Thermal environment and thermal comfort in a passive residential building in the severe cold area of China

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Abstract

Purpose / Context - The outdoor climate in Harbin is more severely colder than German. There- fore, it is important to study indoor thermal environment and human thermal comfort in Harbin passive buildings by applying Germany technology. However, few studies were reported on this topic.

Methodology / Approach - A field measurement on thermal environment was carried out in a passive residential building in Harbin, as well as a subjective survey on residents' thermal re- sponse. 25 residents in 21 apartments volunteered as the participants in this study. Among them, a continuous monitoring was conducted in 7 apartments.

Results - The results show that the mean indoor temperature was 26.2℃, which was over higher than the upper limit of ASHRAE 55-2013. The average relative humidity was 35.9%, close to the lower limit. There was a small temperature difference between the indoor air temperature and the inner surface temperature of the exterior wall, which indicates a good insulation performance and reduces discomfort induced by cold radiation. 50% residents confided that the indoor environment was over warm, and they usually adjusted clothes to the environment. The neutral temperature was 24.2℃, and 90% acceptability temperature was 23.2~25.2℃, a width of 2 ℃, which indicates a weak adaptation and tolerability for the residents.

Key Findings / Implications - A lower indoor temperature was recommended in operation. Not only could residents' thermal comfort be improved, but also the energy consumption was reduced further.

Originality – Thermal environment and thermal comfort in a Harbin passive residential building was researched.

Keywords - Passive house, Thermal environment, Thermal comfort, Thermal adaptation, Field study, Severe cold area

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1. Introduction

Since 1970s, some researchers in developed countries put forward the term –“zero energy building” (ZEB) or “nearly zero-energy building”, as well as some similar definition (Esbensen and Korsgaard, 1977; Voss et al., 1996; Torcellini et al., 2006). Soon later, a lot of demonstration project were built up. In recent years, low-energy buildings were constructed in China.

The technology and practice of passive house was derived in German. In 1991, the first passive architecture was constructed in Darmstadt. This kind of architecture is distinguished for good envelope insulation performance, enhanced air tightness of doors and windows, much less dependence on fossil energy, and some advanced passive technologies used to improve comfortable indoor climate, such as heat recovery. Energy consumption for heating and cooling in passive houses is far lower than that in normal buildings (Heinze and Voss, 2009).

A passive residential building was constructed as the first demonstration project in Harbn in 2013, China, which was cooperated by China and German.

Harbin is located in the severe cold area of China. The heating period lasts for 6 months. The heating energy consumption accounts for a large part of building consumption. The outdoor climate in Harbin is more severely colder than German. Therefore, it is important to study indoor thermal environment and human thermal comfort in the Harbin passive building by applying German technology. However, few studies were reported on this topic. This paper introduced the recent measurement and subjective results in the passive residential building.

2. Methodology

In the winter of 2015-2016, a field measurement on the thermal environment was carried out in the Harbin passive residential building, as well as a subjective survey on residents’ thermal response. The environmental measurements and subjective questionnaires were simultaneously conducted during the investigation. 25 residents in 21 apartments (age ranges from 25 to 84, with an average of 40.2 years, gender ratio is nearly 1:1) volunteered as the participants in this study. Among them, a continuous monitoring was conducted in 7 apartments. All the participants have fully adapted to the local climate.

2.1 Measurement

The indoor air temperature and relative humidity (RH), air speed, globe temperature, inner surface temperature and outdoor air temperature, relative humidity and air speed were measured during the field investigation.

The indoor air temperature and humidity were continuously monitored per 5 min using self- recording loggers which were placed at about 1.0 m above the floor. The indoor air temperature and humidity, globe temperature and air speed were measured near the residents. The surface temperatures were measured at five points in exterior wall and window, and the average value is considered as the surface temperature. In addition, a digital self-recorded thermometer was placed outside for monitoring outdoor temperature and humidity.

In the study, a self-recorded thermometer (WSZY-1A), a self-recorded globe thermometer (HWZY-1), and a hot- wire anemometer (Testo 425) and an infrared thermometer (Testo 830-T1) were used. The test instruments and precision refer to Wang et al. (2014).

