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Thermal model of human body fitted with individual characteristics of body temperature regulation

Satoru Takada [a,*], Hiroaki Kobayashi [b], Takayuki Matsushita [c]

[a] *Department of Architecture, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan*
[b] *Department of Architecture and Civil Engineering, Graduate School of Science and Technology, Kobe University, Rokko, Nada, Kobe 657-8501, Japan*
[c] *Department of Architecture, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan*

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ABSTRACT

To develop a thermal model that can predict the thermal responses of the human body under given environmental conditions, it is necessary for the model to be fitted with the individual characteristics of human body temperature regulation. As the basis for this, in this paper, it is shown that the coefficients that represent the thermoregulatory responses in the two-node model (thermal model of human body) can be identified for individuals. Six coefficients related to the regulation of sweating and skin blood flow in the two-node model are tuned for the individuals involved in the experiments—the core and skin temperatures calculated by the model are fitted with the measured results for the entire thermal transient processes, including exposures to heat and cold.

1. Introduction

The thermal model of the human body (TMHB) consists of equations that describe the heat transfer in the body and regulatory responses such as sweating and blood flow rate control. If it were possible to predict the thermal responses of the human body under a given environmental condition, the TMHB would be useful in the design and evaluation of architectural environments. A large number of TMHBs have been developed for more than fifty decades. Most of them are numerical models in which the temperature distribution in the body is expressed in a discrete manner. The originality of each model lies in the manner in which the body is divided into nodes, and also in the form of the equations describing regulatory responses such as sweating and blood flow rate control. Recent models have tended to divide the body into many nodes. The evaluations of non-homogeneous environments are generally performed numerically by using models with many nodes [1–4]. In the case that many nodes are considered, it is necessary to input detailed local information (for example, blood flow rate between nodes, distribution of thermal properties, heat production, and sweat secretion) to the model; however, such physiological data are limited. Thus, the precision in the prediction of the body temperature distribution is not still sufficient although a higher resolution of the temperature distribution can be obtained in the calculated results.

For practical utilization in the design and evaluation of environments, the calculated results based on the TMHB must agree with the actual responses of the human body. The calculated results in the transient state [5] have been compared with experimental values for stepwise thermal transients [6,7]. However, it should be emphasized that the comparison between the results calculated by the TMHB and those measured in human subject experiments is not sufficient with regard to both quantity and quality, and therefore, the reliability of these models is still not sufficient.

In order to raise the reliability of the models, it is necessary to show that the model describes the real thermal responses of human body well enough through a comparison between experimental and calculated results; however, in such a procedure, another problem arises—the thermoregulatory responses of different individuals are different, even under the same environmental conditions, which makes comparison impossible without a methodology to express individual difference in the model itself. This paper proposes a methodology to consider individual characteristics in thermoregulatory responses in the TMHB.

There are a few studies that take into account individual differences. Havenith [7] expressed the individual differences in

* Corresponding author. Tel.: +81 78 803 6038; fax: +81 78 803 6038.
E-mail address: satoruta@kobe-u.ac.jp (S. Takada).

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Nomenclature

c	specific heat (J/(kg K))
clo	thermal resistance of clothing (clo)
k_{basal}	skin blood flow rate under thermally neutral conditions (L/(m^2 h))
k_{con}	coefficients of vasoconstriction (1/K)
k_{dil}	coefficients of vasodilation (L/(m^2 h K))
k_{sw}	coefficient of sweating rate model (g/(m^2 h K^2))
m_{sw}	regulatory sweating rate (kg/(m^2 s))
p_{rsw}	skin wetness due to regulatory sweating (n.d.)
p_{wet}	skin wetness (n.d.)
q_{diff}	heat loss by skin diffusion (W/m^2)
q_{max}	maximum heat loss by evaporation (W/m^2)
q_{res}	heat loss by respiration (W/m^2)
q_{rsw}	heat loss by regulatory sweating (W/m^2)
r	evaporative heat of water (J/kg)
t	time (s)
v_{bl}	skin blood flow rate (kg/(m^2 s))
F_{cl}	heat transfer efficiency of clothing (n.d.)
F_{pcl}	vapor transfer efficiency of clothing (n.d.)
K_{min}	minimum heat conductance by skin tissue (W/(m^2 K))
M	metabolic rate (W/m^2)
N	number of data obtained in a series of transient state (n.d.)
P_a	saturated vapor pressure of ambient air (mmHg)
P_{sk}	saturated vapor pressure due to skin temperature (mmHg)
S	body surface area (m^2)
T	calculated temperature (°C)
T'	measured temperature (°C)
W	mass (kg)
α	heat transfer coefficient (W/(m^2 K))
α'	moisture transfer coefficient (kg/(m^2 s mmHg))
ϕ_a	relative humidity (fraction) (n.d.)
η	working efficiency (n.d.)

