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# The effect of solar radiation on temperature distribution in outdoor human–clothing–environment systems

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ABSTRACT

The present study investigates heat transfer in the human–clothing–environment system under solar radiation. A new thermal model integrating the solar radiation absorption by clothing, as well as heat conduction within the air layer and heat convection on the clothing surface, is presented. The heat transfer in this system is simply explained based on the heat conduction equation; heat transfer relating to solar radiation is added as the source of heat generation at the surface of clothing. The temperature distributions inside clothing are well predicted with variations in the amount of solar radiation, ambient temperature, air gap depth, and radiative properties. Temperatures are increased or decreased linearly with changes in the air gap distance, confirming that the temperature of the air layer inside clothing is governed by conduction. Temperature distributions differ depending on solar radiation and also radiative properties, particularly absorptance, indicating that radiative heat transfer must be included to evaluate clothing heat transfer.

## 1. Introduction

Clothing influences heat exchange between the human body and the environment, contributing to thermoregulation by creating a moderate micro-climate within the fabric layer. This function provides comfortable thermal environments around humans. Clothing is one of the six influential factors (along with air temperature, humidity, radiation, air flow, and metabolism) in the thermal comfort equation [1].

Many studies have previously addressed clothing effects on comfort. Most evaluated the thermal resistance of the human–clothing–environment system; for example, the thermal insulation characteristics of clothing expressed in clo units [2] are traditionally used in thermal comfort assessments. However, because the clo unit is defined as insulation against specific weather conditions, the treatment of clo units may be insufficient for universal application.

Heat transfer through clothing mainly proceeds by conduction and radiation [3]. Research on detailed heat transport in clothing micro-climates has been conducted both experimentally and numerically. Indoor experiments using hot plates or manikins are typical for measuring clothing insulation capabilities. In order to analyze temperature distributions inside clothing, Morozumi et al. presented a mathematical model of the air gap beneath the clothing material based on heat conduction [4]. Other analysis models have also been formulated [5–8]. These cases considered heat conduction and sometimes long-wave radiation.

Clothing protects human wearers from both cold and heat strain. In daily life, humans are often exposed to solar radiation. The strong influence of solar radiation on humans, especially outdoors, is well recognized [9]. However, in clothing research, studies typically address only heat and moisture transport through fabrics; few include the effects of solar radiation on human clothing in outdoor scenarios. The mean radiant temperature, representing radiant heat exchange, is significant, even indoors [10]. However, the effects of the radiative properties of clothing on thermal comfort have only been reported based on subjective experiences [11]. Because the thermal state of a human is considered to be well described by considering the energy balance of the human, the temperature profile near the human must be thoroughly understood. Thus, radiative effects on clothing are significant in understanding the micro-climate around humans; however, these effects remain to be validated.

Studies on the effect of clothing on human energy balance have been performed previously; however, they were based on the theory of simple heat resistance. The impact of radiative properties, determined by the color of the clothing material, was not consid-

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**Nomenclature**

| | |
|---|---|
| $g$ | gravity acceleration |
| $Gr$ | Grashof number |
| $h_{conv}$ | convection heat transfer coefficient |
| $k$ | thermal conductivity |
| $l$ | thickness of clothing |
| $L$ | infrared radiation |
| $Nu$ | Nusselt number |
| $q$ | heat flux |
| $\dot{q}$ | heat generation |
| $q_L$ | heat flux relating infrared radiation |
| $q_S$ | heat flux relating solar radiation |
| $r$ | reflectance |
| $Ra$ | Rayleigh number |
| $S$ | global solar radiation |
| $T$ | temperature |
| $y$ | coordinate |

*Greek letters*

| | |
|---|---|
| $\alpha$ | absorptance |
| $\beta$ | coefficient of thermal expansion |
| $\delta$ | length of air gap |
| $\varepsilon$ | emissivity |
| $\upsilon$ | kinematic viscosity |
| $\sigma$ | Stefan–Boltzmann constant |
| $\tau$ | transmittance |

