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Thermal Comfort and Thermal Adaptation between Residential and Office Buildings in Severe Cold Area of China

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Abstract

Harbin is located in Chinese severe cold area. Local people stay indoors by most of time in winter. The occupants’ behavioural regulation was greatly different between residents and office staffs, which might lead to the differences of human thermal responses. A field study was conducted in residential and office buildings from September 2013 to May 2014. The thermal environmental parameters were continuously measured and 1050 subjective questionnaires were collected. The results show that the occupants’ behavioural thermal regulation was different between residents and office staffs periodically. There were deviations between indoor air temperature and neutral temperature. The subjects in office buildings expected more to lower the indoor air temperature in winter. The local occupants had adaptation to both cold climate and indoor environment. The strategy of maintaining indoor temperature was suggested according to the different building functions to save energy and keep comfortable.

1. Introduction

In view of increasing concerns about climate change and building energy conservation, more and more researchers paid more attention on occupants’ behavioural adaptation and thermal comfort conditions [1]. And the legitimacy of the adaptive comfort model has been worldwide recognized, and it has been adopted by ISO 7730 [2]

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and specified by ASHRAE Standard 55 [3]. The adaptive comfort model emphasizes the role occupants play in dominating their own thermal comfort compared with PMV model [4]. Based on the presumption, people can actively adapt themselves to their thermal conditions rather than merely accepting it passively. Besides, the research on human thermal adaption should be carried out by and large in different climate zone, different nations and different thermal history respectively. Brager and De Dear proposed the human thermal adaption by three concepts: physiological acclimatization, behavioural adjustment, and psychological habituation or expectation [5]. They also indicated that behavioural adjustment and psychological expectation had more influence on thermal adaptation in buildings compared to the slower process of acclimatization. And, the current research on occupants’ behavioural and psychological adaptation was mainly developed through the field investigation.

Harbin is located in the severe cold area of China with a long and cold winter, and the centralized heating period lasts for 6 months. The indoor design heating temperature is 18°C during the heating period according to Chinese standard. However, the real indoor temperatures are generally higher than 24°C in variety of buildings, also going beyond the upper limits in ASHRAE 55 (2013) and ISO 7730 (2005). The energy consumption for space heating accounts for a huge proportion of the total building energy consumption in the city.

Wang et al. [6-8] carried out a series of field study on occupants’ thermal comfort and thermal adaptation in Harbin. They concluded that local occupants had thermal adaptation to the cold climate. The thermal neutral temperature of local occupants was lower in winter versus in autumn. However, the local occupants always stay indoors in winter, thus, what kinds of thermal regulation will the occupants present during the space heating period? Oseland [9] found that there were significant differences for the perceived warmth of the same group of people in the same clothing and conducting the same activity, at the office, at home, and in a climate chamber. Nevertheless, what kinds of thermal responses will the occupants have in their real life including their thermal perception and thermal behaviours? In allusion to these problems, a field study was conducted in winter and transitional seasons in which 44 volunteer subjects were tracking surveyed in their residential rooms or work offices. Through this study, the periodic thermal responses of the occupants in buildings of different functions were presented, and some suggestions were proposed to maintain thermal comfort and save energy.

### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>PMV</td>
<td>Predicted mean vote</td>
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<tr>
<td>PMV'</td>
<td>Predicted mean vote after standardization</td>
</tr>
<tr>
<td>TSV</td>
<td>Thermal sensation vote</td>
</tr>
<tr>
<td>TSV'</td>
<td>Thermal sensation vote after standardization</td>
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### 2. Methods

The field study was conducted in residential and office buildings from September 2013 to May 2014 which included the whole space heating period and two transitional seasons (late autumn, early spring). The space heating started on October 20, 2013, stopped on April 20, 2014. The outside air temperature started going below -10°C on November 22, 2013 and going above -10°C on March 2, 2014 in winter as shown in Fig. 1. In order to research the variation of occupants’ thermal responses as the climate changes, the whole space heating period is divided into three phases, the early-heating period from October 20 ~ November 22, 2013 (34 days), mid-heating period from November 23, 2013 ~ March 2, 2014 (100 days) and a late-heating period from March 2 ~ April 20, 2014 (49 days).
20 subjects in 9 residential buildings and 24 subjects in 6 office buildings distributed in different districts in Harbin were respectively tracking surveyed. Eight of the occupants were cross subjects. All of the subjects have lived in Harbin more than 20 years. The distribution of subjects’ age spans from 26 to 72, and the gender ratio is close to 1:1.

