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Study on the allowable fluctuation ranges of human metabolic rate and thermal environment parameters under the condition of thermal comfort

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ABSTRACT

People can keep good thermal comfort when they participate in different intensity activities at a certain environment. But their thermal comfort changes greatly even with a slight change of activity intensity at other environment. It means that people's allowable fluctuation range of metabolic rate differs at different environments. Furthermore, the fluctuation ranges of thermal environment parameters also have different impacts on thermal comfort. Based on the body heat balance equation, this paper explored the influencing factors of the allowable fluctuation range of metabolic rate and the comfortable ranges of thermal environment parameters. The mathematical model between thermal environment parameters and the allowable fluctuation range of metabolic rate was established through the adoption of orthogonal experimental design test and multiple regression analysis. To verify the validity of theoretical results, questionnaire surveys were conducted in Changsha. The results showed that the air temperature is the most significant factors which affect the allowable fluctuation range of metabolic rate within the thermal comfort zone, the next are relative humidity and air velocity. There is a strong linear relationship between these three factors and the fluctuation range of metabolic rate. Combining the established model and questionnaire surveys, the comfortable ranges of temperature and relative humidity were obtained. These conclusions not only can provide a simple and feasible method to determine the allowable fluctuation range of metabolic rate in a given weather condition, but can also provide valuable references to set a standard for air-conditioning design parameters and indoor operating parameters according to different functional architectures.

1. Introduction

People are exchanging heat with the surroundings every moment through the ways of convection, radiation and evaporation, and generating power through metabolism [1]. To ensure the normal conduct of life, the body's core temperature should be kept in a certain range. Because the core temperature is directly related to the metabolic rate (M), metabolic rate has a certain scope to ensure thermal comfort of the body. In hot-summer and cold-winter zone where the weather is sultry and humid, people often have such experiences: under a certain kind of weather conditions, people's thermal comfort state may not change too much when they participate in activities of different intensity, no matter sitting still or walking; under another kind of weather conditions, people feel comfortable when they are engaged in low-intensity activities such as sitting still, but once the intensity changes, even slightly, the thermal discomfort emerges. The changes of activities means that the corresponding metabolic rate changes as well. The reason why people have the aforesaid different thermal sensations in different weather conditions is that the allowable fluctuation range of metabolic rate (ΔM) is different. When the weather is humid and temperature is high, it is likely that the range is narrow. However, when the weather is relatively dry, this range may be wide. In other words, if the metabolic rate is different, the acceptable range of temperature and relative humidity is also different. Thus, the research about the allowable fluctuation range of metabolic rate and the analysis about the comfortable ranges of thermal environment parameters are both meaningful. It not only can guide people to participate in appropriate activities in certain weather conditions, but can also serve as

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references for the air-conditioning design parameters of buildings with different functions considering the differences of occasions. On the premise of satisfying thermal comfort, the goal of energy conservation can be achieved.

At present, the indoor design thermal environment parameters which are provided by the authorized standards of human thermal comfort such as ASHRAE55 [2] and ISO 7730 [3] are mainly applicable to lower metabolic rate, rather than higher metabolic rate, however. As early as 1967, McNall [4] began to study the influence of metabolic rate on thermal comfort, he found that the relative humidity (*RH*) has slightly effect on thermal comfort when metabolic rate is low, but at a high metabolic rate, the effect of relative humidity on thermal comfort is prominent. Threlkeld [5] found that there is a limited temperature range for people with moderate activity intensity. In this range, the body can maintain thermal equilibrium state without additional action. The activity level and clothing will affect this range. This range is about 27.1–30 °C for the naked people who are taking a break. Fountain et al. [6] conducted a study about thermal comfort in the artificial laboratory and found that the influence of *RH* on human thermal comfort of people who are sitting still is not significant, but with the increases of metabolic rate, *RH* will have obvious effects on human body. When metabolic rate is greater than 1.6 met, according to the survey data, the dissatisfied percentage of people with the thermal environment is over 25%. Ye [7] measured the metabolic rate while people were sitting in the cold environment and the comfortable environment, respectively. The conclusion is that *M* of cold environment is higher than that of comfortable environment, which means that the metabolism will be enhanced to keep body's core temperature in a certain range when people exposure to the cold environment. Lu et al. [8] analyzed the influence degree of metabolic rate and wet black bulb temperature on humans' bearable time in hot and humid temperature. Shi et al. [9] also studied the combined effect of temperature, humidity and metabolic rate on human strain, the relative results can help people to understand the effects of environment and work intensity on human strain better. Zhai et al. [10] found that subjects' expectations of thermal comfort are different during various intensity activities. When the metabolic rate is 4 met, they preferred a slightly warm sensation, but a warm sensation at 6 met, which results in the difference of acceptable temperatures in different metabolic rate. Choi et al. [11] took heat rate which is closely related to metabolic rate into consideration and conducted a research on thermal comfort, the results show that the heart rate increases obviously with 2.6met in the warm environment. Compared to 0.8met, the heat rate also changes significantly with 1.0met. Goto et al. [12] proposed a method to estimate transient thermal sensation after metabolic step-changes. Lu et al. [13] studied physiological indexes at the heat tolerance limits with light, moderate and heavy metabolic rate.

