}$  with use of Eq. (5).

The permeation depth of the Nomexes is 0.26 mm to 0.29 mm (about 50 % of  $d_{sp}$ ) for the long wave. The one for the solar is 0.21 mm to 0.24 mm and is smaller than the one for the long wave. (The  $\bar{\Delta}_{sp}$  of Orange needs further examination). For the reflective mesh,  $\bar{\Delta}_{sp}$ s in the cases of exposure to the long wave and the solar were 0.19 mm (86 % of the  $d_{sp}$ ) and 0.11 mm (55 % of the  $d_{sp}$ ), respectively. These results reflect the difference in the wavelength of the two radiation.

## CONCLUSION

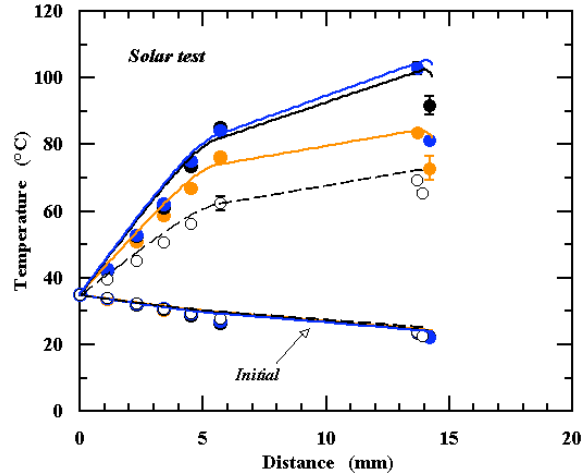


Figure 5 Temperature distribution obtained from the experiment and the calculation in the clothing system with/without the exposure to the solar wave.

A series of experiments was performed for the radiant heat transfer in the simulated protective clothing system for the long-wave and the solar irradiations. An analytical model has been developed and the calculated results agree well with the experiment. The permeation depth of the radiant heat flux is obtained for the tested protective clothing materials. The depth for the long-wave is found to be larger than that for the solar.

The analytical model reveals the reason why the highest temperature arises not over the surface but inside the protective clothing.

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