

Thermal Environment and Thermal Adaptation in Residential Buildings



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Abstract

Purpose / Context - The winter in the severe cold area of China is long and cold, with a long heating period. In recent years, the indoor air temperature during heating in residential buildings kept increasing. In order to study the thermal comfort and adaptation in such an overheated environment, a field study was carried out in Harbin.

Methodology / Approach - A tracking investigation was conducted during the heating period in 2013-2014. 10 apartments were selected from 9 buildings in 5 residential communities, with 20 participants. The indoor and outdoor air temperatures, as well as relative humidity were monitored continuously, while the residents were interviewed on their thermal responses online every week. 308 valid questionnaires were collected. The heating periods were separated into three phases based on the outdoor temperature.

Results - The results show that the mean indoor air temperatures in the early-, mid- and late-heating periods were 23.6°C, 24.3°C and 25.0°C, respectively, which were larger than or close to the upper limit recommended by thermal comfort standards, and slightly higher than the related thermal neutral temperatures. With the heating process, the mean clothing insulation of residents decreased. Opening windows and reducing clothing were mainly taken by the residents to adapt to the overheated environment.

Key Findings / Implications - The neutral temperature rose with the mean air temperature increasing in the heating period. The lower limit of the temperature range in winter is to be suggested in heating design to achieve a sustainable indoor environment.

Originality - It was found that human thermal neutral temperatures in residential buildings changed with the indoor, and many evidences of thermal adaptation were got.

Keywords - Thermal comfort, Thermal adaptation, Thermal environment, Field study, Residential building



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1. Introduction

The winter in the severe cold area of China is long and cold. Especially, the heating period lasts for 6 months in Harbin, a representative city in the area. According to outdoor temperatures, the heating period is divided into three phrases: early period, mid period and late period.

During the long heating period, outdoor temperatures fluctuate significantly, while indoor temperatures stay almost constant. On the basis of thermal adaptive theory put forward by de Dear and Brager (1998), the thermal neutral temperature changes with different climatic conditions. So, does the thermal neutral temperature change with different heating periods? Should the indoor design temperature change with different periods? And how do thermal comfort and adaptation perform in the residential buildings?

Based on previous outcomes, Wang (2006) and Wang et al.(2003, 2011, 2014) found that the thermal neutral temperature changed when space heating began in residential buildings, and the thermal neutral temperatures in winter and spring during space heating were different in teaching buildings. The thermal neutral temperature in winter was lower than that in spring. When the indoor air temperature was overly high, people would feel uncomfortable. Cao et al. (2011) found that once people adapt to the warmer environment, they would lose adaptability to cold outdoor climate, which would cause energy wastes and health problems.

Our previous investigations were conducted in different periods or in different kinds of buildings. How do thermal responses change during the whole heating period? These are focused here.

2. Methodology

In the winter of 2013-2014, a continuous tracking measurement was conducted in residential buildings, as well as subjective questionnaires on residents' thermal responses.

The measurement and questionnaires were processing at the same time. A digital self-recorded thermometer was placed in the main occupied room for continuous measurement. The participants filled in questionnaires online once every week. 308 valid questionnaires were collected.

2.1 Subjects

10 apartments were selected from 9 buildings in 5 residential communities, with 20 participants. The male to female ratio was almost 1:1. The participants in this study ranged in age from 28 to 72, with an average of 48.5. They had lived in Harbin about 40 years in average, completely accustomed to the climate. Table 1 shows the backgrounds of the participants.

Table 1: Participants' backgrounds

Number of participants		Age	Years in Harbin
20	Mean	48.5	39.7
	Std. Dev.	13.6	20.1
	Max	72	70
	Min	28	13

2.2 Measurement

Thermal parameters involved indoor and outdoor air temperatures, as well as relative humidity (RH). The air temperature and RH were measured continuously. A self-recorded thermo-hygrometer was set at about 1.0m above the floor in each occupied room.

2.3 Subjective questionnaire

The subjective survey was conducted through online questionnaires, which were filled in by respondents every week.

The subjective survey included the following:

- (1) The thermal responses of subjects, such as thermal sensation, comfort, expectation and acceptability. Vote Scales were shown in Table 2.

