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Prediction of whole-body thermal sensation in the non-steady state based on skin temperature

Satoru Takada*, Sho Matsumoto, Takayuki Matsushita

Department of Architecture, Graduate School of Engineering, Kobe University, Rokkodaicho, Nada, Kobe 657-8501, Japan

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ABSTRACT

The goal of this study is to propose a new model for predicting thermal sensation in the non-steady state based on skin temperature and its time differential. A multiple regression equation for the prediction of the transient thermal sensation as a function of mean skin temperature and its time differential is determined based on the data obtained in subject experiments involving various non-steady state patterns during sedentary conditions. The results indicate a high correlation and a trend in good agreement between the predicted and experimental thermal sensations in a non-steady state, and showed that the proposed equation can predict transient whole-body thermal sensation with high precision. In addition, experiments incorporating processes with changes in metabolic rate (walking) were conducted on the subjects, and the applicability of the proposed equation, which was based on the data for sedentary conditions, to the conditions involving such a change in metabolic rate was studied. When the skin temperatures of all the body segments increase or decrease simultaneously, the predicted thermal sensation agrees well with the experimental results, allowing for the use of the proposed equation, while the application of the equation is more difficult for the cases in which skin temperature increases and decreases coexist over the segments of the body.

1. Introduction

The predicted mean vote (PMV) [1] has been widely used to predict thermal sensation in the steady state. The thermal sensation vote as a function of the thermal load (i.e., deviation from thermally neutral conditions) and the comfort equation are the essence of PMV and enable the prediction of thermal sensation based on thermal environmental elements, including air temperature, humidity, air velocity, thermal radiation, clothing, and metabolic rate, in a simple manner. However PMV cannot be adapted to predict thermal sensation in the non-steady state, necessitating the development of a method to predict thermal sensation in non-steady state.

The first step for the prediction of thermal sensation in the non-steady state is to obtain the thermal sensation vote in subject experiments. Gagge et al. [2] compared thermal sensation in a transient state with physiological responses and suggested that the change rate in skin temperature causes a sensation. Gagge et al. [3] referred to the prediction of thermal comfort in thermal equilibrium. Gonzalez et al. [4] showed experimental data on the sensation of warm discomfort under stepwise changes in ambient temperature, and the authors compared it with calculated SET* for the time series. Nevins et al. [5] showed experimental data on thermal sensation for thermal transients. Rohles et al. [6] showed the relationship between ET* and thermal sensation vote in the steady state. These studies discussed the relationship between psychological quantity (thermal sensation) and the physiological response or physical quantity of thermal environment and can be regarded as early attempts to predict thermal sensation in non-steady state. In these studies, the one-dimensional scale, which has two ends (hot and cold), was used to describe thermal sensation. Kuno et al. [7] pointed out the problems associated with using a one-dimensional scale for a transient state and proposed a two-dimensional description of thermal sensation, but it is not expressed in a quantitative form. Goto et al. [8] studied the time series of thermal sensation in the step-change in metabolic rate and proposed an equation related to thermal sensation. However, it is applicable only to a specific stepwise change and is not a general model for transient state.

The prediction of thermal sensation for a given thermal environmental condition can be divided into two processes as shown in Fig. 1. The first is the prediction of thermophysiological responses (e.g., skin and core temperatures) based on the given

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

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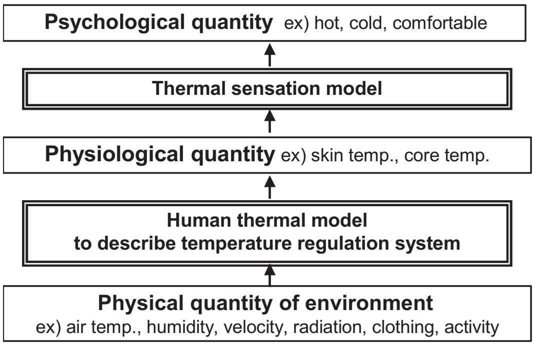

Fig. 1. Schematics for the prediction of psychological responses under the given environmental conditions.

environmental physical conditions (e.g., air temperature, humidity, air velocity, and radiant temperature), and the second is the prediction of psychological responses (e.g., hot, cold, or comfortable) based on thermophysiological responses. For PMV, as an index for steady state, the two procedures are not divided, and the predicted thermal sensation in the steady state can be calculated directly from the given thermal environmental conditions. However, for non-steady state, because the number of the state to be handled is far greater, it might be more convenient to divide the processes into two parts. When real-time thermophysiological responses are available based on measurements, we need only to build a model to predict thermal sensation from thermophysiological responses. If the real-time physiological responses are not available as measured data, it is possible to obtain them from the human thermal model, though the error in this model [9,10] will be mixed in the prediction of the thermal sensation.

