International Journal of Heat and Mass Transfer 115 (2017) 523–529

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Investigation of heat transfer and temperature distribution in outdoor human–clothing–environment systems with double-layered ensemble

Yasuhiro Shimazaki [a,*], Atsumasa Yoshida [b], Takanori Yamamoto [c]

[a] Department of Human Information Engineering, Okayama Prefectural University, 111 Kuboki, Soja, Okayama 719-1197, Japan
[b] Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
[c] Technology Research Institute of Osaka Prefecture, 2-7-1 Ayumino, Izumi, Osaka 594-1157, Japan

ARTICLE INFO

Article history:
Received 17 February 2017
Received in revised form 27 May 2017
Accepted 19 July 2017

Keywords:
Solar radiation
Clothing layer
Thermal modeling
Outdoor climate
Air enclosure

ABSTRACT

The thermal behavior in a clothing microclimate is an important aspect related to thermal comfort. Situation-dependent analyses are required to understand the heat transfer of clothing; thus, the heat transfer and temperature distributions in a double-layered human–clothing–environment system in the presence of solar radiation are investigated as practical application in this study. A new heat transfer model modified from the previously proposed outdoor thermal model with single-layered clothing is developed. The new model integrates the radiative effects on clothing, the heat conduction within the air layer, and the heat convection on the outer surface of clothing. Radiation heat transfer is included as a source term for the clothing. Measurements of the temperature distributions are obtained under typical summer and winter atmospheric conditions with or without solar radiation to validate the model. A comparison confirms that the prediction model is valid. Subsequently, the effects of layered clothing are analyzed. Since insulation fundamentally influences the temperature distributions in the steady-state system, the temperatures at the boundary and air gap determine the slopes of the temperature distribution. Since the absorbed solar energy is more influential than the release of heat by conduction or even convection for clothing, the solar radiation and radiative properties are relatively dominant at the temperature distribution of clothing and consequently the entire system. Overall, the effects of solar radiation and the properties related to radiation are essential for evaluating the microclimate inside clothing.

1. Introduction

The heat transfer in a human–clothing–environment system influences the thermal states of humans; thus, clothing is considered to be one of the influential factors (air temperature, humidity, radiation, air flow, metabolism, and clothing) regarding thermal comfort [1]. Clothing is a human-controllable factor, and human thermal experiences can be improved by clothing quickly and easily depending on the time, situation, and personal preferences. In this regard, clothing is a basic means of creating preferable thermal environments, and an investigation of the heat transfer mechanisms in a human–clothing–environment system is effective for understanding the performance of clothing and designing better environments for humans.

Traditionally, the thermal function of a human–clothing–environment system was considered as the insulation characteristics of clothing, "*clo* units" [2]. *clo* is an experimentally measured value under specific manikin and climatic conditions without solar radiation [3], indicating that *clo* is a property of specific indoor wearing conditions. The thermal performance of clothing depends on the properties of the fabric, the air trapped between the human and the clothing, the clothing layers, and the air layer adjacent to the environment, and heat transfer through clothing consists mainly of conduction and radiation [4]. Convection effectively works at the clothing's outer boundaries under even the ordinary circumstances of the living environment [5], even though dry heat transfer is solely incorporated by one property value in the *clo* unit system.

The protective function of clothing against the outer environment may be exerted in severe outdoor scenarios in the presence of strong radiation and hot or cold environment. However, there are few studies that address the effects of clothing outdoors. Additionally, although layered clothing is typically worn, model predictions with single-layered clothing have been conducted in order to understand the thermal performance of clothing. Layered-clothing effects have been estimated by simply summing the heat resistance of each piece of clothing as in the *clo* system, and experiments on the detailed heat transfer in a clothing microclimate have not been reported. It is qualitatively understandable

* Corresponding author.
E-mail address: shimazaki@ss.oka-pu.ac.jp (Y. Shimazaki).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.07.086
0017-9310/

Nomenclature

d	length of the hot plate
g	acceleration due to gravity
Gr	Grashof number
h_{conv}	heat transfer coefficient for convection
k	thermal conductivity
l	thickness of clothing
L	infrared radiation
Nu	Nusselt number
q	heat flux
$\dot{q}$	heat generation
q_L	heat flux related to infrared radiation
q_S	heat flux related to solar radiation
Ra	Rayleigh number
S	global solar radiation
T	temperature
y	coordinate