Table 2: 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 unbearable
Thermal Acceptability	acceptable, unacceptable

- (2) The adaptive measures taken to improve indoor thermal environment, such as opening or closing windows, changing clothes and activity levels, having hot drink.

2.4 Research phases

The outdoor temperatures during the investigation are given in Figure 1. The whole heating period is divided into 3 phases (early heating period (EH), mid heating period (MH), and late heating period (LH)) according to outdoor temperature in Harbin.

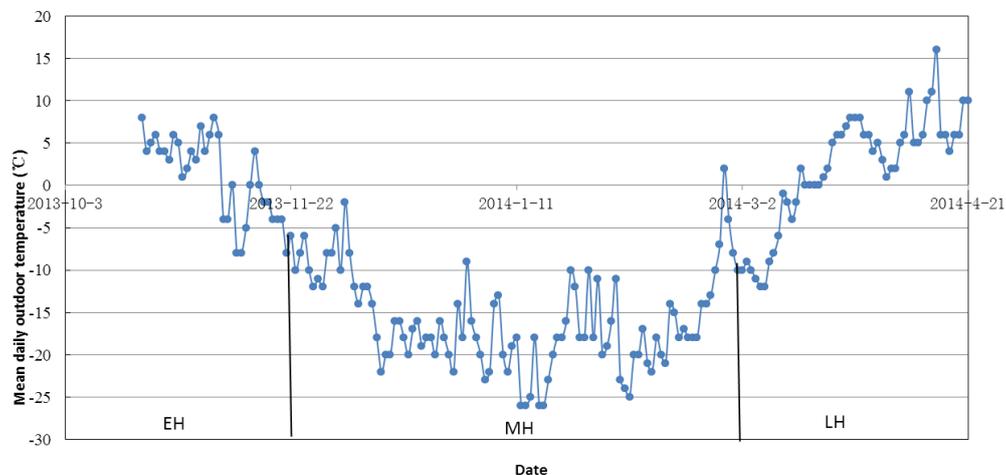


Figure 1 Outdoor temperature and phase division of heating period

Figure 1 shows that the daily mean outdoor air temperature descended below -10°C on 22 November 2013 and rebounded above -10°C on 2 March 2014. So the two days were termed as the beginning and end of MH respectively. The mean outdoor temperature of EH and LH were 1.4°C and 2.2°C , which were close. The maximums of the two phases were 11°C and 16°C , and the minimums were -8°C and -12°C . The outdoor temperature of MH varied from -26°C to 2°C , with an average of -16°C , which was the lowest in the periods.

3. Results and discussion

3.1 Air temperature and relative humidity (RH)

The mean indoor air temperatures and RH of 10 apartments were shown in Table 3.

Table 3: Mean indoor air temperature and RH in three phases

Parameter	RH	MH	LH	Whole Period
Mean Air Temperature (°C)	23.6	24.3	25.0	24.3
Mean RH (%)	46.9	34.6	34.7	37.2

As known in Table 3, the mean air temperature during the whole period was 24.3°C. In LH, the mean indoor air temperature was at the maximum, 25.0°C. In the three phases, the mean air temperatures were close to or beyond the limit (24°C) recommended by ASHRAE standard. The mean RH ranged in 30%-50%.

The mean daily air temperatures and RH of 10 apartments is given in Figure 2.

