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Water Vapour Transfer in the Simulated Protective Clothing System with Exposure to Intensive Solar Radiation

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ABSTRACT
A series of experiments has been performed to study the moisture transfer in the protective clothing exposed to a high short wave (solar) radiant heat flux at a normal condition of 20 °C with 40 % RH in terms of heat stress caused by accumulated sweat in underwear. To simulate a practical situation, an experimental set-up was composed with a hot plate simulating the skin, one layer underwear, one of air gap of 8 mm thick, and one protective clothing (PC) layer. Three types of the PC materials made of para-polyamide fibre were employed. The underwear was soaked completely wet with 560 g·m⁻² distilled water to simulate the heavy sweating. Temperature of each layer was measured with thermocouples. Rate of mass transfer was calculated from the change of weight in a specific period. The water vapour transfer rate during exposure to the solar radiation dropped significantly down to 50 % to 70 % of the one without the radiation, since the water vapour evaporated from the underwear was transferred not only to the environment but also to the skin. The transferred mass flux from the underwear to the skin indicated substantial heat stress, which was estimated to be equivalent to about 3 to 4 K increase in the body temperature of an average-sized man.

Key words: protective clothing, heat and water vapour transfer, solar, high radiative heat flux, heat stress

INTRODUCTION
Protective clothing (PC, hereafter) effectively protects the body from harsh hot and cold environments while it also produces physiological problems for the body such as an additional load and heat stress because of the heavy weight and restricted evaporated heat loss by sweating and a decrease in free-movement due to stiffness. Where a wearer of the PC works under a high radiant condition, an additional risk that might be accidentally inflicted is that of steam burns of the skin originating from the wearer’s sweat [Heus et al., 2005].
In the present study, the heat and water vapour transfer relevant to risks such as the heat stress and the steam burn under a high solar radiation has been discussed through a series of tests using a simulation model.

EXPERIMENTAL

Material
Three materials of the PC made from para-polyamide fibre Nomex®, which were coloured in orange, black, and navy, were selected for the test. Properties of the materials are summarised in Table 1. The tested Nomexes are identical except the colour and the thermal conductivity. One additional material was also selected as the test material, which was aluminised on the face-side but not on the reverse-side (henceforth, reflective mesh). The vapour permeable reflective material was roughly woven, while the tested Nomexes were tightly woven materials.
One knitted material (polypropylene; PP in Table 1) was chosen as the underwear in the experiment.

Simulating skin model
Figures 1 shows the experimental setup to simulate
the PC system for the solar radiation test. The temperature of the plate was maintained at 35 °C constantly.

One-layer of the underwear was put on the plate directly. The test PC material was set over the underwear with an air gap of 8 mm thick. Fine thermocouples were employed for measurement of temperature in the system. They were mounted on surfaces of the plate, the underwear, and each side of the test material.

A Thorn-CSI lamp was employed as the solar radiation source of about 700 W·m⁻², (at the level of the outer fabric), which was located just above the PC system. In order to simulate the high sweat rate due to a heavy workload, the underwear was completely soaked with 560 g·m⁻² distilled water.

**Procedure**

All measurements were performed in a climate chamber in which the environmental temperature and relative humidity were controlled at 20 °C and 40 %.

Laminar air flow of 1 m·s⁻¹ was provided by an air blower over the PC system.

The measurement was conducted for 40 min in total because a linearity of water vapour transfer within that period was ensured from our preliminary tests. For the first 10 min, the experiment was conducted without the solar radiation and then with or without the irradiation for the next 30 min, depending on the condition selected.

**RESULTS**

The temperature distribution in the PC system is shown in Figure 2. Without the exposure to the solar radiation, the temperature distribution of the each PC material indicated almost the same value. During the exposure to the solar radiation, temperature of the PC material was the highest among those of the underwear, the plate and the environment.

Transferred mass flux through the PC system is shown in Figure 3-a. Rate of the transferred mass flux with the solar fell significantly 30 % to 50 % of that without the solar irradiation.