The indoor air temperature and humidity were continuously recorded per 5 min, through using self-recording loggers which were placed about 1.0 m above the floor in the living room or office in these buildings. The black ball temperature, air speed and envelop surface temperature were measured once a week.

The subjects were asked to fill in the online questionnaires weekly including their thermal sensation and comfort, thermal preference, thermal acceptance and thermal behavioral adjustments, etc. The thermal sensation vote (TSV) adopted a seven-point scale ranging from cold (-3) to hot (+3), with neutral (0) in the middle. Thermal preferences were assessed using a three-point scale: ‘warmer’, ‘maintained’, and ‘cooler’. Clothing insulation was calculated according to ASHRAE standard (2013). 1050 questionnaires were collected totally. During the field survey, most of the residential subjects were seating or relaxed standing and majority of the office subjects was typing or reading. Therefore, the metabolic rate of both office and residential subjects could be considered in the range of 1.0~1.1 met.

3. Results

3.1. Indoor thermal environment

The indoor air temperature fluctuated as the fluctuation of outdoor air temperature during the researching periods as shown in Fig. 2. The indoor air temperature of offices was close to the residential rooms. The indoor air temperature of studied offices and rooms was close to or over the upper temperature of ASHRAE 55 (2013) 24°C during whole space heating period. The frequency beyond 24°C was respectively 49% for surveyed offices, and 73% for apartments. The relative humidity was higher in residential rooms compared with offices, due to the fact that the residential occupants tend to grow flowers or keep fish tanks indoors. The indoor air speed ranged in 0.03~0.05m/s and 0.03~0.07m/s respectively in the studied rooms and offices, which met the thermal comfort standard. The difference between indoor operative temperature and air temperature was within ±0.5°C, thus, the air temperature could be used as the environmental assessing index.
Fig. 2. Daily mean indoor air temperature and humidity of residential and office buildings.

3.2. Thermal behavioral regulation

Fig. 3 shows a weekly variation of occupants’ clothing insulation. It illustrated that the clothing insulation changed with season. There was an evident difference of clothing insulation between residents and office staffs during the space heating period, but they were closer in transitional seasons, late autumn and early spring. The range of clothing insulation was 0.69~0.85clo for the residents, and 0.98~1.34clo for the office staffs in this field study.

Fig. 3. Weekly variation of clothing insulation between residents and office staffs.

The variation of clothing insulation with indoor air temperature is demonstrated in Fig. 4. The figure shows that the occupants’ clothing insulation reduced as the increasing of indoor air temperature, and the clothing insulation of residents was all greater versus office staffs at each temperature. The slope of the linear regression fitting line of residential group was higher than office group, which demonstrated the residents had a more sensitive clothing adjustment as indoor air temperature. The coefficient of R² was regarded as an index of fitting accuracy, the R² value of residential group was 0.92 that also explained this significant pertinence of clothing adjustment regulation.
The difference of behavioral regulation between residents and office staffs when they felt hot is shown in Fig. 5. Opening widows was the main adjustment method for office occupants, and reducing clothing or drinking water was secondary as shown in the figure. The average frequency of office windows opening was 40% during early heating period, and 65% during the subsequent heating periods. However, the frequency of choosing opening widows as a method of thermal adjustment was relatively much lower for the residents except in early spring. Most of the residential subjects didn't feel hot in late autumn and early heating period.
3.3. Thermal psychological responses

Fig. 6 shows the indoor air temperature and thermal neutral temperature between residential and office environments in different periods. The indoor air temperature was totally higher than neutral temperature during the space heating period in winter except the transitional seasons. There existed a deviation between indoor air temperature and neutral temperature, and it was much bigger for the office group versus the resident group although the mean indoor air temperature was close in each space heating period.