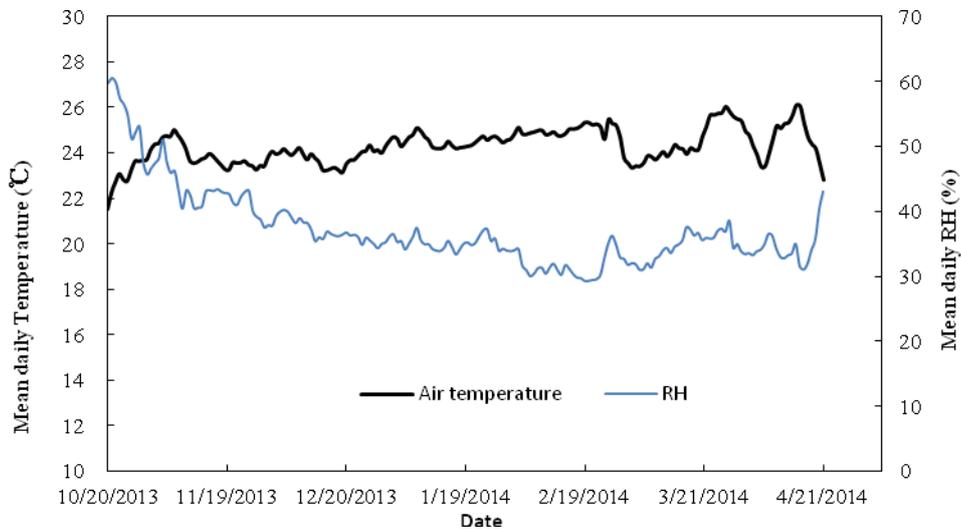


Figure 2 Mean daily air temperature and RH in apartments

As indicated in Figure 2, the indoor air temperature became stable since the centralized heating was used, ranging in 21.5-26.1°C. The mean daily RH varied in 29.4%-60.5%.

3.2 Clothing insulation

The clothing insulation values of respondents in residential buildings are shown in Figure 3. It shows that the clothing insulation decreased with the heating period processing, when people had gradually adapted to the indoor air temperature. Clothing adjustments suggest that people can adapt to the indoor environment well through behavioral adjustment.

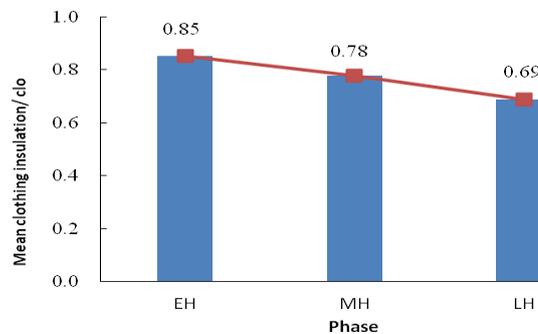


Figure 3 Mean clothing insulation in three phases

3.3 Thermal sensation

The distribution of thermal sensation vote (TSV) of respondents in the residential buildings is given in Figure 4. The TSV frequency followed a normal distribution in each phase.

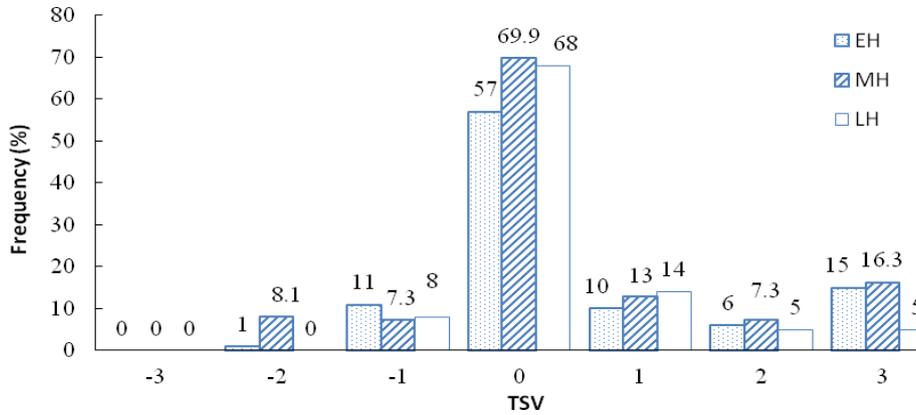


Figure 4 Distribution frequency of TSV

With the space heating going on, the TSV gradually shifted to the warm side. In three phases, only few respondents voted for -1,-2 or -3, while more respondents felt warm (vote for +1, +2 or +3). 36.6% of respondents felt warm in MH, so did 21.0%, 24.0% in EH and LH. This is also a valid evidence of overheating in residential buildings.

Figure 5 shows the air temperature distribution and clothing insulation at TSV of 0, +1, +2 and +3, to demonstrate a deep relationship between thermal sensation and air temperature.

As seen in Figure 5, at votes of +1 and +2, 50% of the relative indoor air temperatures were higher than 24°C. At the vote of +3, 95% of the temperatures were higher than 24°C. Meanwhile, there is no obvious discrepancy between clothing insulations at different votes. Metabolic rates were almost constant because respondents were required not to do heavy activity. Generally, people felt warm mainly because of overheating indoors.

