Adaptive Thermal Comfort Model in Naturally Ventilated Buildings

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Abstract. An investigation was carried out in naturally ventilated buildings in Zunyi, China, which was located in HSCW climate zone, covering the period of wintertime, from November, 2018 to January, 2019 and yielded 1177 datasets in total. Based on the gathered data, the adaptive thermal comfort model using Griffith’s method taking into account running mean outdoor temperature was developed. 55.9% of data points representing proposed comfort temperatures were not within comfort zones specified in ASHRAE 55 standard and CEN 15251. The proposed adaptive comfort model provides guides on building simulation with more accuracy and indoor thermal environment optimization in this area.

1. Introduction
In China, around 28.5% of total social terminal energy is consumed by building sector [6]. With the rapid urbanization, the figure would be greater. Therefore, building sector has the responsibility to energy saving but without sacrificing indoor thermal comfort in response to global energy crisis and climate changings caused by Greenhouse Gas (GHG) emissions.

Creating and maintenance comfortable indoor thermal environment will benefit for working efficiency and building energy performance. There are two main thermal comfort theory, heat balance theory and adaptive thermal comfort theory, respectively. However, since the occupants’ adaptations in terms of physiological, behavioral and psychological dimensions were not considered by heat balance theory, there were significant discrepancies in thermal sensations between the Predicted Mean Vote (PMV) and Actual Mean Vote (AMV) when applying heat balance theory to predict thermal comfort under non-air-conditioned space [1][2]. On contrary, from the point of view of adaptive thermal comfort theory, the achieved thermal comfort can be viewed as the result of comprehensive effects of three categories of adaptations. The principle of adaptive theory is also incorporated into the latest versions of international standards, such as ASHRAE 55 Standard [3], ISO 7730 [4].

In China, the investigations on adaptive thermal comfort in Hot Summer and Cold Winter (HSCW) zone have been performed in last twenty years and yielded many valuable results [5][6][7]. But the similar studies were seldom carried out in Guizhou Province. Brager and de Dear [8] argued that thermal comfort is a multivariate phenomenon that was influenced by behaviour and expectations, as well as by environment and memory. Therefore, more field studies are essential with the aim of implementing database for indoor thermal environment optimization and building energy-saving reconstruction.
2. Methodology
In this study, environmental parameters measurement and thermal comfort questionnaire survey were employed.

2.1. Environmental parameters measurement
The environmental variables including indoor and outdoor air temperature, air velocity, relative humidity and mean radiant temperature were measured at the interval of 1 second. The measurement duration for each environmental parameter was no less than 3 minutes. The readings then were averaged as representative values of corresponding environmental variables. The instruments, measurement vertical levels, position and duration in this survey were in accordance with the requirements regarding on-site measurements specified in ASHRAE 55 standard [43] and ISO 7726 [44].

2.2. Questionnaire survey
The questionnaire survey used in this investigation was mainly for collecting subjective thermal perceptions and adaptive behaviors in naturally ventilated buildings. Various scales were adopted to quantify subjective thermal perceptions, such as ASHRAE 7-point scale, 5-point scale and binary scale. Clothing insulation values were determined by referring to ASHRAE 55 standard. Metabolic rate was assumed to be 1.2 met in this study. Environmental variables measurement and questionnaire survey were carried out simultaneously, 2-3 days per week.

2.3. Surveyed buildings
The surveyed buildings are naturally ventilated buildings, which are located in Zunyi Normal University, Guizhou Province, China. Each surveyed building comprises classrooms, administrative offices, labs, PC rooms. The orientation, structure and window type for investigated buildings are south-north orientation, brick-concrete structure and sliding type windows with double-glazed aluminum alloy frames.

2.4. Running mean outdoor temperature ($T_{rm}$)
In a practical way, $T_{rm}$ can be determined by solving equation (1):

$$T_{rm} = \alpha T_{rm(t-1)} + (1-\alpha) T_{out(t-1)}$$

(1)

Where, $T_{rm}$ is running mean outdoor temperature. $\alpha$ reflects the changing rate of running mean temperature. Here $\alpha = 0.8$. $T_{out(t-n)}$ represents the daily mean outdoor temperature for the day that $n$ days previous before time $t$.

2.5. Griffiths’ method
The equation (2) represents the relationship between comfort temperature ($T_{comf}$) and three independent parameters.

$$T_{comf} = T_{in} + \frac{(0 - AMV)}{\alpha}$$

(2)

Where, $T_{comf}$ and $T_{in}$ are comfort temperature and indoor temperature, respectively. $\alpha$ is Griffiths coefficient and usually to be set as 0.25, 0.33 and 0.5, respectively.

3. Results and Analysis
3.1. Thermal conditions and thermal sensations
The mean values of indoor air temperature, air velocity and relative humidity over the investigation period were 14.83°C, 0.15m/s and 72.50%, respectively. The lower air temperatures and higher relative humidity levels are accordance with the climatic characteristic of cold-humid in winter in hot summer and cold winter (HSCW) climate zone. With respect to thermal sensation, 22.5%, 11.8% and 26.4% of occupants regarded indoor thermal environment as ‘slightly cool’, ‘cool’ and ‘cold’, respectively. 29.2%
of surveyed people viewed indoor thermal environment as ‘neutral’. 6.2% and 3.9% of participants felt ‘slightly warm’ and ‘warm’, respectively. No respondents regarded indoor thermal environment as ‘hot’ during this investigation.

3.2. Comfort temperature
By substituting $\alpha = 0.25, 0.33$ and 0.5 into equation (2), the comfort temperatures were calculated accordingly. The results are presented in table 1.

| Sample | $\alpha = 0.25$ | $\alpha = 0.25$ | $\alpha = 0.25$ |
|--------|-----------------|-----------------|-----------------|
| TSV(0) | 341             | 14.64(1.75)     | 14.64(1.75)     | 14.64(1.75) |
| TSV(± 1) | 683            | 15.92(3.24)     | 15.64(2.73)     | 15.35(2.25) |
| TSV(± 3) | 1177           | 19.10(5.81)     | 18.02(4.49)     | 16.88(3.16) |

Since the mean neutral temperatures varied in a narrow range when $\alpha = 0.5$, the value of $\alpha$ was determined as 0.5. Then, neutral temperature and comfort ranges were 14.64 ± 1.75°C and 12.66 ± 1.17°C -17.01 ± 1.70°C, respectively.

3.3. Adaptive comfort model
The relationship between $T_{comf}$ and $T_{rm}$ is shown in figure 1. The corresponding adaptive comfort model was expressed by equation (3).

$$T_{comf} = 0.438T_{rm} + 12.722 \left( R^2 = 0.0304 \right)$$

Figure 1. Comfort temperature against running mean outdoor temperature.

Based on the collected data, the comfort temperature in winter in Zunyi was 16.88 ± 0.55°C with minimum and maximum values of 15.81°C and 17.69°C, respectively.

4. Conclusions
The conclusions of the study are summarized as below:
- The mean values of indoor air temperature and relative humidity are 14.83°C and 72.50%, respectively. They are not within the comfort zone with respect temperature and relative humidity specified in ASHRAE 55-2004.
- More than half (57.9%) of occupants’ thermal sensation votes are within the central three categories of ASHRAE’s 7-point scale. However, 38.2% of respondents feel ‘cool’ or ‘cold’ during the survey period.
- The comfort zones and neutral values in this study are 12.66 -17.69°C and 14.64 ± 1.75°C, respectively.
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