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Feedback from human adaptive behavior to neutral temperature in naturally ventilated buildings: Physical and psychological paths

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A B S T R A C T

This study provides new insight into the feedback from human adaptive behavior to thermal neutral temperature in naturally ventilated buildings and proposes a theoretical model, the “adaptive behavior feedback (ABF) model”, to quantitatively describe the feedback. Using the ABF model, the adaptive increments in occupant neutral temperature due to the feedback of the adaptive behavior (the use of various controls) were obtained based on the data from a long-term field survey conducted in two typical naturally ventilated offices located in Changsha, China. Furthermore, the roles of different feedback paths (physical and psychological paths) were quantified. The results revealed that the psychological feedback path had a more significant role in causing a change in the neutral temperature of the subjects with the use of a door, a window and an air conditioner. These results also indicated that the ABF model could provide an effective method for quantifying the feedback from occupant adaptive behavior to their thermal comfort in naturally ventilated buildings.

1. Introduction

With the dramatic increase in worldwide energy consumption, increasing attention has been focused on naturally ventilated buildings in recent years. Compared with air-conditioned buildings, naturally ventilated buildings can provide a wider range of comfortable indoor temperatures with less energy consumption [1–3]. The principle underlying the thermal adaptation indicated the significance of the feedback from human adaptive behavior to thermal comfort in naturally ventilated buildings [4], which was revealed by the field evidence [i.e., Refs. [5,6]]. Therefore, adaptive behavior in naturally ventilated buildings has attracted many researchers in recent years.

Most existing studies have explored the patterns of the adaptive behavior of occupants due to different climate conditions and have established various models to reflect the quantitative relation between them [i.e., Refs. [7–9]]. According to these studies, the way in which the adaptive behavior works could be predicted based on the indoor or outdoor temperature. However, these results are not yet sufficient if our goal is to design naturally ventilated buildings for a more comfortable indoor thermal environment under the impact of climate change. As indicated in Fig. 1, it is also important to know exactly how the thermal comfort of occupants is affected by their adaptive behavior (the feedback loop).

Regretfully, few studies have been devoted to the feedback from the adaptive behavior to thermal comfort. A 1.5 °C difference was observed in the neutral temperature between occupants with high and low usage degrees of windows in Brager et al. [5]. Rijal et al. discussed the effect of some controls (windows, doors and fans) on the indoor thermal environment [10]. Their study did not reveal a direct relationship between the adaptive behavior of the occupants and thermal comfort. Afterward, Yao et al. presented a theoretical adaptive model of thermal comfort (aPMV) by considering various adaptive factors, including behavioral adaptations [11]. However, their model could not reveal the separate effects of adaptive behavior. Recently, Haldi and Robinson introduced a new adaptive model for predicting the comfort temperature, which explicitly accounts for probable adaptive actions and their thermal feedback [12]. Their model is valuable for describing the effect of adaptive behavior on the comfort temperature. However, the model might not be the most appropriate form when two independent variables, the adaptive behavior and the outdoor temperature, are closely related. More importantly, the principle for the influence of the adaptive behavior on the thermal comfort of occupants was not clearly presented in the existing studies, and this influence still needs to be fully understood.

This study proposed a model to quantify the variation in the neutral temperature of occupants due to the use of various controls in naturally ventilated buildings. Then, this model was realized

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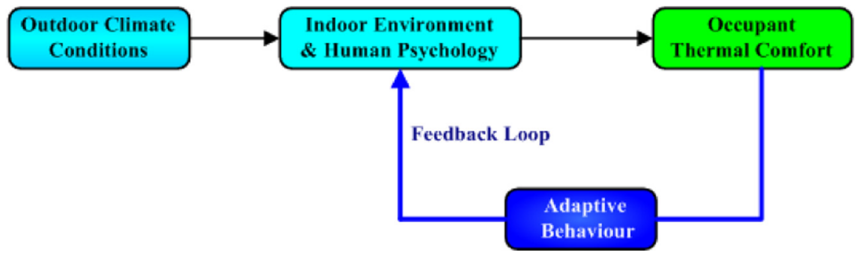

Fig. 1. The relationship between climate, human adaptive behavior and thermal comfort.

using the data from a long-term (more than one year) survey in Changsha, China [13]. The feedback from the adaptive behaviors of occupants to their neutral temperature via different paths was analyzed based on the model.