2.2 Subjective questionnaire

Paper questionnaires were adopted. The subjective survey included the following:

1) Residents' background information (gender, age, education, etc.), clothing and activity.
2) The thermal responses of subjects, such as thermal sensation, comfort, expectation and acceptability.

The vote scales of thermal response are shown in Table 1.

Table 1: Vote scales of thermal response

Vote	Scale
Thermal Sensation	-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot
Thermal Preference	-1 cooler, 0 no change, +1 warmer
Thermal Comfort	0 comfortable, +1 slightly uncomfortable, +2 uncomfortable, +3 very uncomfortable, +4 unbearable
Thermal Acceptability	acceptable, unacceptable

A total of 44 valid questionnaires were collected.

3. Measurement Results

3.1 Indoor climate

The statistic results of indoor climates in 21 apartments were given in Table 2.

Table 2: Thermal conditions in 21 apartments

	Mean	Maximum	Minimum	S.D.
Air Temperature (℃)	26.2	28.7	23.8	1.24
RH(%)	35.9	51	24.9	7.51
Air Speed (m/s)	0.05	0.15	0.03	0.03
Inner Surface Temperature in the Exterior Wall (℃)	24.5	26.6	22.3	1.14
Inner Surface Temperature in the Exterior Window (℃)	23.3	27.1	19.3	2.23

The mean indoor air temperature was 26.2℃, 2℃ higher than the upper limit recommended by ASHRAE 55-2013. The average RH was 35.9%, close to the lower limit of the standard. According to subjective responses, most residents felt dry. Therefore, effective actions should be taken to improve indoor humidity. The air speed ranged in 0.03-0.15 m/s, which met the standard. The average inner surface temperature in the exterior wall was 24.5℃, 1.7℃ lower than the mean indoor air temperature. The inner surface temperature in the exterior window ranged in 19.3-27.1℃, for the high performance of low-e windows.

It is rather cold on 25 December, 2015. The outdoor temperature varied between -21.9℃ and 14.3℃. The indoor/outdoor temperature and RH for a typical apartment were given in Figure 1.

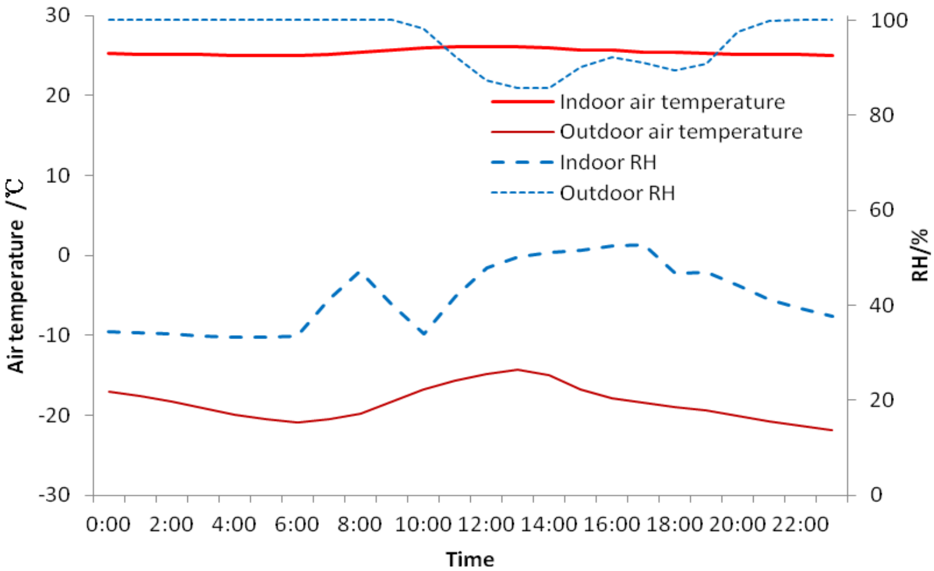

Figure 1 Indoor/outdoor air temperature and RH on 25 Dec.

As seen in Figure 1, the indoor air temperature ranged in 25.0-26.1℃, with an average of 25.4℃. The width of indoor air temperature was 1.1 ℃, which indicates a good stability of air temperature.

The indoor RH ranged in 33.2%-52.6%, with average of 41.8%. In addition, the RH increased significantly during daytime, when residents were active. Therefore, indoor RH was mainly influenced by residents' activity.