In summary, there have been a significant number of valuable studies on metabolic rate. These studies mainly concentrated on the effects of thermal environment parameters on human thermal comfort which based on a certain metabolic rate. However, few scholars studied on the allowable fluctuation range of metabolic rate under different thermal environment specifically. For this reason, the objectives of this paper are threefold:

(1) Investigate the fluctuation range of metabolic rate of different thermal environment based on theoretical analysis;
(2) Study the significance degree of the thermal environment factors which affect the allowable fluctuation range of metabolic rate, establish the simplified model between the allowable fluctuation ranges of metabolic rate and thermal environment parameters by the methods of orthogonal test and multivariate regression;
(3) Verify the simplified model through the adoption of questionnaire surveys and obtain the comfortable ranges of thermal environment parameters.

2. Theoretical model

2.1. The introduction of theoretical model

This study is based on the thermal comfort of human body. Thus, it is necessary to understand what thermal comfort is and how to evaluate thermal comfort. Through many years' study on thermal comfort, Fanger [14] put forward three conditions which can satisfy thermal comfort: 1) heat production and heat loss should satisfy the heat balance equation under the condition of steady state; 2) skin temperature should be adapted to the thermal comfort level; 3) the optimal sweating rate should corresponding to the condition of thermal comfort. Only satisfying these three conditions at the same time can thermal comfort be realized. On this basis, some of the thermal comfort evaluation indexes emerged, such as *PMV-PPD*, effective temperature (*ET*) and standard effective temperature (*SET**) and so on [15]. This paper based on these three thermal comfort conditions to carry on this research.

2.1.1. The body heat balance equation

The suitable temperature is necessary to maintain the body's normal life activities. Therefore, the body's heat production and heat dissipation should be in balanced. The body heat balance equation can be obtained as follows [16]:

$$M - W = (C + R + E_{sk}) + (C_{res} + E_{res}) + S \tag{1}$$

where M[W/m^2] is metabolic rate, W[W/m^2] is mechanical work, °C [W/m^2] is the convection heat loss of skin, R[W/m^2] is the radiation heat loss of skin, E_{sk} [W/m^2] is skin evaporation heat loss, C_{res} and E_{res}[W/m^2] are sensible and latent respiratory heat loss, respectively, S [W/m^2] is heat storage of human body.

In general, W is very low, for most kinds of activities, $W \approx 0$ [17]. S is an important factor which affects the thermal comfort of dynamic environment [18]. However, the mainly consideration of this paper is steady state, so $S = 0$. The detailed computational methods of variables in Eq. (1) can be expressed as follows [16]:

1) Convection heat loss C is the convection heat transfer between the body surface and the surrounding environment. When air temperature is higher than the surface skin temperature, the value of C is positive, otherwise, the value of C is negative. Convection heat loss can be obtained as follows:

$$C = f_{cl} h_c (t_{cl} - t_a) \tag{2}$$

$$f_{cl} = 1/(1 + 0.155 \times (h_c + h_r) \times I_{cl}) \tag{3}$$

$$t_{cl} = t_{sk} - 0.155 \times I_{cl}(M - W - (C_{res} + E_{res}) - E_{sk} - S) \tag{4}$$

where f_{cl} is the clothing area coefficient; h_c[W/(m^2 °C)] is convective heat transfer coefficient, $h_c = 8.3V^{0.5}$; h_r[W/(m^2 °C)] is radiation heat transfer coefficient; t_{cl}[°C] is the clothing surface temperature; t_a[°C] is air temperature; t_{sk}[°C] is skin temperature; I_{cl}[(m^2 kPa)/W] is clothing insulation.