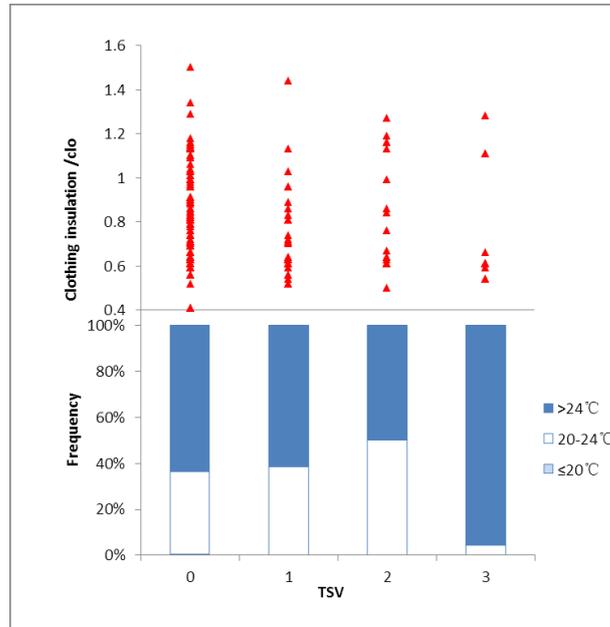


Figure 5 Air temperature distribution and clothing insulation at different TSV

3.4 Behavioral adjustment

Figure 6 shows the distribution of behavioral adjustments when respondents felt hot in residential buildings.

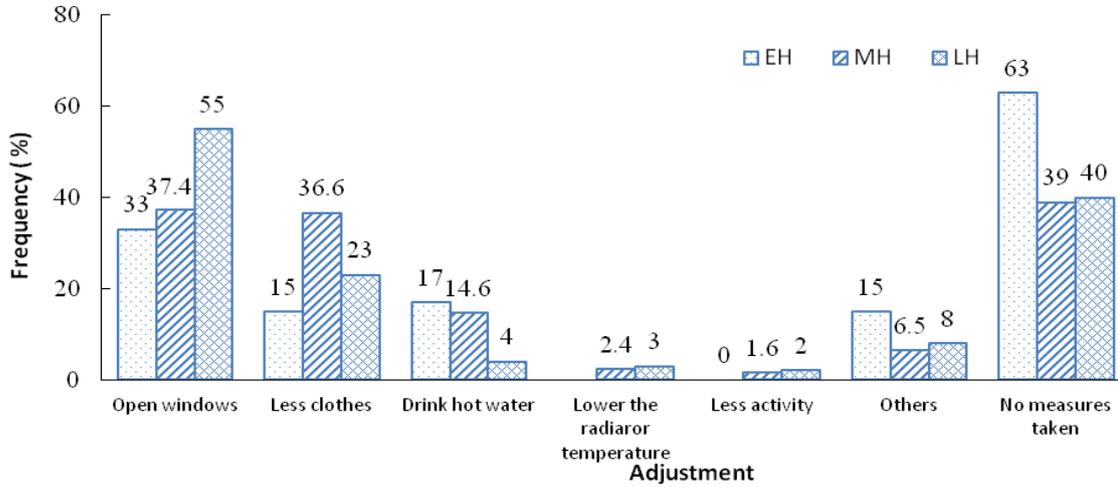


Figure 6 Distribution frequency of adjustments in residential buildings

Through the heating period, residents commonly improved the indoor environment by opening window in warm environment. Before and after the space heating, opening window could enhance natural ventilation and improve thermal comfort. However, in the heating period, opening window would cause energy waste for a hot indoor environment.

As seen in Figure 6, 37.4% of the subjects opened windows when they felt hot in EH, so did 37.4% in MH and moreover 42.0% in LH. Therefore, the over high indoor air temperature led to a waste in winter.

3.5 Thermal neutral temperature

The relationship between respondents' MTS and indoor air temperature in three phases (EH, MH and LH) are shown in Figure 7. It is seen that the thermal neutral temperatures in different phases were figured out, which are 21.8°C, 22.9°C and 23.0°C, respectively.