Suffix

bl	blood
c	convective
cr	core
o	ambient
r	radiative
set	set point
sk	skin

the thermal resistance and capacitance of body components and in the sweating and skin blood flow rate on the basis of several individual characteristics such as body surface area, mass, and body fat percentage, and incorporated them into the model. Zhang et al. [8] used the "body builder model," which expresses individual differences by inputting elements similar to those expressed by Havenith. In these studies, the results simulated by considering the differences between individual body builds were compared with the results for which the differences were not considered; however, the results considering the differences were not clearly superior for transient states, leaving room for further study on individual differences in the thermoregulatory control system such as in regulatory sweating and skin blood flow control. There are two approaches to deal with the problem of individual differences: one is from the passive systems [9] of the body, such as thermal capacitance, thermal resistance, or surface area related to heat transfer. The other is from the controlling systems [9] of the body, such as regulatory sweating or skin blood flow. This study focuses on the latter.

The simplest model is used in this study: the two-node model proposed by Gagge et al. in 1971 [9]. In this model, regulatory sweating and skin blood flow rate are expressed as functions of the core and skin temperatures. In this study, keeping the shape of the equations as they are, the possibility of tuning the coefficients in the equations is examined based on the experimental results. First, experiments involving four subjects (naked, sedentary) are conducted. In the experiments, the subjects are exposed to a neutral temperature, which is then varied in a stepwise manner to a low temperature, high temperature, and finally neutral temperature. Second, based on the experimental data on the core and skin temperatures, the physiological constants (set point temperature of core and skin, coefficients in the dynamic model of regulatory sweating and skin blood flow rate) included in the two-node model [9] are optimized so that the difference between the experimental and calculated values of the core and skin temperatures reduce to the minimum values throughout the transient process.

2. Subject experiment

2.1. Method

Four healthy male students (Table 1) seated back to back were exposed to transient thermal conditions: nearly (thermally) neutral conditions, followed by a low air temperature, a second neutral condition, a high air temperature, and finally, a third neutral condition. The experiments were conducted in two climate chambers. The settings of the climate chambers are shown in Fig. 1 along with the schedule of the experiment. All the subjects wore only trunks (undershorts) and remained sedentary in the thermally neutral condition (29.4 °C, 47% rh) for 1 h before the experiment began. During the experiments, the core and skin temperatures, heart rate, and environmental conditions (air temperature, humidity, globe temperature, and wind velocity) were measured continuously at intervals of 10 s. For the skin temperature measurements, the Hardy and DuBois seven-point

Table 1
Information on subjects

	Age (year)	Ht (cm)	Wt (kg)	Sex	BSA (m^2)	Fitness
A	25	169	55.6	Male	1.64	Healthy
B	24	167	66.0	Male	1.73	Healthy
C	24	163	54.8	Male	1.59	Healthy
D	24	174	76.8	Male	1.89	Healthy

HT, height; WT, weight; BSA, body surface area calculated from height and weight [10].

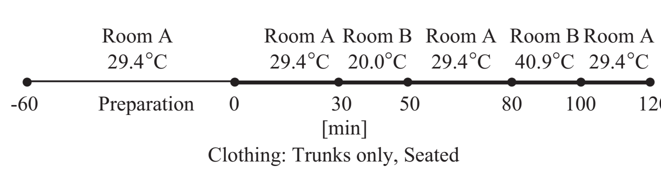

Fig. 1. Schedule of experiment.