In the figure, the condensed and absorbed mass flux in/over the PC are also plotted in Figure 3-b. Before exposing to the solar radiation, condensation and absorption didn’t occur in/over the Nomex orange but they took place during the exposure to the radiation. Without the solar irradiation, a small amount of the condensation and the absorption was observed for the black and navy Nomexes even though the selected three Nomexes have almost the same properties. On the other hands, during the exposure to the solar, the...
DISCUSSION

In the temperature distribution (see Figure 2), during the exposure to the solar radiation, the highest temperature peak is seen on the inside of the PC material. According to our analysis of the temperature distribution in the PC system, the temperature peak must appear inside of the PC material itself [Fukazawa et al., 2005]. Additionally, it was indicated by the analysis that the actual surface temperature of the PC facing to the solar source must be several degrees Celsius higher than the measured one.

We assume that in the system the water vapour evaporates from the underwear surface and not from the plate and that total resistance is given by sum of the resistances of the underwear, the air gap, the PC material, and from the PC surface to the environment; that is, a serial resistance network is assumed.

Water vapour resistance of the underwear and the PC has been estimated from a relation expressing the resistance, thickness, and packing factor [Fukazawa et al., 2000]. In order to obtain the mass transfer coefficient from the PC surface to the environment, Reynolds-Colburn analogy [Holman, 1997] is applied from the heat transfer coefficient. Total resistance is calculated from the water vapour pressures of the underwear and the environment, and the transferred mass flux. Consequently, the water vapour resistance of the air gap can be obtained by subtracting the resistances inside the material and between the PC surface and the environment from the total resistance.

The estimated water vapour concentration profiles are given in Figures 4-a (initial) and 4-b (irradiation). The experimental results of temperature are also plotted against the distance from the plate.

During exposure to the solar radiation (see Figure 4-b), the distribution of the water vapour pressure differs noticeably from the one of the temperature. The highest value of the temperature is seen on the inside of the PC while that of the water vapour is observed on the surface of the underwear. The results infer that water vapour also transfers from the underwear to the plate simulating the skin.

The water vapour evaporated from the underwear surface and its downside begins to dry due to the irradiation. Since the plate temperature is kept constant and becomes colder than the underwear during the irradiation, the water vapour of the underwear surface is transferred not only to the environment but also to the plate. The transferred water vapour condenses once on the plate and then is absorbed in the underwear again. The condensed water vapour on the plate releases sensible heat. The released heat becomes about 14 W·m⁻² for the reflective mesh. On the other hands, comparatively larger values of 250 W·m⁻² to 320 W·m⁻² are resulted in the Nomex materials. Although we have not found reports describing the relation between steam burn and given heat flux to the skin yet, the body should be imposed with remarkably larger heat stress when this condensation takes place. These heat stresses are equivalent to 4.3 K for the Nomex orange, 3.3 K for the Nomex black and navy, and 0.2 K for the

Figure 3-a Transferred mass flux though the PC material with/without the solar radiation. Blank bar expresses without the solar and filled one with the solar.

Figure 3-b Condensed mass flux in/over the PC material with/without the solar radiation. If a negative value is indicated during the radiation, it means that the condensed water vapour without the radiation is dried out due to the radiation.
reflective mesh in terms of the increase in body temperature of the average-sized man [ISO 8996, 1990]. These results imply that the Nomex orange gives the body a larger heat stress because the underwear in the PC system indicates about 1 to 2.5 °C higher temperature, although its temperatures of the PC and the air gap are the lowest among the Nomex PCs.

According to our analysis of the radiation heat transfer in the PC system [Fukazawa et al., 2005], during the irradiation, the given heat flux to the skin is quite large due to the incident heat from the radiation source. We speculate that the steam burn is caused not only by the released sensible heat flux from the condensed water vapour but also by the increased heat flux due to the enhanced conduction through the wet underwear.

CONCLUSION

Water vapour transfer in the protective clothing system with exposure to the solar radiation was discussed through the experiment. The highest temperature peak appears inside the PC material while the highest water vapour pressure is seen over the underwear.

In our future works, analysis of the heat and water vapour distribution will be performed further. Discussion about the difference in profiles of the temperature and the water vapour concentration will be also conducted.

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REFERENCES


