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Determination of required core temperature for thermal comfort with steady-state energy balance method ☆

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Abstract

In this study, apart from the other studies related to thermal comfort, it is combined that the fundamental equations given in the steady-state energy balance and the empirical relations expressing effects of the thermoregulatory control mechanisms of the body. In the first section of this simulation, body core temperature is calculated by using the equations expressing thermoregulatory control mechanism, the required skin temperature and sweat rate values. Variation of the calculated body core temperature is investigated with the activity level based on required skin temperature and sweat rate values. In the second section of the simulation, heat losses from the body (convection, radiation, evaporation, and respiration) and ratio of the each heat loss mechanism to total heat loss are calculated and discussed in detail.

Keywords: Thermal comfort; Core temperature; Energy balance

1. Introduction

Various biomechanical reactions occurring in the human body can be treated as an open thermodynamical system by using eaten foods and inhaled oxygen. Thermal energy resulted from these reactions must be regulatory emitted to the environment in order to maintain vital body functions and thermal comfort. However, energy balance alone is not sufficient for thermal comfort. Beside the energy balance of the human body, the second fulfillment condition is the actual combination of skin temperature and the body's core temperature provide a sensation of thermal neutrality [1–4].

Thermal comfort is generally associated with a neutral or near neutral whole body thermal sensation. Thermal sensation depends on body temperature, which in turn depends on thermal balance and the effects of environmental factors (air temperature, relative humidity, air velocity, and mean radiant temperature), as well as personal factors (metabolism and clothing). Skin and internal temperatures, skin moisture and physiological processes all contribute to human satisfaction. Comfort seems to occur when body temperatures are maintained with the minimum physiological regulatory effort.

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Some studies related with thermal comfort have been carried out on the thermal manikin (Burke et al. [5], Dozen [6], Meinander [7], Fan and Keighley [8], Burke et al. [9]). It was early recognized that a heated thermal manikin could also be used for evaluation of the microclimate conditions caused by different ventilation systems (HVAC). This application has increased in recent years, in particular within the automobile industry (Wyon et al. [10], Olesen [11], Palazzetti et al. [12], Nilsson et al. [13], Nilsson [14]). Nilsson et al. [15] and de Dear et al. [16] also used the similar measurement principles for detailed analysis of indoor air evaluation.

Extensive clothing research with manikins has been carried out by McCullough et al. [17,18] and Olesen [19] and, in recent years, more clothing studies are done by Wyon et al. [20], Holmér [21] and Meinander [22].

A number of models have been developed during the past years in order to describe human thermal response to various conditions (Stolwijk et al. [23], Gagge et al. [24], Wissler [25], Fiala et al. [26], Huizenga et al. [27], Kaynakli and Kilic [28]). Moreover, the interest in using virtual thermal manikins in research has grown in recent years. Some of the researchers who used Computational Fluid Dynamics (CFD) for numerical predictions of the indoor environment were Murakami et al. [29], Murakami et al. [30], Han et al. [31], and Tanabe [32].

Burch et al. [33,34], Maué et al. [35], Guan et al. [36,37], Martinho et al. [38] and Kaynakli et al. [39] studied on the determination of the thermal conditions (air temperature, humidity, velocity and radiant temperature distribution and features) in an automobile compartment and the effects of these conditions on the human comfort. And also several studies (e.g. Fanger [40], Daanen et al. [41], Srinavin and Mohamed [42]) have been carried out about the effects of the thermal conditions on the performance of persons so on the effectiveness of the work.

Continued investigations based on the examination and development of the current models will be useful the HVAC system engineers and so the system users. For that reason, much more study and investigation still has to be done.

In this study, the heat exchange between the body and environment is analyzed on the basis of the steady-state energy balance model. Firstly, basic equations given for steady-state energy balance and empirical equations related to thermoregulatory control mechanisms are utilized for the calculation of body core temperature (T_{cr}). Apart from the human thermal comfort studies in the literature, body core temperature is calculated with using the required skin temperature ($T_{sk,req}$) and required sweat rate ($Q_{rsw,req}$) equations in the steady-state conditions. Since the calculations are performed based on the values of $T_{sk,req}$ and $Q_{rsw,req}$, predicted body core temperature is considered as the required body core temperature ($T_{cr,req}$). Then, in the second part of the simulation, using the personal and environmental independent variables, heat losses from the body (convection, radiation, evaporation, and respiration) and thermal comfort indices (PMV, PPD) commonly used in the steady-state model are calculated. The effects of the ambient temperature on the heat losses from the body and thermal comfort indices are investigated.

2. Mathematical model

2.1. Heat loss mechanisms of the body

Two models are commonly used for thermal interaction between the human body and the environment. First is Steady-State Energy Balance model developed by Fanger [43] and the other one is Two-Node Transient Energy Balance model developed Gagge et al. [24]. Steady-state model assumes that the body is in a thermal equilibrium and its energy storage is negligible. The energy balance of body is expressed as:

$$M-\hat{W} = Q_{sk} + Q_{res}$$
$$= \left(Q_{cv} + Q_{rd} + Q_{e,sk}\right) + \left(Q_{s,res} + Q_{e,res}\right) \tag{1}$$

The rate of convective and radiative energy exchange between the clothed body and its environment may be expressed as:

$$Q_{cv} = f_{cl} h_{cv} (T_{cl} - T_a) \tag{2}$$

$$Q_{rd} = f_{cl} h_{rd} (T_{cl} - \bar{T}_{rd}) \tag{3}$$