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Feedback effect of human physical and psychological adaption on time period of thermal adaption in naturally ventilated building

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A B S T R A C T

This study proposed a method to determine time period of thermal adaption for occupants in naturally ventilated building, and analyzed the synergistic and separate feedback effect of the physical and psychological adaption modes on the time period of thermal adaption. Using the method, the values of the time period of thermal adaption were obtained on the basis of the data from a long-term field survey conducted in two typical naturally ventilated offices located in Changsha, China. The results showed that the occupants need to take 4.25 days to fully adapt to a step-change in outdoor air temperature, under the synergistic feedback effect of the physical and psychological adaption modes. The time period of thermal adaption increased to 13 days, if only the feedback effect of the physical adaption mode was accounted for. The difference between the two values of the time period of thermal adaption indicated that the psychological adaption mode can speed up the process of thermal adaption to the variation in the outdoor climate condition. This study presented a new insight into the feedback from the thermal adaption modes to occupant thermal comfort.

1. Introduction

Building energy consumption contributes to the global energy crisis. With significant potentiality of energy saving, naturally ventilated buildings get most of the attention of the world. However, indoor thermal environment in a naturally ventilated building always changes with outdoor climate, leading to variable thermal comfort requirement of occupants [1,2]. Therefore, how to create a comfortable indoor thermal environment is one of the key problems for the sustainable development of naturally ventilated buildings, under the impact of adverse climate conditions, such as the global warming and increasing extreme climate events.

Understanding the mechanism of human thermal comfort in naturally ventilated building is the basis to solve the above key problem. In present, thermal adaption has been widely accepted as the theoretical principle of thermal comfort in naturally ventilated buildings. Human thermal adaption has three modes with different feedback paths: physical (behavioral adjustment), physiological (acclimatization) and psychological (expectation and habituation) adaption [3]. The adaptive principle ("*If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" [4]) indicated the significance of the feedback from the thermal adaption modes to thermal comfort. As depicted in Fig. 1, the physical adaption plays a role on occupant thermal comfort by modifying indoor or personal thermal environment, which in turn changes thermal physiological response governing body's thermal balance. The psychological adaption directly alters one's perception of thermal comfort due to the change of one's habituation and expectation. The physiological adaption, resulting from variation in the settings of the physiological thermoregulation system over a long period, can also exert influence on occupant thermal comfort. However, there was general agreement that the effect of the physiological adaption is not significant in the moderate conditions found in buildings [3,5,6].

Occupants in naturally ventilated building can adapt themselves to outdoor climate change by the thermal adaption modes. As a result, their thermal comfort temperature (or neutral temperature) changes with outdoor temperature during thermal adaption process [7,8]. Time period of thermal adaption, the period of the thermal adaption process, is a key factor to occupant adaptive thermal comfort [9,10]. Occupants need sufficient time to fully adapt to the change in outdoor climate conditions in order to

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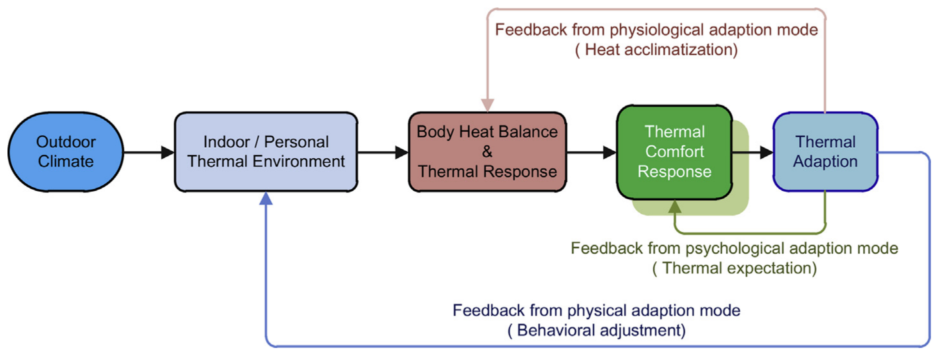

Fig. 1. Feedback from human thermal adaption to thermal comfort.

restore thermal comfort. As shown in Fig. 1, the thermal adaption modes have feedback effect on adaptive thermal comfort response as revealed by the existing studies [i.e. Refs. [3,11,12]], which can cause the change of the time period of thermal adaption. However, until up to now it still remains unknown that in what degree the time period of thermal adaption is influenced by the feedback from the thermal adaption modes.

