Study on adaptive thermal comfort of personnel in residential buildings based on tracking test

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Abstract: most of the middle and lower reaches of the Yangtze river in China are hot in summer and cold in winter. In order to study the adaptive thermal comfort of indoor personnel in residential buildings in these areas, a tracking test was conducted on 10 free-running residential buildings in Chongqing from July 2017 to August 2018 through a combination of field test and questionnaire survey. Through the study, in this area, occupants' evaluations of thermal environment were summarized and analyzed, the relationship between activity level, Clothing insulation and air temperature was established, the thermal neutral temperature and acceptable temperature range in summer and winter were obtained, and the characteristics of adaptive thermal comfort of people in free-running residential buildings were revealed, which provided a reference for improving the thermal environment of residential buildings in the area with hot summer and cold winter in the Yangtze river basin.

Keywords: hot-summer and cold-winter zone; residential buildings; tracking test; adaptive thermal comfort

1. Introduction

Residential building is an important carrier of the family in modern society and the comfort level of the house has a great impact on the individual's life. Developing science and technology and social economy contribute to residents' living standard, which lead to higher requirements of occupants for indoor thermal environment. At present, the ideal living environment pursued by people not only has comfortable performance, but also needs to meet the needs of mental and physical health. Study on indoor thermal comfort has always been the focus of domestic and foreign experts and scholars. Runming Yao and Baizhan Li of Chongqing University have conducted a long-term study on adaptive thermal comfort. And according to Runming Yao, human thermal adaptability is a process in which thermal sensation makes negative feedback adjustment to human body, and an adaptive model mechanism of thermal comfort was established\textsuperscript{(1)}. In addition, based on 28000 field survey data in five climate zones and more than 500 set of climate chamber experiment, using the theory of "black box" to reflect the physiological regulation and the relationship between the thermal sensation, and considering the psychology and behavior of "Adaptive feedback" stimulation, Run- ming Yao \textsuperscript{(2)} established aPMV model (Adaptive Predicted Mean Vote). Zhao Yuyuan \textsuperscript{(3)} conducted a tracking test on the current situation of thermal environment of office buildings in Chongqing in the summer of 2016, and compared the tracking test method with the traditional test method. Numerous studies \textsuperscript{(4-7)} have shown that the human body's thermal sensation and its adaptability are the key to the study of adaptive thermal comfort. In this paper, the methods of field test and questionnaire survey were used to track and test the residential buildings in Chongqing and the adaptive thermal comfort characteristics of people in residential buildings in Chongqing were revealed.
2. Methodology

The existing research results on thermal adaptation all directly or indirectly indicate that thermal experience is an important factor affecting human thermal adaptation [8] [9]. Dynamic and continuous changes in the thermal and humid environment will definitely affect the thermal response of human body [10] [11]. Therefore, 10 representative residential buildings were selected to conduct tracking test from August 2017 to August 2018, including collection of indoor thermal environment parameters and subjective questionnaire survey.

2.1 Comparison between tracking test method and traditional test method

| Elements                  | Tracking method                                      | Traditional test method                      |
|---------------------------|-----------------------------------------------------|----------------------------------------------|
| Occupant                  | Fixed samples, long-term monitoring                 | Unfixed sample, random survey                |
| Environmental parameters  | Consistent with traditional methods                | Indoor and outdoor air temperature/ relative humidity, Indoor air velocity/black ball temperature/carbon dioxide concentration |
| Instrument installation   | Install it on the test site and avoid to affect the normal life of the tested households | No installation required, just a handheld test households |
| Data storage              | Store data or upload data instantly                 | Manual record                                |
| Questionnaire design      | short questionnaire, which involves few questions, and costs about 1 minute to fill in. | Unfixed sample and mostly fill in once. long questionnaire, which involves many questions, and costs about 3 minute to fill in. |

As can be seen from Tab.1, the tracking test method can monitor the test site for a long time, collect continuous indoor thermal environment parameters, and more fully understand the dynamic change of the actual thermal environment, which is not available in traditional test methods. By combining indoor and outdoor environmental parameters and tracking questionnaire results, the dynamic information of the adaptive thermal comfort performance of the test subjects and the influences of other factors on the adaptive thermal comfort (such as regulating behaviors, living habits, indoor and outdoor environment, etc.) can be analyzed. It effectively complements the existing research results based on static data analysis and provides data support for the research of adaptive thermal comfort.

2.2 Environmental parameters

The thermal environment parameters observed mainly include indoor air temperature, air relative humidity, air velocity and mean radiant temperature. The usage of air conditioner is collected by electric power recorder. The door and window on/off records are collected by magnetic switch recorder. The temperature and humidity recorder and the carbon dioxide recorder are recorded every 15 minutes, and the electric power recorder is recorded every 5 minutes. In order to obtain more accurate objective environmental parameters, the layout plan of measuring points is determined according to ASHRAE 55-2013. The measuring point is at least 0.6m away from the external wall, away from direct sunlight, away from human body, computer and other heat sources. The movement state of the subject at home is not fixed, and the vertical height of the measuring points is 1.5m away from the ground according to the standard.
2.3 Subjective questionnaire design
The questionnaire should be filled out every few days according to the actual test requirements, and the filling time should be controlled within 1-2 minutes, which can help reduce the fatigue of the subjects and ensure the authenticity of their answers.

The subjective questionnaire mainly contains the following contents:
① Basic information of subjects: gender;
② Objective parameters of subjects: clothing collocation and activity level.
③ Subjective voting of subjects: thermal sensation, thermal comfort, thermal expectation, etc.;
④ Modified behavior of subjects: such as on/off strategy of air conditioning, setting temperature of air conditioning, etc.