3.2 Inner surface temperature in the exterior wall

The continuous monitoring results of inner surface temperature in the exterior wall for the same apartment were shown in Figure 2.

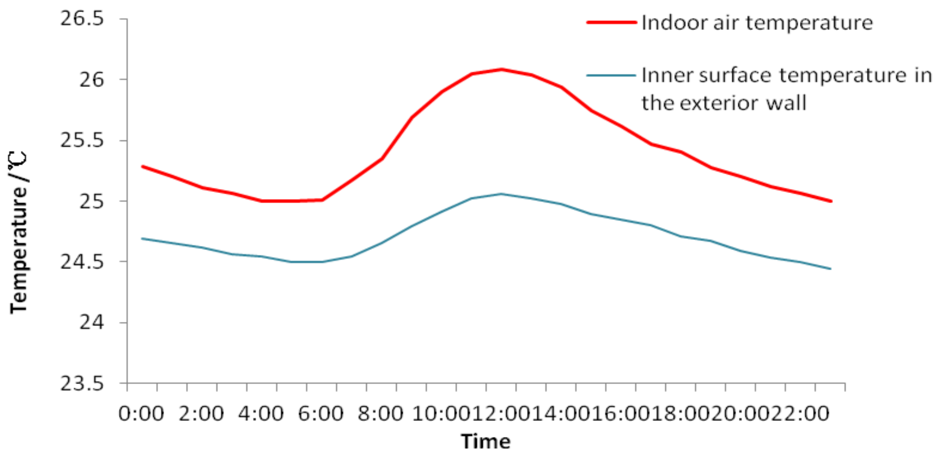

Figure 2 Inner surface temperature in the exterior wall and air temperature on 25 Dec.

As shown in Figure 2, the inner surface temperature in the exterior wall ranged in 24.4-25.1℃, with an average of 24.7℃. Compared with the indoor air temperature, the surface temperature were gentle. The temperature difference between the indoor air temperature and the surface temperature varied in 0.46-1.02℃, with an average of 0.70℃. Therefore, the difference was very small, which suggests that the heat transfer from indoor air to the exterior wall was little. Furthermore, the good insulation performance of the exterior wall induced a small heat loss of the envelope. Due to a high inner surface temperature, with a small difference from indoor air temperature, local discomfort induced by cold radiation could be reduced.

4. Subjective Results

4.1 Clothing insulation

The residents' clothing insulation was 0.52-1.00 clo, with an average of 0.69 clo. Figure 3 shows the frequency distribution of clothing insulation.

In the severe cold area of China, the residents' clothing insulation was 1.37 clo for normal apartments (Wang, 2006), higher than that for this passive building. As seen in Figure 3, more than 50% of residents' clothing insualtion were in 0.5-0.7 clo. In such an overheated microclimate, to get access to the neutral, residents would prefer changing clothes. In general, when it is over warm in the passive building, residents mainly adapted to the environment by adjusting clothing.

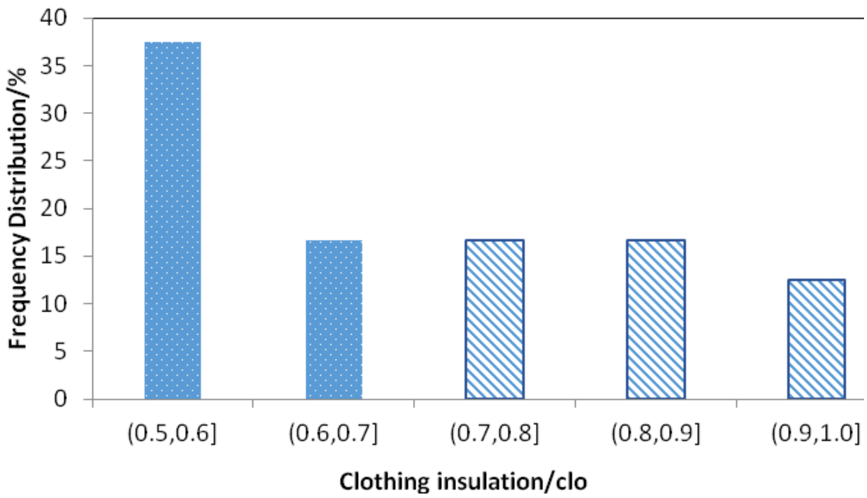

Figure 3 Distribution of residents' clothing insulation

4.2 Thermal sensation

The distributions of actual thermal sensation votes (TSV) was seen in Figure 4. The percentage of voting for "slightly cool", "neutral" and "slightly warm" was 50%, and the percentage of voting for "warm" and "hot" was another 50%. It indicates that half residents felt warm, which means overheating in this building subjectively.