*Subscripts*

| | |
|---|---|
| *air* | air |
| *clo* | clothing |
| *skin* | skin |

ered. Existing clothing heat-transfer models can only be applied to indoor situations. In order to determine the influence of solar radiation on human comfort, in this study, we propose a simple heat-transfer model for the human–clothing–environment system that can be applied to situations including outdoor solar radiation. In the model, dry-heat transfer is assumed to be simply governed by conduction and the steady state of the system is assumed to be fully developed. Because radiation is released and received at solid surfaces, radiative heat transfer is interpreted as a heat-generating source at solid surfaces, such as human skin and the clothing surface. Subsequently, the results predicted by the model are compared with values obtained by experiments.

## 2. Energy flow in human–clothing–environment system under solar radiation

### 2.1. Analytical model description

Fig. 1 shows the one-dimensional coordinate system for single-layered clothing, consisting of the skin surface, air layer (or air gap), clothing, and ambient air. The heat transfer in this system can be modeled based on heat transfer between horizontal parallel plates.

The heat transfer mechanism within the air gap and clothing is conduction. The steady-state heat transfer can be generally expressed as

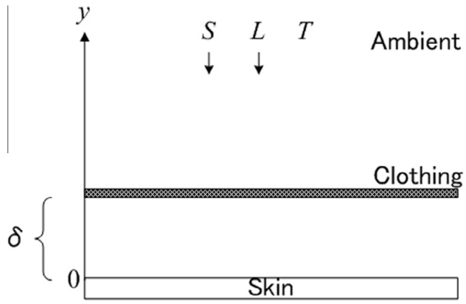

**Fig. 1.** One-dimensional model for single-layered skin-clothing-environment system.

$$\frac{d^2T}{dy^2} + \dot{q} = 0, \tag{1}$$

where $\dot{q}$ is the source term representing radiative heat generation at $y = \delta$. This radiative heat generation occurs only at the clothing interface. If the air gap depth is not specified ($y \neq \delta$), the source term $\dot{q}$ does not exist.

In the system, the clothing is characterized by the porosity of the material. Solar radiation is directly absorbed at the clothing surface depending on the absorptance of the material. Some solar radiation is transmitted to the skin surface through clothing and is absorbed there. Solar radiation reflected at the skin surface is absorbed at the inner clothing surface. Notably, reflection is considered to occur only once. The heat transfer related to solar radiation is expressed as

$$q_{S,clo} = S\alpha_{clo} + S\tau_{clo}r_{skin}\alpha_{clo}. \tag{2}$$

Infrared radiation from the sky is directly absorbed at the clothing surface. Infrared radiation is simultaneously exchanged between clothing and the skin surface based on the Stefan–Boltzmann law depending on the surface temperature. This heat transfer related to infrared radiation is expressed as

$$q_{L,clo} = \varepsilon_{clo}\left(L - \sigma T_{clo}^4\right) + \varepsilon_{clo}\sigma\left(\varepsilon_{skin}T_{skin}^4 - T_{clo}^4\right). \tag{3}$$

Thus, the source term of radiative heat gained by clothing is expressed as

$$\dot{q} = \frac{q_{S,clo} + q_{L,clo}}{l} \quad (y = \delta). \tag{4}$$

As boundary conditions between the skin surface and the air gap and between the air gap and clothing, convective heat transfer is assumed and expressed as

$$q_{skin} = h_{conv}(T_{skin} - T_{air}) \quad \text{for skin surface;} \tag{5}$$

$$q_{clo} = h_{conv}(T_{clo} - T_{air}) \quad \text{for clothing surface.} \tag{6}$$

The convection heat transfer coefficient is expressed as

$$h_{conv} = Nu\frac{k_{air}}{\delta}. \tag{7}$$

When $Ra$ is less than ~1700, heat transfer is caused almost exclusively by conduction and $Nu$ can be set to 1.0. Heat transfer changes from conductive to convective as $Ra$ becomes larger [4]. The $Nu$ cor-