3. Investigation results and analysis

3.1 Indoor and outdoor thermal environment parameters
Figure 1 shows the weekly change in indoor and outdoor temperature. It can be seen that indoor temperature changes less than that of outdoor temperature. In the moderate season, the temperature difference between indoor and outdoor is small. During the summer and winter, bigger variation can be observed, and the largest gap can be up to 7.65 ℃ in winter. The obvious phenomenon in air conditioning season is mainly caused by the artificial adjustment of indoor temperature.

![Figure 1. Indoor and outdoor air temperature (weekly changes)](image1)

![Figure 2. Indoor and outdoor relative humidity (weekly changes)](image2)

Figure 2 shows the curve of weekly indoor and outdoor relative humidity. It can be seen that, as Chongqing is a humid area, the annual difference of indoor and outdoor relative humidity is small and maintains at a high level, and the indoor mean relative humidity can reach 69.26%.

Thermal environment parameters of test analysis above knowable: in summer, indoor temperature of residential building in Chongqing is higher and maximum weekly mean temperature can up to 30.83 ℃. In winter, the lowest weekly mean temperature is 11.72 ℃. The mean relative humidity can reach 69.26%, which shows the relative humidity in this area is high.

3.2 Insulation of clothing
The insulation of clothing was calculated according to the questionnaire filled by the subjects. The insulation of seat attachment adopted 0.1clo, which according to the insulation values of various types of clothing and seat attachment in ISO 7730-2005. Figure 3 shows the relationship between indoor air temperature and the mean Clothing insulation of the tested subjects.
As can be seen from figure 3, the mean insulation of clothing in Chongqing can reach 1.83clo at most and 0.24clo at least. The change of insulation of clothing decreases obviously with the increase of air temperature. In summer, when the outdoor air temperature reaches more than 28℃, the insulation of personel's clothing is stable at about 0.3clo.

![Figure 3. Relationship between Clothing insulation and outdoor air temperature](image1)

![Figure 4. Frequency distribution of thermal sensation votes](image2)

3.3 Thermal sensation
ASHRAE's seven-point scale is adopted to get thermal sensation vote in the questionnaires. Figure 4 shows the distribution frequency of thermal sensation vote in the questionnaires. From figure 4: the frequency distribution of TSV is close to the normal distribution, and the voting value within the acceptable range (thermal sensation voting is -1, 0, 1) accounts for 77.3%.

3.4 Acceptable temperature and thermal neutral temperature
In order to obtain maximum and minimum acceptable temperature in Chongqing in the summer and winter respectively, The temperature frequency method \[12\] was used to process the thermal sensation voting values and the corresponding indoor temperature of the subjects. Dividing the intervals of temperature 1 ℃, the central temperature of each divided temperature interval was taken as the independent variable, and the mean value \(M\) of the thermal sensation voting value of the surveyors in each temperature interval was taken as the dependent variable. Through linear regression, the results were shown in figure 6. The relation between the mean value \(M\) of thermal sensation voting value and \(t_{\text{in}}\) of indoor air temperature is as follows:

Chongqing summer: \(M = 0.2621t_{\text{in}} - 6.6027\), \(R^2=0.9385\) \(3\)
Chongqing winter: \(M = 0.2071t_{\text{in}} - 3.9970\), \(R^2=0.8018\) \(4\)
Where: \(R^2\) is the correlation coefficient.

![Figure 5. Relation between thermal sensation voting values and air temperature](image3)
M is 0.85 in winter and +0.85 in summer. According to equations (3) and (4), the maximum and minimum acceptable temperatures in summer and winter for 80% of residents can be calculated. Acceptable upper limit of temperature of 80% residents of free-running residential building in Chongqing in the summer is 28.43 ℃, and the lower limit of that is 15.20 ℃ in winter. According to the comparative analysis, the acceptable temperature range in summer and winter in Chongqing is large. As the hot-summer and cold-winter zone residential building energy efficiency design standards [13] saying: the provisions of the bedroom temperature should be controlled in 16 ~ 18 ℃ in winter, 26 ~ 28 ℃ in summer. It can be seen that the acceptable temperature range obtained in this paper is larger than the standard provisions, which indicates that in the free-running residential building, the behavior adjustment ability of the occupants can be given full play, such as switching air conditioning, increasing or decreasing clothing, switching doors and Windows, etc.

When the mean thermal sensation vote TSV=0, the thermal neutral temperature is obtained. Through calculation, thermal neutral temperature of occupants in free-running residential building in Chongqing is 25.19 ℃ in the summer and 19.30 ℃ in winter.

4. Conclusion
(1) Indoor temperature of residential building in Chongqing is higher in summer, and the weekly average temperatures can up to 30.83 ℃. In winter, by contrast, lowest weekly average temperatures reach 11.72 ℃. In addition, relative humidity is higher, the weekly average relative humidity is 69.26%.
(2) When filling in the questionnaire, 91.37% of the subjects are sitting, and 63.41% are sitting (relaxing). During that time, the activity level of the subjects is concentrated between 0.8-1.2met, which is not directly related to indoor air temperature. In Chongqing, the mean insulation of the clothes of the subjects can be as high as 1.83clo and as low as 0.24clo, and the change of insulation of the clothes decreases obviously with the increase of air temperature.
(3) The frequency distribution of thermal sensation voting is close to the normal distribution, and the voting value within the acceptable range (i.e., thermal sensation voting is -1, 0, 1) accounts for 77.3%; The correlation between thermal expectation and thermal sensation is very high. 80% of occupants in Chongqing residential building summer acceptable limits of temperature of 28.43 ℃, the lower limit of the acceptable temperature of 15.20 ℃ in winter. Occupants thermal neutral temperature of residential building in Chongqing is 25.19 ℃ in summer and 19.30 ℃ in winter.

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