THE CHARACTERISTICS OF THERMAL ENVIRONMENT AND COMFORT OF RESIDENTIAL BUILDINGS DURING WINTER IN HOT SUMMER AND COLD WINTER CLIMATE ZONE OF CHINA

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Abstract. In order to study the characteristics of thermal environment and comfort of residential buildings during winter in hot summer and cold winter (HSCW) climate zone of China, this study conducted a questionnaire survey and field test. It was found that 70.9% of residential buildings in HSCW climate zone had space heating equipment, among that the percentage of air conditioning, electric equipment (electric oil-filled radiator and fan heater) and other were 56.0%, 27.6% and 16.4%, respectively. Furthermore, 77.3% (48.7%) of residents only heat their bedrooms (living rooms), and 76.5% of residents heat their rooms only in cold weather, which shows the "part-space" and "part-time" space heating characteristics in HSCW climate zone. For rooms with space heating, the thermal environment is category I in general, but more than 30% of these residents hope a higher indoor temperature. For rooms without space heating, the indoor temperature is below the hygiene limit of 12°C, which belongs to category II, but thermal feeling for 55% of residents is cold and 90.9% of residents hope a warmer indoor environment. The results indicated that the existing evaluation criteria in HSCW climate zone are inconsistent with the thermal sensation and expectation, and an advanced evaluation criterion is needed.

1 Introduction

At present, the energy consumption of building operation accounts for 22% of the total energy consumption in China[1], and the energy consumption of heating accounts for a quarter[2]. Hot summer and cold winter (HSCW) climate zone are non-central heating areas. The average outdoor temperature in the coldest month ranges from 0°C to~10°C[3], while the average indoor temperature is usually lower than 10°C[4], and the indoor thermal environment is uncomfortable. With the continuous improvement of residential living level, the demand to improve indoor thermal comfort is increasing, which also brings energy consumption.

The indoor thermal environment and spacing heating methods in HSCW climate zone have been studied and discussed. The indoor thermal environment test of rural buildings in Hunan and Jiangxi shows that the average indoor temperature in winter is around 7°C[5]. Based on the thermal environment test of 16 residential communities in Suzhou, Nanjing and Shanghai, it is found that the average indoor temperature during winter in HSCW climate zone is 6°C lower than that in the UK climate zone with similar conditions[6]. After testing four typical cities, Nanchang, Wuhan, Chengdu and Hefei, it is pointed out that the indoor temperature of residential buildings in winter is far below the relevant standards of thermal comfort, and the indoor thermal comfort level is low[7]. The annual thermal comfort measurement and questionnaire survey were conducted in Wuhan, and it was found that the average thermal sensation vote in the region ranged from -0.5 to 0.5, with a temperature range of 18.1°C to 30.9°C[8].

This paper gives a research on the thermal environment of residential buildings in HSCW climate zone of China. The field test (Nanyang, a typical city in HSCW climate zone) and questionnaire survey were conducted, the space heating methods, thermal environment, clothing condition, activity state, acceptable indoor temperature and thermal expectation was investigated and analysed.

2 Methods

2.1 Questionnaire survey

The questionnaire survey was conducted in January 19~25, 2021, and 189 valid questionnaires (including Nanyang, Wuhan, Shanghai and Chengdu) were obtained. The survey research includes basic information (gender, income, clothing, activity status, etc.), the feelings and evaluation of thermal environment under different space heating methods.

2.2 Field test

The field tests were carried out on 4 residential buildings in Nanyang, as a case study of field test, during January 13 to 29, 2021. The test residential buildings could be divided into two types. One is with

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space heating equipment, which included air conditioning heating, coal stove heating and electric oil-filled radiator, another is buildings without space heating equipment. The air temperature and relative humidity recorder (AZ88163, ±0.5°C/0.1%RH) and black ball thermometer (WBGTAZ8778, ±1°C) are arranged according to the "Evaluation standard for indoor thermal environment in civil buildings" (GB/T 50785-2012)[9], and the variation of temperature, humidity and average radiation temperature were tested for 48 hours continuously, and the collection interval was 30s.

2.3 Evaluation index

According to GB/T 50785-2012, the thermal sensation of thermal environment in heated and cooled buildings was evaluated by two indexes, predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). For thermal environment in free-running buildings, the adaptive coefficient λ was introduced and the evaluation index was aPMV. The thermal environment category and evaluation indexes are shown in Table 1.