This study proposed a method to determine the value of time period of thermal adaption for occupants in naturally ventilated building and analyzed the synergistic and separate feedback effect of the physical and psychological adaption modes on occupants' time period of thermal adaption, which gave a new insight into the feedback from the thermal adaption modes to thermal comfort.

2. Method

2.1. Principle and modeling

2.1.1. Time period of thermal adaption

Time period of thermal adaption is defined as the time that occupants spent in adapting to outdoor climate change with the thermal adaption modes. Numerically, time period of thermal adaption should be determined based on human thermal comfort response after a step-change in outdoor climate condition as shown in Fig. 2. However, the actual outdoor climate condition always continuously changes within day and from day to day. The step-change in outdoor climate condition almost does not occur. Therefore it is hard to directly obtain the value of time period of thermal adaption according to the actual conditions. However, the quantitative relation between the thermal comfort response and outdoor climate condition can be established based on field investigation data under actual conditions, which provides a basis to the determination of time period of thermal adaption.

Neutral temperature is defined as the operative temperature at which an average person will be thermally neutral [13]. Neutral temperature is always used as occupants' comfort temperature to establish adaptive comfort models and thermal comfort standards for naturally ventilated buildings [1,2]. Therefore, this study selected neutral temperature as a key index to reflect human thermal comfort response in naturally ventilated buildings.

The existing studies indicated that occupant neutral temperature is associated with his thermal history with more recent experiences being more influential [14]. Therefore, the exponentially − weighted running mean outdoor temperature was adopted to reflect the significant role of the past and current thermal experiences with outdoor climate condition, which had been applied as the basis of the adaptive thermal comfort model for free-running buildings in European standards EN15251 [14].

The equation for the running mean outdoor temperature is [14]

$$T_{rm} = (1-\alpha)\left\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} \ldots\right\} \quad (1)$$

where T_{rm} is the running mean outdoor temperature at time t, T_{t-n} the instantaneous outdoor air temperature (the mean for equal time-interval − hours, days, etc.) at n time-intervals previously. α can be seen as a time constant ($0 \le \alpha < 1$) that quantitatively reflects the rate at which the effect of any past temperature decays. The bigger the value of α the greater is the effect of past temperature.

According to equation (1), the time series gives a running mean outdoor temperature that is decreasingly affected by past outdoor temperatures as time passes. Therefore, the running mean outdoor temperature can reflect the time-dependence of the adaptive thermal comfort on the outdoor air temperature experienced, by establishing the relationship between the neutral temperature and running mean outdoor temperature.

The quantitative relationship between running mean outdoor temperature and occupant neutral temperature was developed as,

$$T_n = aT_{rm} + b \quad (2)$$

where T_n is neutral temperature, a the variation rate of neutral temperature with running mean outdoor temperature and b a constant.

As illustrated in Fig. 2, the value of time period of thermal adaption was calculated as the time span that the neutral temperature reaches a new steady value after a step-change in outdoor climate condition. Using equation (2), the trend of the neutral temperature after a step-change in outdoor air temperature can be obtained.

Based on equations (1) and (2), the time period of thermal adaption can be obtained as the following equation (see Appendix),

$$TP = round\left[\frac{\ln(1-r)}{\ln(\alpha)}\right] \times \Delta d \quad (3)$$

where the function *round* [data] means the data in the square brackets is rounded up. *TP* is the time period (day) of thermal adaption and r is a ratio reflecting the degree that the neutral temperature at the final time-interval is close to its limit value during the adaption process. α is the time constant and Δd is the time-interval in equation (1).

2.1.2. The feedback effects of different thermal adaption modes

Among the thermal adaption modes, the feedback from the physical and psychological adaption modes to thermal neutral