2. Principle and modeling

Neutral temperature is defined as the operative temperature at which the average person will be thermally neutral [14]. Neutral temperature is always used as the comfort temperature of the occupants to establish adaptive comfort models and thermal comfort standards for naturally ventilated buildings [12,15]. Therefore, this study selected neutral temperature as a key index to reflect human thermal comfort.

2.1. Influence factors on the neutral temperature

The influence factors of the neutral temperature in naturally ventilated buildings mainly include two classes: physical and psychological factors. Although it is also one mode of thermal adaptation, the physiological factor (acclimatization) appears unlikely to affect the neutral temperature of occupants under typical conditions in residences and office buildings [16,17].

The physical factor, which contains thermal environment and personal parameters, affects the neutral temperature by changing the heat loss from the human body. Its influence can be well explained with Fanger's PMV model. According to the PMV model, the value of the neutral temperature (PMV = 0) is determined by other five parameters (the physical factor), including the air velocity, the humidity, the mean radiant temperature, clothing insulation and metabolic rate. Thus, the variation of these parameters can alter the value of the neutral temperature. For example, an increase in indoor air velocity would increase the neutral temperature due to the enhanced convective heat transfer coefficient between the human body and the indoor air.

The psychological factor can cause a variation in the neutral temperature due to the role of psychological adaptation in thermal comfort. The influence is supported by the principle of thermal adaptation. As an important mode of thermal adaptation, psychological adaptation directly affects one's thermal response and cognitive assessment of acceptability in naturally ventilated buildings. According to related studies, the effects of psychological adaptation mainly result from the expectations of occupants [17]. Therefore, expectation is regarded as the key parameter of the psychological factor.

To summarize, the relationship between the neutral temperature and its influence factors is expressed as the following function:

$$\begin{aligned} NT &= f\left(F_{phy},\ F_{psy}\right) \\ &= f\left(V,\ \overline{t_r},\ \ d,\ \ I_{cl},\ \ M, e\right) \end{aligned} \quad (1)$$

where NT is the neutral temperature and F_{phy} and F_{psy} are the physical and psychological factors, respectively. V indicates the air velocity, $\overline{t_r}$ indicates the radiant temperature, d is the air humidity, I_{cl} is the clothing insulation, M is the metabolic rate, and e is the expectation.

2.2. Feedback from the adaptive behavior to the neutral temperature

Feedback from the adaptive behavior to the neutral temperature is an important mechanism underlying its effect on thermal comfort. According to the influence factors of the neutral temperature, the feedback is divided into the physical and psychological paths, as shown in Fig. 2.

The physical path means that the adaptive behavior affects the neutral temperature of occupants by altering the physical factor. The field studies provided evidence for this path [i.e., Ref. [11]]. For example, the use of windows, doors and fans could increase the indoor air velocity, and the adjustment of clothing means a change of clothing insulation.

The adaptive behavior can also affect the neutral temperature of occupants by altering the psychological factor, which is defined as the psychological path. Direct evidence revealed a significant role of the use of controls in one's expectations [17], which could cause a variation in the neutral temperature as mentioned previously.

2.3. A model to quantify the feedback

According to the aforementioned feedback principle, the adaptive behavior of occupants affects their neutral temperature based

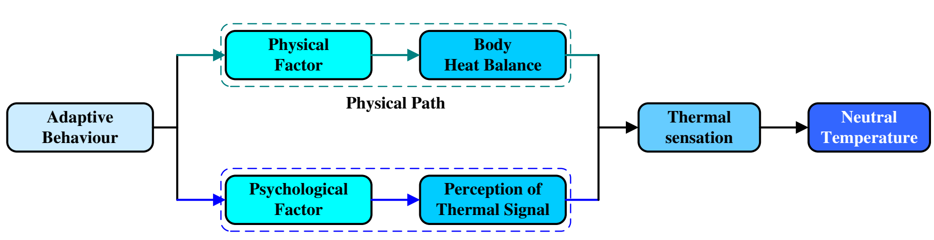

Fig. 2. The feedback path from human adaptive behavior to the neutral temperature.