Development Adaptive Predicted Mean Vote (aPMV) Model for Naturally Ventilated Buildings in Zunyi, China

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Abstract. Fanger's predicted mean vote (PMV) model which is as a result of climate-chamber-based experiments is a good tool to evaluate indoor thermal comfort for air-conditioned buildings in global wide. However, PMV model has defect of predicting people's real thermal sensation under non-air-conditioned conditions. It is reflected by the significant discrepancies between PMV values and Actual Mean Vote (AMV) values. The aim of this study is to develop an Adaptive Predicted Mean Vote (aPMV) Model on the basis of 'black box' theory considering occupants' adaptations to improve prediction performance. A field study was carried out in naturally ventilated educational buildings in Zunyi, China. The developed aPMV model produces more reliable results and shows better prediction performance, comparing with values predicted by PMV model. It indicates that aPMV model is of great benefit to connect traditional PMV model and adaptive comfort model and consequently to provide guidance on building design, operation and maintenance, which contribute to achieve building energy conservation and emission reduction target.

1 Introduction

People spend more than 80% of lifetime indoors [1], comfortable indoor thermal environment is consequently essential for occupants' well-being. With increasing in disposable income, people would like to seek for better indoor thermal conditions. Therefore, how to reduce building energy consumption to meet energy saving requirement without sacrificing thermal comfort becomes a major concern to building designers, system managers and building users.

Predicted Mean Vote (PMV) which is based on Fanger's heat balance theory [2] has been widely used to assess thermal environment and thermal comfort in worldwide. However, since heat balance theory is on the basis of climatic chamber experiments, as a result, more and more field studies reveal that PMV cannot predict subjects' real thermal sensations, particularly in case of non-air-conditioned buildings [3-6]. Specifically, PMV model either underestimate occupants' thermal sensations, for instance, Simone et al. [7] carried out field study in retail trade building in Southern Italy and found PMV-index underestimated subjects' thermal sensations leading to cooler predictive values due to the unevenly clothing insulation distribution on human body. Meanwhile, PMV model sometimes overestimate the thermal sensation of occupants under warm condition, e.g. Yang et al. [8] investigated thermal environment in cotton textile workshop by performing a field research in Zhengzhou Hongye Textile Co., Ltd., China. PMV model overestimated the mean thermal sensation of the worker up to 0.67 scale points. In order to evaluate

thermal comfort in real environment, adaptive thermal comfort approach focusing on reflecting the actual thermal status of occupants in a real environment has been applied in recent similar studies.

Guizhou is located in the southwest of China and is a traditional undeveloped area. For quite a long time, there are scarcity of researches on indoor thermal environment and thermal comfort in Guizhou area. With the rapid GDP growth rate in recent 5 years in Guizhou, local people's requirements on quality of indoor thermal conditions are increasing accordingly. Therefore, it is essential to collect relevant data via performing field investigations to help with full understanding of real conditions of thermal environment and thermal sensations of subjects, and consequently providing guidance on thermal comfort improvement in Guizhou Province.

This paper proposes an Adaptive Predicted Mean Vote (aPMV) model based on adaptive thermal comfort theory. The proposed aPMV model helps with better understanding of the influences of adaptations from the point of view of quantity and subsequently provide guidance on building energy saving.

2 Methods

2.1 Adaptive thermal comfort theory

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: if change occurs such as to produce discomfort, people react in ways

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which tend to restore their comfort [9]. At this point, people under certain thermal conditions are no longer passive recipients of ambient thermal stimuli but positive individuals interacting with the person-environment system. The adaptations of occupants in the built environment context are classified into three categories [10]: physiological (genetic adaptation and acclimatization), behavioural (personal, technological or cultural) and psychological (expectation or habituation).

2.2 Theoretic basis of aPMV model

According to adaptive thermal comfort theory, the three categories of adaptations significantly help occupants to achieve or to restore thermal comfort. However, the corresponding mechanism is still not clear currently. Therefore, 'black box' method which is normally used to establish relationship between the system input and output, regardless of how variables within black box interact with each other and what mechanisms are applied. Various adaptations of occupants are then regarded as 'feedbacks' to black box. If PMV is expressed as:

$$PMV = G \times \delta \quad (1)$$

aPMV can be written in the following form:

$$aPMV = G \times \delta - aPMV \times K_{\delta} \times G \quad (2)$$

Where:

G: transfer function;

δ : physical stimuli;

K_{δ} : psychological and behavioural impact coefficient.