Table 1. Evaluation index of indoor thermal environment[9]

Level	Heated and cooled buildings		Free-running buildings
Category I	PPD≤10%	-0.5 ≤PMV≤0.5	-0.5 ≤aPMV≤0.5
Category II	10%＜ PPD≤25%	-1≤ PMV＜-0.5 or +0.5＜ PMV≤+1	-1≤ aPMV＜-0.5 or +0.5＜ aPMV≤+1
Category III	PPD＞25%	PMV＜-1 or PMV＞+1	aPMV＜-1 or aPMV＞+1

3 Results and discussion

3.1 Space heating methods and characteristics

The space heating methods of residential buildings in HSCW climate zone are shown in Fig.1. It can be seen that 70.9% residential buildings have heating equipment, and heating methods mainly include air conditioning heating, electric equipment (electric oil-filled radiator and fan heater) and other heating devices, accounting for 56.0%, 27.6% and 16.4% respectively. Buildings without space heating accounted for 29.1%, and residents who keep warm by wearing heavy clothes, using hand warmers and other low-cost ways.

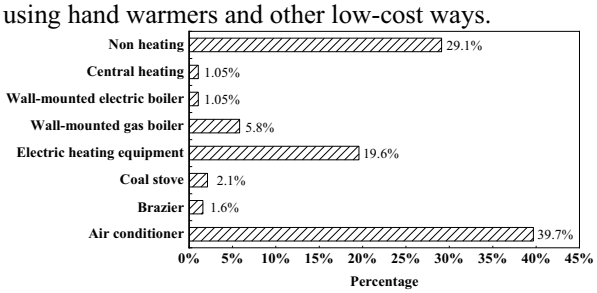

Fig. 1. Situation of heating methods.

According to the survey, the habits of residents to use different space heating equipment are similar, which shows in Fig.2 and Fig.3. 76.5% of residents only use heating in cold weather, while bedrooms and living rooms are the main heating rooms, accounting for 77.3% and 48.7% respectively. Other types are mainly braziers and coal stoves. In a word, the space heating characteristics in HSCW climate zone have a significant characteristic of "part-time and part-space".

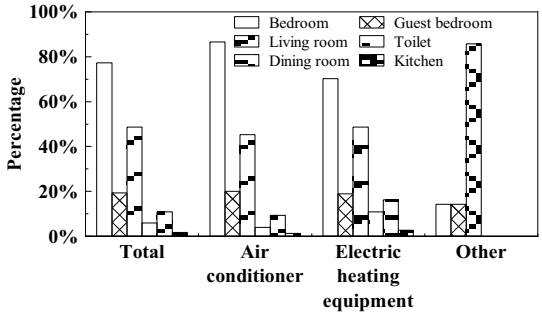

Fig. 2. Use habits of heating equipment for rooms.

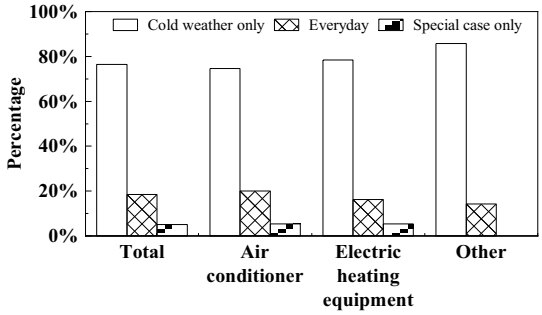

Fig. 3. Use habits of heating equipment for time.

3.2 General evaluation of thermal environment

The temperature and humidity changes of rooms with air conditioning, coal stove, electric oil-filled radiator (The higher relative humidity of the room during the daytime because the steam invaded into the room, which caused by steaming bun in the courtyard.) and rooms without space heating shows in Fig. 4 and Fig. 5. It can be seen that the operation of three space heating methods was intermittent. Air conditioning and electric oil-filled radiator heating were mainly used for heating at night, while coal stove heating was used in the daytime. The air conditioning heating room temperature is basically maintained at about 15°C, the relative humidity is about 45%.

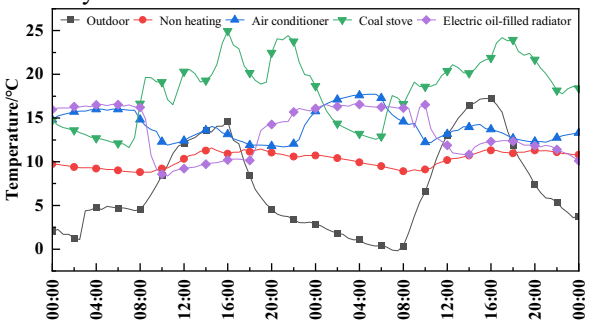

Fig. 4. Indoor temperature under different heating methods.