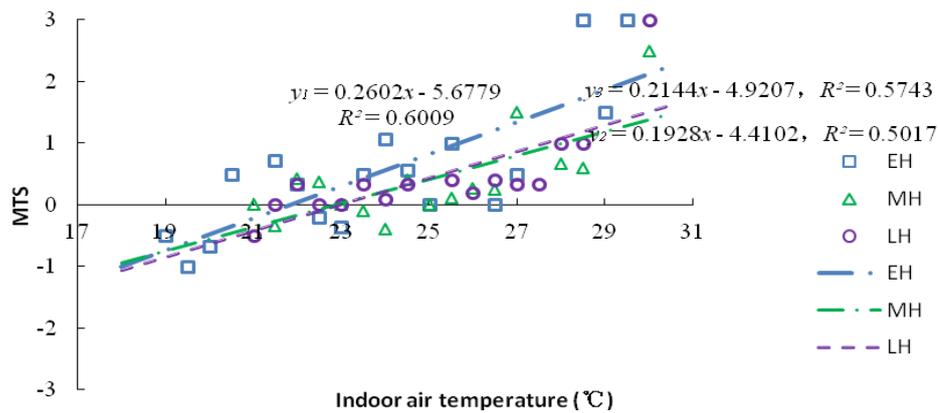


Figure 7 Relationship between respondents' MTS and indoor air temperature in three phases

Table 4 shows the comparison between thermal neutral temperatures and mean air temperatures of different phases, which suggests a significant discrepancy between the two temperatures.

Table 4: Thermal neutral temperatures and mean air temperatures of different phases

Parameter	EH	MH	LH
Average Air Temperature: t_a (°C)	23.6	24.3	25.0
Thermal Neutral Temperature: t_n (°C)	21.8	22.9	23.0
$t_a - t_n$ (°C)	1.8	1.4	2.0

After space heating began, the indoor air temperature increased significantly, so most residents did not adapted to the thermal environment, and felt warm, which resulted in a low thermal neutral temperature, with a difference of 1.8°C.

In MH, the outdoor temperatures decreased, while the mean indoor air temperature rose by 0.7°C. Meanwhile, respondents built up some adaptation to the indoor environment, with the thermal neutral temperature increased by 0.9°C, 1.4°C lower than the mean air temperature.

In LH, the outdoor temperatures rebounded, and the mean indoor air temperature still rose by 0.7°C. The thermal neutral temperature was 2.0°C lower than the mean air temperature. It is found that the neutral temperature rose with the mean air temperature increasing in the heating period, which indicates that the residents got used to the indoor thermal environment gradually.

On the other hand, the neutral temperatures were always below the mean air temperatures, suggesting overheating in residential buildings, which might cause discomfort and energy wastes.

When residents' dependence to the indoor warm environment is built up, resistibility to the cold outdoor climate would be weakened. As a result, in addition to energy wastes, overheating would be against health. This finding further confirms conclusions by Cao et al. (2011).

In general, overly high temperatures would weaken residents' thermal adaptation, and indoor thermal history affects thermal adaptation significantly.

4. Conclusions

In EH, MH and LH, mean indoor air temperatures were 23.6°C, 24.3°C, 25.0°C. This result shows that there did exist overheating in residential buildings.

At MTS vote of +1 and +2, 50% of the relative indoor air temperatures were higher than 24°C. At the vote of +3, 95% of the temperatures were higher than 24°C. Meanwhile, there is no obvious discrepancy between clothing insulations at different votes. Therefore, people felt warm mainly because of overheating indoors.

In the heating period, more than 20% respondents felt warm (vote for +1, +2 or +3) and above 30% respondents opened windows to release overheat. The clothing insulation decreased with the heating period processing.

The neutral temperature rose with the mean air temperature increasing, which indicates that the residents got used to the indoor thermal environment gradually. On the other hand, the neutral temperatures were always below mean air temperatures, suggesting overheating in residential buildings.

Due to high temperatures indoors, residents commonly adapt to the indoor environment by opening window or taking off clothes. However, it would cause energy increase and discomfort. Therefore, the indoor temperature should be kept at the lower limit of the comfort range in winter to keep residents' adaptation and realize sustainable building designs.

5. Acknowledgement

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6. References

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