The clothing insulation was recommended 1.0clo indoors in winter by ASHARE 55 (2013) and ISO 7730 (2005). The residents’ clothing insulation was 0.74clo by average. The residents’ clothing insulation was standardized by 1.0clo, and the neutral temperature was recalculated as shown in Fig. 6. The calculation formula is as following.

\[ PMV = f(t_a, t_r, \varphi, v, I_{clo}, M) \]  
\[ PMV' = f(t_a, t_r, \varphi, v, \bar{I}_{clo}, M) \]  
\[ \Delta PMV = PMV - PMV' \]  
\[ TSV' = TSV - \Delta PMV \]

80% thermal acceptable temperature range was shown in Fig. 7. It is clear that the thermal acceptable air temperatures of both upper and lower limits of office staffs were lower than those of the residents during the whole surveyed periods. Moreover, the range of the 80% thermal acceptable air temperature was wide for all the subjects in both office and residential environments.
The thermal preference was shown in Fig. 8. Most of residential subjects tend to maintain the current indoor air temperature during the heating period, but the frequency that expected decreasing indoor air temperature (-1) was higher for office staffs versus residents.

4. Discussions

The indoor air temperature of both built environments was close to the winter upper limit that ASHARE 55 (2013) specified through the field survey. There existed evident differences of behavioral adaptation between residents and office staffs. The clothing insulation of office staffs was more, and fluctuated with the outdoor temperature compared with residents. The clothing insulation of residents was mainly affected by indoor air temperature. The frequency of widows opening was obviously increased for residents to improve the indoor air quality in early spring, and the clothing insulation of residents was close to the office staffs. As shown in Fig.5, the clothing insulation of residents changed 0.05clo, and it was changed 0.02clo for office staffs as the indoor air temperature changed 1°C. That indicated that the residents were more sensitive to the indoor air temperature changes than office staffs. On the other side, the staffs were inconvenient to change their clothing in the office. Besides, this habit of office staffs directly leads a thermal expectation to lower the current indoor air temperature.
Meanwhile, the frequency of opening windows for office environment was higher than residents, which shows that the office staffs tend to open window in winter to lower indoor air temperature.

The neutral temperature of office staff was lower than residents due to the differences of occupants’ behavioral adaptation. It was found that the clothing insulation of residents was all in a lower state during the whole heating period, which was not in accordance with the recommended value in ASHRAE 55 (2013). So the residential clothing insulation was suggested to use 1.0clo instead of the current value, and a standardized neutral temperature was given after recalculation. All of above, a space heating strategy was suggested that the indoor air temperature should be lowered and provided according to the neutral temperature in different heating periods. If so, it could not only maintain the human comfort, but also could save space heating energy.

According to China’s national standard, the indoor design heating temperature is 18°C in Harbin, and the outdoor design temperature is -26°C. If the indoor heating temperature of two types of buildings was supplied refer to the neutral temperature in each heating period to maintain human comfort, then the energy consumption is respectively decreased by 5% for residential building and 6.7% for office building. The calculation formula (e.g., residential building) is as the following.

\[
N = \frac{t'_n - t_n}{t_n - t_w} = \frac{34}{183} \times \frac{23.6 - 21.4}{21.4 - (-26)} + \frac{100}{183} \times \frac{24.1 - 22.0}{22.0 - (-26)} + \frac{49}{183} \times \frac{24.6 - 21.6}{21.6 - (-26)} = 0.05
\]

where \(N\) is the percentage of saved energy, and \(t_n\) is the indoor design heating temperature, \(t_w\) is the outdoor design temperature, \(t'_n\) is the indoor temperature.

The occupants in severe cold area of China often expose themselves to both high air temperature indoors and lower air temperature outdoors in winter. Both climate and indoor environment affect the thermal adaptation of local people. Through the data analysis, it has demonstrated that there was a wide range of thermal acceptability temperature for local people, and the office staffs had a lower range of occupants’ acceptable temperature.

5. Conclusions

- The indoor air temperature in investigated offices was close to the residential rooms. The frequency beyond 24°C was respectively 49% for surveyed offices, and 73% for surveyed apartments.
- The neutral temperature of office staffs was lower than residents due to the difference of occupants’ behavioral adaptation in different built environments. The office occupants preferred to open windows to reduce the high indoor temperature and their clothing insulation was much higher than residents during the whole surveyed period.
- The indoor air temperature should not be excessively high, and it was suggested to supply refer to the neutral temperature in buildings of different functions in different heating period. Under the premise of maintaining human comfort, if so, the energy consumption would be respectively decreased by 5% for residential building and 6.7% for office building.
- There existed a wide range of occupants’ acceptable temperature, which demonstrated the occupants in the severe area of China had adaptation to both outdoor and indoor environments in winter.

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References