Low indoor temperature will lead to the decrease of metabolic rate, slow breathing, and many unhealthy diseases. Preventive medicine sets the lower limit of human "cold tolerance" at 11°C [10]. The survey found that 89% residents believed that not heating their homes would lead to lower productivity, frostbite on hands and feet and extra spending on heating. For users who do not provide heating, the indoor thermal environment is harsh, resulting in the prevalence of chilblains (reach to 79%).

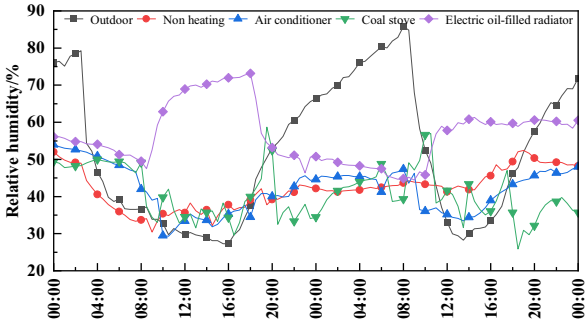

Fig. 5. Indoor relative humidity of different heating methods.

The thermal and wet sensation of residents with different heating methods are shown in Fig. 6 and Fig. 7. 77% of residents felt the room was in a state of cold to slightly cool. As for the feeling of humidity, 50% residents thought that the indoor relative humidity was moderate, but 35% residents thought that the indoor humidity was humid.

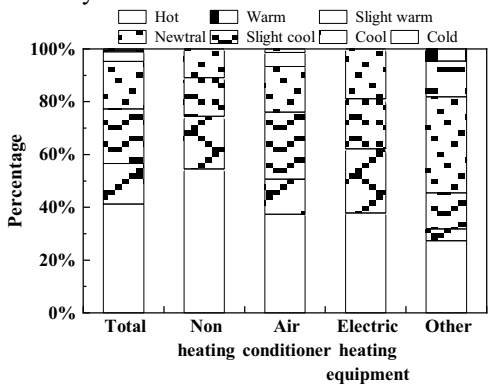

Fig. 6. Thermal sensation of residents with different heating methods.

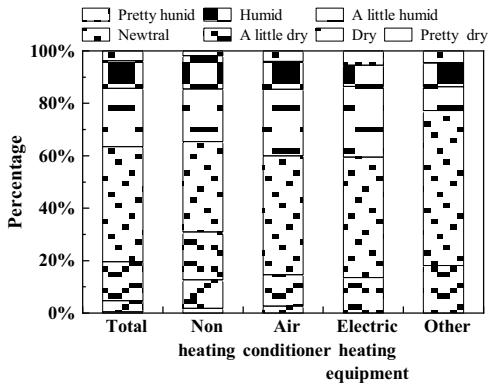

Fig. 7. Wet sensation of residents with different heating methods.

The thermal expectation of residents is an indirect evaluation of thermal environment under the current heating method. As shown in Fig. 8, compared to the residents without space heating, those who with heating had a higher thermal expectation of indoor temperature. It can be seen that the current non-heating users have a strong desire for heating and are eager to improve the temperature of the room. For heating users, the current heating method does not reach their expected temperature, so they hope that the indoor temperature can be improved to meet better indoor thermal comfort requirements.

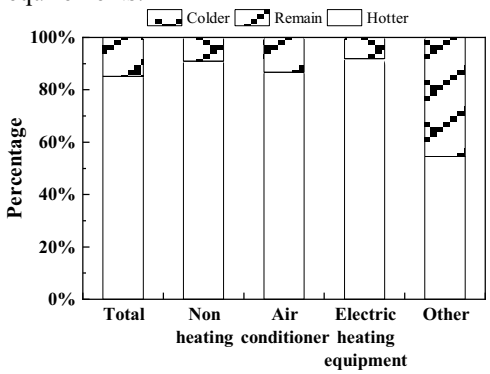

Fig. 8. Thermal expectations of residents with different heating methods.

PMV, aPMV and PPD under different heating methods are shown in Fig.9 and Fig.10. To no space heating room, the indoor thermal comfort environment is poor, and the dissatisfaction rate of residents is high. The aPMV of room without space heating was about -0.87, which belonged to category II.

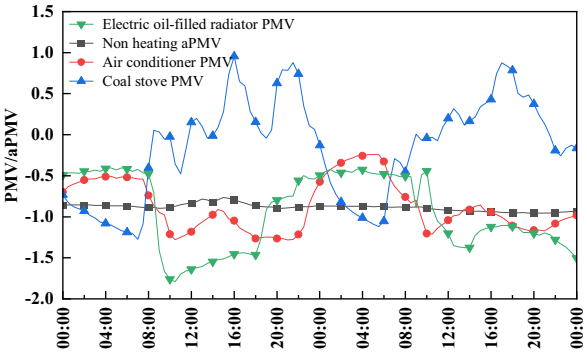

Fig. 9. PMV or aPMV under different heating methods.