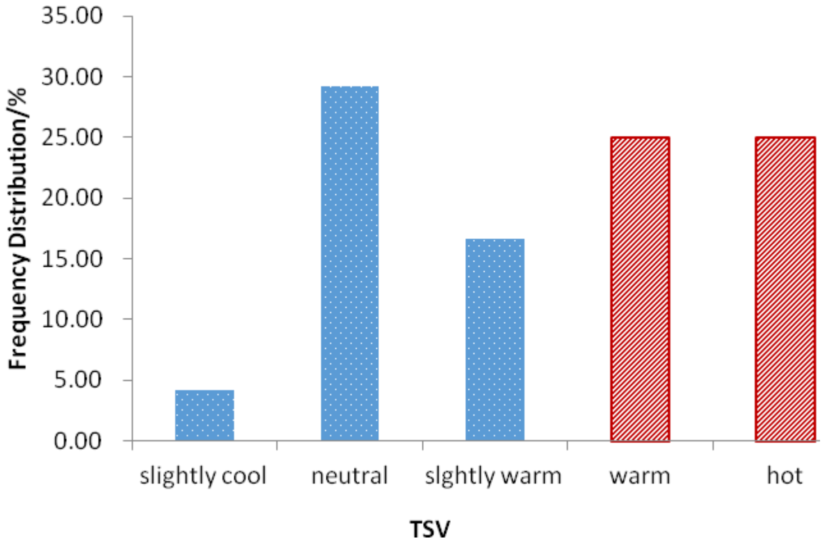

Figure 4 Distribution of residents' thermal sensation vote

4.3 Thermal preference

The distributions of thermal perference were given in Figure 5.

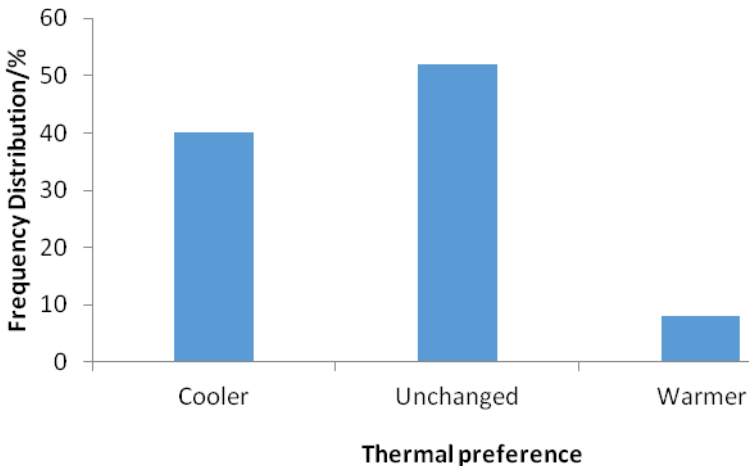

Figure 5 Distribution of residents' thermal preference

As seen in Figure 5, 52% residents preferred the temperature unhanged, when 40% residents would like a lower temperature, and only 8% residents want a warmer environment. The results are in accord with thermal sensation vote, which proved that the indoor temperature was so high that residents would expect a lower temperature psychologically.

The 52% residents preferred the temperature unchanged, which means that they have adapted to the over warm environment. The overheated indoor environment in winter will not only cause energy waste, but also weaken human tolerance with the cold outdoor climate.

4.4 Thermal comfort

The distribution of actual thermal comfort votes (TCV) was presented in Figure 6.