By substituting equation (1) into equation (2), then

$$aPMV = \frac{PMV}{1 + \frac{K_{\delta} \times PMV}{\delta}} \quad (3)$$

Assuming $\lambda = \frac{K}{\delta}$, equation (3) can be transferred

in the form as:

$$aPMV = \frac{PMV}{1 + \lambda PMV} \quad (4)$$

Where:

λ : transfer function representing subjects' adaptive capacity in response to variations in surrounding thermal environment.

Based on the discrepancies between PMV and Actual Mean Vote (AMV) values demonstrated in summer case or winter case field studies in worldwide, PMV normally overestimates the influence of thermal stimuli on occupants' thermal sensations and results in worse predictions. Specifically, it is normally following the tendency that under warm condition (e.g. summer case), PMV usually yields higher predicted thermal sensation values than AMV and produces more cooler thermal sensation predictions in cool condition (e.g. winter case), comparing with AMV values. Therefore, in order to narrow the discrepancies between PMV and AMV and subsequently improve the prediction performance, in theory, the λ should be less than zero in cool case and

more than zero in warm case, respectively reflecting the comprehensive effect of adaptations on thermal sensations of subjects under different thermal conditions.

2.3 Questionnaire survey

Questionnaire was designed in this investigation to collect subjective information comprising two sections. Section one was mainly used to gather subjects' basic information, such as gender, age, the length of living in Zunyi, clothing ensembles and activity levels. A checklist presenting in questionnaire was employed to help participants to choose the clothes which were in agreement with those they were wearing. Since the occupants were engaging in sedentary activities, 1.2 met was thus determined as subjects' metabolic rate in this investigation. The questions regarding subjective perceptions with respect to temperature, air velocity and relative humidity, thermal acceptability and preferences, etc. were included in section two.

2.4 Environmental parameters measurement

In order to calculate PMV values, indoor air temperature, air velocity, global temperature and relative humidity were measured in this study. Indoor air temperature and air velocity were measured by using hot wire anemometer (TESTO 425) with accuracy of ± 0.5 °C for air temperature and of ± 0.03 m/s for air velocity, respectively. A heat index checker (model: 8778) from AZ Instruments was adopted to determine global temperature and relative humidity. The corresponding accuracy were ± 0.6 °C for the temperature ranged from 0 °C to 50 °C and $\pm 0.1\%$ for relative humidity, respectively.

Questionnaire survey and environmental parameters collection are performed simultaneously, two to three three working days per week covering the period from November to January of next year in non-air-conditioned educational buildings in Zunyi, Guizhou Province, China. A total of 178 subjects participated into this field study.

2.5 Surveyed buildings

The surveyed buildings are all located in Zunyi Normal University, Zunyi city, China and are designed as multi-functional with a south-north orientation, of brick-concrete structure and double-glazed with aluminum alloy frames. The west-east corridor divides the internal space of surveyed buildings into two parts, the south part and the north part, respectively. Figure 1 shows the façades of the surveyed buildings.

Fig. 1. The surveyed buildings.

3 aPMV model development

3.1 Determination of adaptive coefficient λ

In order to determine the value of adaptive coefficient λ , least square method was applied in this study. Let, $x = \frac{1}{PMV}$ and $y = \frac{1}{aPMV}$, equation (4) can be rewritten as:

$$y = x + \lambda \quad (5)$$

Based on the principle of least square method,

$$\lambda = \frac{\sum_{i=1}^n (y_i - x_i)}{n} \quad (6)$$

Where:

n: the number of data sets.

$$\lambda = \frac{\sum_{i=1}^8 (y_i - x_i)}{8} = -0.28 \quad (7)$$

Equation (4) for Zunyi case now is:

$$aPMV = \frac{PMV}{1 - 0.28PMV} \quad (8)$$

3.2 Model verification

Figure 2 depicts the distributions of AMV, PMV and aPMV in response to variation of indoor air temperatures.

The prediction performance is significantly improved by using aPMV model. The values of aPMV are much closer to AMV and demonstrates a good fit in winter for Zunyi case. The adaptive coefficient λ for cool case in non-air-conditioned buildings in Zunyi is -0.28.

Fig. 2. Distributions of AMV, PMV and aPMV.

4 Conclusions

This study proposes aPMV model to improve the poor prediction performance of PMV model for non-air-conditioned spaces. The conclusions are summarized as below:

- PMV model seldom considers subjects' adaptations and overestimates the impact of cold environment on thermal sensations of occupants, as a result, yields cooler thermal sensation votes.
- Adaptive coefficient λ for Zunyi case in cool environment is determined by applying least square method. The corresponding aPMV model is also developed on the basis of black box theory.
- The proposed aPMV model provides a better understanding of effects of various adaptations on thermal comfort from a quantitative point of view and bridges connections between conventional heat balance theory and adaptive thermal comfort theory.

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