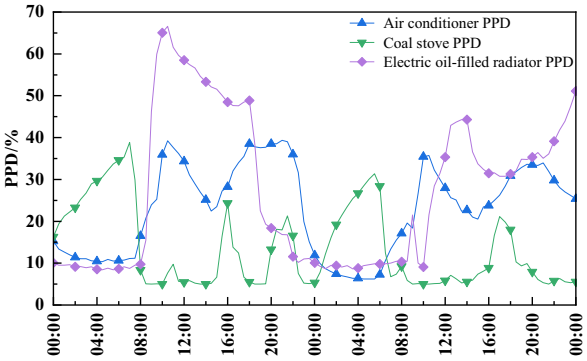

Fig. 10. PPD under different heating methods.

Different space heating methods room had different PMV and PPD. For the air-conditioned heating room, the PMV value fluctuated around -0.5. The dissatisfaction rate drops below 10% after the equipment was opened for a period of time, which was

thermal environment category I in general. For the room with electric oil-filled radiator, it had the same tend to air conditioning room, PMV value raised after equipment turned on for a period of time, and finally stabilized above -0.5. PPD decreased from 30% to 10% around. The overall evaluation is thermal environment category I. During the heating period, the PMV value of coal stove is above 0, and the dissatisfaction rate is below 10%.

3.3 Clothing condition and activity state

The clothing insulation and activity state are shown in Fig. 11 and Fig.12. Residents in HSCW climate zone generally wear thick clothes.

According to the Evaluation standard (GB/T 50785-2012), the thermal clothing insulation was calculated. The percentage of clothing insulation above 1.2 Clo was 59.8%. The clothing insulation was calculated as 1.27 Clo by weighted average method for the whole sample in HSCW climate zone.

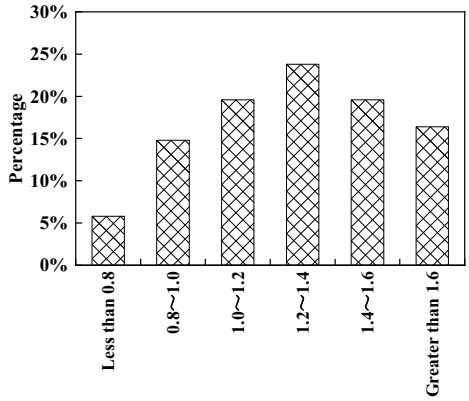

Fig. 11. Clothing insulation.

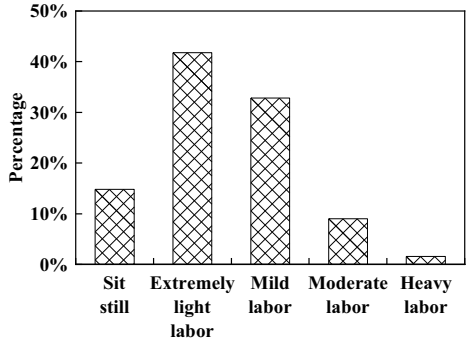

Fig. 12. Activity state

The Activity state in residential buildings are mainly sit still, extremely light labor and mild labor, accounted for 89.4%. According to the typical activity level in ASHRAE Standard 55-2017, the weighted average of metabolic rate of the surveyed residents was 1.3 Met in this climate zone.

3.4 Acceptable indoor temperature and thermal expectation

According to the GB/T 50785-2012, the internal temperature range of indoor artificial and non-artificial cold and heat source environment was calculated. In order to reduce the invasion of cold wind, residents in this area do not often open windows, and the airflow velocity does not exceed 0.3m/s. Therefore, the indoor air velocity[10] is 0.1 m/s. Calculating the aPMV and PMV at different temperatures and relative humidity conditions, the temperature and humidity in the range of |aPMV|≤0.5 and |PMV|≤0.5 is regarded as the acceptable indoor temperature range, which shown in Fig.13 and Fig.14.

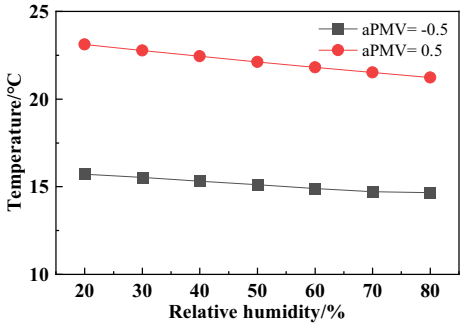

Fig. 13. Acceptable temperature of residents without space heating.