Greek letters

α	absorptance
β	coefficient of thermal expansion
δ	length of the air gap
ε	emissivity
υ	kinematic viscosity
ρ	reflectance
σ	Stefan–Boltzmann constant
τ	transmittance

Subscripts

air	air
clo	single-layered clothing
env	environment
f	forced convection
inner	inner clothing
n	natural convection
outer	outer clothing
skin	skin

that layered clothing warms humans owing to insulation; however, complete determination of the thermal behavior of layered clothing is complex process. Actually, each clothing layer experiences a different situation. For example, solar radiation affects the outer clothing surface at most. Convection is most developed in the ambient atmosphere rather than the inner air enclosure, and the mechanism of heat transfer varies depending on where the clothing is positioned. The inner air gap between clothing and skin influences the thermal insulation, and fit of clothing has been reported to influence the effects of clothing and subsequently the thermal comfort of humans [6]. To evaluate the comfort of humans, the thermal behavior of clothing depending on the situations and wear conditions is required; thus, the conventional treatment of *clo* cannot be applied universally. Thermal resistance models are not suitable for an outdoor environment, and corrections to the insulation method for each situation have been proposed by researchers [4,7]. Evaluation of the heat transfer and temperature of the clothing microclimate is required to explain the experiences of those who wear clothes. Therefore, the detailed heat transfer in an outdoor double-layered ensemble was investigated.

The objective of this study is to determine how layered clothing influences heat transfer for humans outdoors as a practical application. The authors previously and successfully proposed a steady-state outdoor thermal model with single-layered clothing that integrated the radiative effects on clothing, the heat conduction within the air layer, and the heat convection on the clothing surface [8]. This previous model is modified to develop a new heat transfer model with double-layered clothing in this study. The temperature distribution in the system is also experimentally investigated. Subsequently, the results predicted by the model are compared with values obtained by experiments for validation. Furthermore, the effects of radiation and layering are evaluated.

2. Energy flow in the clothing microclimate

2.1. Analysis model

The developed model is an extension of the existing single-layered human–clothing–environment system in the presence of solar radiation [8]. Fig. 1 shows the one-dimensional coordinate system for single-layered and double-layered clothing based on horizontal parallel plates. In this study, dry conditions, where moisture transfer is absent, are investigated. Dry-heat transfer is simply governed by conduction and radiation, and the steady state is fully developed. Because radiation is released and received at a solid surface, heat transfer due to radiation is included as a source term at the clothing surface. Reflection and transmission are considered at once.

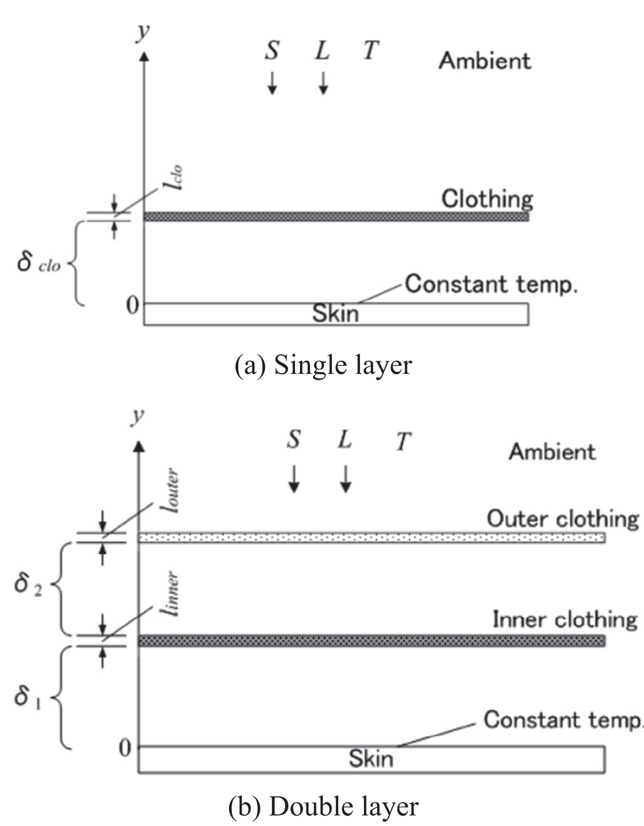

Fig. 1. One-dimensional models for the human–clothing–environment system.