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Validity of the two-node model for predicting steady-state skin temperature

Satoru Takada*, Takuya Sakiyama, Takayuki Matsushita

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

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ABSTRACT

The validity of the two-node model for predicting the skin temperature in the thermal steady state is studied by comparing the calculated and experimental results for various thermal conditions. For the experimental results of steady-state skin temperature, in addition to the authors' original experimental data, literature data for mean skin temperature are collected, incorporating 56 conditions and 233 subjects in total. The results show that the two-node model (the 1986 edition) that is widely used for calculating SET* predicts effectively the steady-state skin temperature in the low-activity conditions. Additionally, the changes that were made to the two-node model by Gagge et al. and ASHRAE are summarized. It is shown theoretically and by experimental validations that, of these changes, the addition of the shivering model represents the most significant improvement in terms of predicting the skin temperature in the steady state.

1. Introduction

Many thermal models of the human body have recently been proposed, and several of these models treat the thermal system of the human body as a set of many nodes [1–4]. These models are expected to be utilized for a wide variety of purposes. In order to apply these models to designing or controlling the architectural environment, it is important to clarify their reproducibility [5], which has not been done sufficiently. Validation of a model requires a comparison of its results with experimental data. In reality, however, it is not easy to obtain an experimental data set large enough for the model validation, because the data sets need to cover a wide range of thermal conditions and human subject characteristics. Therefore, there are only a limited number of the thorough validations of thermal models of the human body [2,5–10].

Individual differences in the characteristics of the thermophysiological responses of the human body are also an important issue in this field [11–13]. These differences make it difficult to validate the thermal models of the human body. Thus, one of the approaches is to determine the average behavior of the human thermal system for a large number of subjects.

From these perspectives, this paper evaluates the validity of the two-node model, which is one of the simplest human thermal models, by focusing on the steady state. The two-node model (TNM) was proposed by Gagge et al. [14]. It is famous not only as a necessary scheme for calculating SET* but also as a foundation for developing a new human thermal model. The steady-state solutions of the TNM for skin temperature, skin heat flux, and skin wettedness are used to calculate SET*, and the steady-state solution is a basis for studying non-steady-state solutions. This paper combines the authors' original data with literature skin temperature data from several sources that cover a wide range of environmental conditions from low temperatures to high temperatures. The data are compared with the results calculated by the TNM. The selected experimental data were collected and describe a sedentary steady state. The validity of the calculated steady-state skin temperatures is compared against two versions of the TNM: the 1971 (original) edition [15] and the 1986 edition, which is the latest edition by Gagge et al. that is typically recognized as the TNM [16].

2. Methodology

2.1. Experimental data

Theoretically, the thermophysiological state in steady state is decided when the six elements of the thermal environment (air temperature, air humidity, wind velocity, thermal radiation, clothing, and metabolic rate) are given, unless the condition is too hot or too cold to be well regulated. In order to obtain the experimental data on the thermophysiological state in steady state, the subjects are put into an artificial climate chamber, and the six

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

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