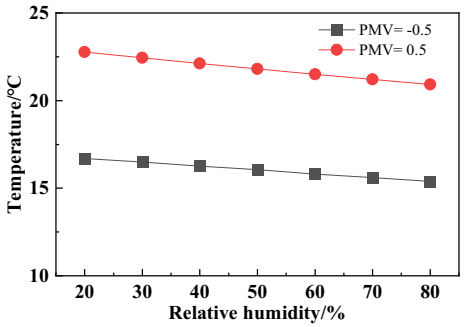

Fig. 14. Acceptable temperature of residents with space heating.

As shown in the figure, for residents without space heating, the acceptable indoor temperature range is 23.1°C~14.7°C, and the average acceptable temperature is 18.9°C. For the residents with space heating, which is 22.8°C~15.4°C, and the average acceptable temperature is 19.1°C. D. A. Mc Intyre proposed the subjective temperature of the thermal environment in the evaluation chamber, which can predict the temperature generating thermal comfort with given clothing thermal resistance (I_{clo}) and metabolic rate (W)[11]. The calculation formula is below.

$$T_{usb}=33.5- 3\ I_{clo}- (0.08+0.05\ I_{clo})\ W \quad (1)$$

The clothing thermal resistance of 1.27 Clo and metabolic rate of 1.3 Met were converted to 75.66W/m^2, and the subjective temperature was 18.8°C, which was close to the calculated acceptable average temperature and within the acceptable temperature range.

According to GB/T 18883-2002 and GB 50176-2016, 30%~60% is selected as the acceptable humidity range in terms of hygiene and comfort.

The acceptable temperature and humidity of space heating and non-space heating buildings in HSCW climate zone are shown in Fig.15 and Fig.16. The enclosed area is the acceptable thermal comfort zone. It can be seen that the minimum acceptable thermal comfort limit cannot be reached in non-space heating room. While space heating room with air conditioning

heating, coal stove heating or electric oil-filled radiator heating was in an acceptable thermal comfort zone. Though space heating room with air conditioning and heating oil heater heating meet the thermal comfort requirements partly. The thermal comfort of coal stove heating is better, and basically meets the requirements.

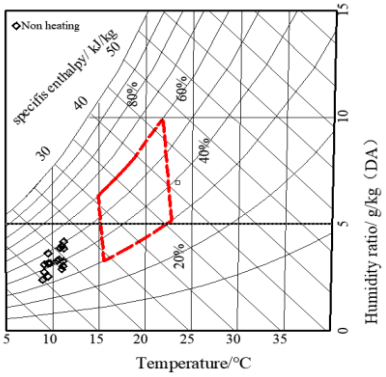

Fig. 15. Acceptable thermal comfort zone (non-space heating room).

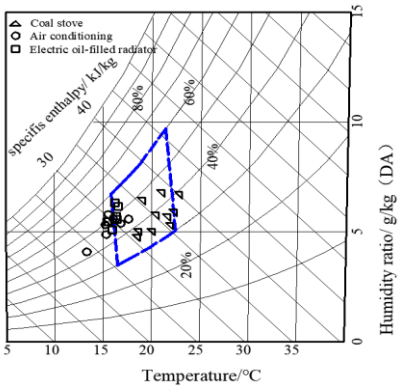

Fig. 16. Acceptable thermal comfort zone (space heating room during heating period).

4 Conclusion

Through a questionnaire survey field test of indoor thermal environment, the conclusions are as follows:

(1) The space heating methods in HSCW climate zone were dominated air conditioning and electric heating equipment now, and performance a typical feature of "part-time and part-space".

(2) The indoor temperature of residents without space heating was between 9°C and 12°C, and 55% of residents' thermal sensation was cold. The aPMV of indoor environment is -0.87, which belongs to category II. Residents had to spend extra money on clothes to keep warm. 80% of these residents hope to improve their comfort level.

(3) The indoor temperature of residents with space heating can reach more than 15°C, but more than 27% of residents thought that the indoor environment is cold. The PMV was above -0.5, PPD was below 10%, the overall evaluation was Category I. However, residents still wear thick clothes and dissatisfied with the current thermal environment. They still hope the indoor temperature could be higher.

(4) For residents without space heating, the indoor acceptable temperature range is 14.7~23.1°C, and the average acceptable thermal comfort temperature is 18.9°C. For residents with space heating, the indoor acceptable temperature range is 15.4~22.8°C, and the average acceptable thermal comfort temperature is 19.1°C.

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