Several models for predicting transient thermal sensation based on thermophysiological responses have been proposed with this point of view in mind. Mori et al. [11] presented a regression equation for thermal sensation based on physiological variables (mean skin temperature and its time differential, tympanum temperature and its time differential, and heat flux at the skin's surface). Fiala et al. [12] proposed a similar equation based on the mean skin temperature and its time differential and core temperature. Recently, Zhang et al. [13–15] proposed a model for predicting not only whole-body thermal sensation but also local thermal sensation in the non-steady state by using the mean and local skin temperatures, their time differential, and the time differential of the core temperature. However, the necessity of considering the core temperature or its time differential as an explanatory variable for the transient thermal sensation is not clearly indicated in these studies. Frank et al. [16] experimentally studied the contribution of core and skin temperatures to thermal comfort, and showed that core and skin temperatures contribute approximately equally to thermal comfort. However this was a physiological experiment conducted by cooling the core using a neurotransmitter, which varies from the ordinal conditions experienced in daily life. Meanwhile, using water bath experiments, Mower [17] showed that thermal sensation is independent of the core temperature. In contrast, there is clear evidence that skin temperature and its change rate are the input to thermoreceptors, which suggests that they should closely relate to thermal sensation. Hensel [18] has used neurophysiological experiments to show that the general properties of cutaneous thermoreceptors have a static response (dependent on skin temperature) and a dynamic response (dependent on skin temperature changes). Based on this study, Ring et al. [19,20] developed a model to describe the dynamic response of cutaneous thermoreceptors to temperature stimuli based on the heat conduction equation for skin. Ring et al. [19] showed that the relationship between the thermal sensation and the dynamic responses of cutaneous thermoreceptors are linear.

It would be impossible to completely neglect the influence of core temperature on thermal sensation. However, it is true that the evidence supporting its influence is weaker than that of skin temperature. Moreover, as a realistic problem to predict thermal sensation based on the body temperature, it is not convenient to consider core temperature because the range of variation in core temperature is in general significantly smaller than that of skin temperature [21], and because variation in core temperature among individuals is not small [22]. Skin temperature is significantly easier to measure than core temperature, and its change is more dynamic. If the intrinsic information used to predict transient thermal sensation is confined to skin temperature and its time differential, the prediction is significantly reduced in complexity in comparison to that considering both skin and core temperatures.

This study attempts to build and validate an equation that explains whole-body thermal sensation in the non-steady state based only on mean skin temperature and its time differential. This approach relies on nonlinear regression and uses the data obtained in the following three types of the experiments.

- Experiment 1 (described in Section 2): this is the basic experiment used to build the equation, and is conducted in a thermally homogeneous environment, which is realized in artificial climate chambers. Sedentary subjects are used, exposed to thermally transient conditions (a stepwise change in air temperature). By using the data, the regression analysis is performed and the equation is developed.
- Experiments 2 & 3 (described in Section 3): these experiments are used to validate the proposed equation, and simultaneously, to identify the applicable range of the equation. Experiment 2 is conducted under the situation of ordinary indoor and outdoor spaces (in a university campus), including exposure to a thermally inhomogeneous environment, as well as walking processes. Based on Experiment 2, the validity of the proposed equation is shown. In Experiment 3, the walking process in the thermally homogeneous environment is focused on. In this situation, the skin temperature of some parts of the

Table 1
Air temperature settings for Experiment 1 (conducted in an artificial climate chamber).

<table>
<tr><th rowspan="2">Schedule</th><th colspan="20">Time[min]</th></tr>
<tr><th colspan="20">0 20 40 60 80 100 120 140 160 180 200</th></tr>
<tr><td>1</td><td colspan="3">29ºC</td><td colspan="3">35ºC</td><td colspan="6">26ºC</td><td colspan="8"></td></tr>
<tr><td>2</td><td colspan="3">29ºC</td><td colspan="2">20ºC</td><td colspan="3">29ºC</td><td colspan="2">38ºC</td><td colspan="2">29ºC</td><td colspan="8"></td></tr>
<tr><td>3</td><td colspan="3">29ºC</td><td colspan="2">20ºC</td><td colspan="6">29ºC</td><td colspan="2">38ºC</td><td colspan="2">29ºC</td><td colspan="5"></td></tr>
<tr><td>4</td><td colspan="3">29ºC</td><td colspan="2">20ºC</td><td colspan="6">29ºC</td><td colspan="2">🟨 38ºC</td><td colspan="2">29ºC</td><td colspan="5"></td></tr>
<tr><td>5</td><td colspan="3">29ºC</td><td colspan="4">20ºC</td><td colspan="6">29ºC</td><td colspan="4">🟨 38ºC</td><td colspan="3">29ºC</td></tr>
</table>

🟨 70%RH * Other processes are 50%RH