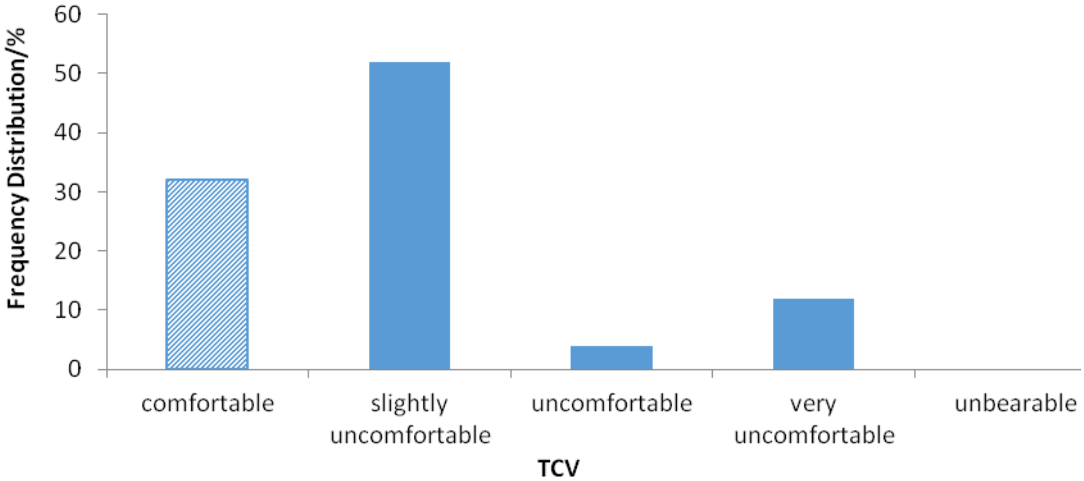

Figure 6 Distribution of residents' thermal comfort vote

As seen in Figure 6, only 32% residents felt comfortable in the environment. And the other 68% residents felt uncomfortable. In general, when residents felt over warm and uncomfortable, they preferred an environment with lower indoor air temperature.

5. Discussion

5.1 Neutral temperature

After linear regression of mean thermal sensation (MTS) votes with indoor air temperature (ta), the relationship was given in Equation (1).

$$MTS = 0.5t_a - 12.083 \quad (1)$$

Where MTS is the mean thermal sensation vote, and t_a is the indoor air temperature, ℃.

The thermal neutral temperature was 24.2℃, a difference of 2.0℃ from the mean indoor air temperature (26.2℃).

5.2 Thermal adaptation

The adaptive theory proposed by de Dear and Brager (1998) suggested that people get access to comfort through thermal adaptations including psychological adaptation, physiological adaptation and behavioral adjustments.

There were little positive effects of behavioral adjustments on human thermal comfort in centralized heating buildings. As a result, people would adapt to the indoor environments psychologically and physiologically. Because physiological acclimatization could be formed in several days or weeks, and the indoor temperature was relatively constant during the heating period, residents would adapt to the environment psychologically.

In the passive building, the neutral temperature was higher than that in normal apartments, and the clothing insulation was lower than normal apartments, which both indicate residents' adaptation to the current environment. However, this adaptation was kind of limited. When the indoor air temperature was over high, most residents would feel uncomfortable and preferred a lower temperature. As a result, a lower indoor temperature was recommended in design and operation. Not only could residents' thermal comfort be improved, but also the energy consumption was reduced.

6. Conclusions

(1) The mean indoor air temperature was 26.2℃, 2.2℃ higher than the upper limit recommended by ASHRAE 55-2013. The average RH was 35.9%, meeting the standard. And according to sub- jective responses, most residents felt dry.

(2) The temperature difference between the indoor air temperature and the surface temperature in the exterior wall was small, which suggests a good insulation performance of the exterior wall. And local discomfort induced by cold radiation could be reduced.

(3) The neutral temperature was 24.2℃, and 90% acceptability temperature was 23.2-25.2℃, a width of 2 ℃, which indicates a weak adaptation and tolerability for the residents.

(4) Half residents felt warm, which means overheating in this building subjectively. Residents mainly adapted to the environment by adjusting clothing. When residents felt over warm, they felt uncomfortable and preferred a lower indoor air temperature.

(5) A lower indoor temperature was recommended in design and operation. Not only could residents' thermal comfort be improved, but also the energy consumption was reduced.

7. Acknowledgement

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