A comparative winter study on thermal comfort in several climate regions in China

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Abstract
The article introduces a comparative winter thermal comfort field study in four cities representing different climate zones in China, which are Harbin for SC (Severe Cold), Beijing for C (Cold), and Shanghai for HSCW (Hot Summer & Cold Winter) zones. Measurements of environment parameters and subjective investigations using questionnaires were conducted in teaching buildings on campus. Totally 740 valid questionnaires were collected for analysis. Due to the huge difference of outdoor temperatures and the different conditions of indoor space heating between climatic zones, several distinctive features were found. Although it was warmer outdoors, the indoor temperature in Shanghai was much lower than Harbin and Beijing, due to the lack of space heating. The clothing level of Shanghai occupants was similar to Harbin and lower than Beijing. When the indoor environment was colder than neutral, the mean TSV values in Shanghai were higher than Beijing, revealing people in Shanghai had better adaptation to cold environment. Results show the indoor temperature in Harbin was sometimes overheated, and people in Harbin had been used to the warm environment during winter.

Keywords: thermal comfort; thermal adaptation; winter; space heating; over-heating

Nomenclature
\begin{itemize}
\item $t_a$: air temperature
\item $RH$: relative humidity
\item $t_g$: globe temperature
\item $v_a$: air velocity
\item $\bar{T}_r$: mean radiant temperature
\item $t_{op}$: operative temperature
\item $I_{cl}$: clothing insulation
\item $t_{out,d}$: daily mean outdoor temperature
\item $t_n$: neutral temperature
\item $t_c$: comfort temperature
\item TSV: Thermal sensation vote
\item PMV: predicted mean vote
\item PPD: predicted percentage of dissatisfied
\item HVAC: heating, ventilating, and air conditioning
\end{itemize}
1 Introduction
Indoor thermal comfort in cold climates is an important topic, since it determines how much heating people need indoors, which further relates with issues such as energy consumption and air pollution nowadays. In China, due to the different climate features between climate zones, the situations for winter are complicated. According to the national standard Thermal Design Code for Civil Building (MOHURD, 1993), five climate zones are defined as Severe Cold (SC), Cold (C), Hot Summer & Cold Winter (HSCW), Hot Summer & Warm Winter (HSWW), and Mild (M) zones. Despite the M zone, all the other four zones have obvious temperature variations during the year. Temperature differences between climate zones in winter are much more significant than they are in summer. In the hottest month (July), temperature in HSWW is no more than 10°C higher than it is in SC. However in the coldest month (January), SC is nearly 35°C colder than HSWW.

Having the huge outdoor temperature difference between climate zones, the existence of difference between space heating modes makes the issue more complicated. Among these climate zones, only urban buildings in SC and C zones have district heating. A few people in the HSCW, HSWW, and M zones might use individual heating devices, although in fact they are not widely and continuously utilized. Regarding both the outdoor and indoor differences, it is worthy to know: Are the zones in the north “really colder” than those in the south? And, how do the local people evaluate their indoor thermal comfort in winter?

2 Methodology
2.1 Time and place
The study was conducted in three cities, which are Harbin (SC), Beijing (C), and Shanghai (HSCW). Field studies were taken place from December to February. The target buildings were all teaching buildings on campus. During the study period, buildings in Shanghai weren’t supplied with space heating, while in Harbin and Beijing they had district space heating indoors. The district heating did not have terminal control, which means the occupants were not able to adjust the indoor temperature by themselves.

2.2 Instruments and questionnaire
The field measurements were conducted once a week. Multiple instruments were involved, including AM-101 PMV and PPD indices meter, WSZY-1A Self-recording thermometer & hygrometer, FB-1 Self-recording anemometer, and HWZY-1 Self-recording globe thermometer. The AM-101 PMV and PPD indices meter, which was used in the Beijing study, recorded \( t_o, \, e_r, \, RH \text{ and } v_o \). In Harbin and Shanghai investigations, the WSZY-1A, FB-1 and HWZY-1 were used as a combination. The measuring range and accuracy of the above instruments is shown in Table 1. During field measurements, the sensors were placed no more than 1m far from the occupants, and at a height of 0.6m from the floor.
Table 1. Measuring range and accuracy of the instruments used in this study

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Variables</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM-101 PMV and PPD indices meter</td>
<td>$t_a$</td>
<td>15~35°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td></td>
<td>$t_g$</td>
<td>15~35°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td></td>
<td>$\overline{E_r}$</td>
<td>15~35°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>20~80%</td>
<td>±3%</td>
</tr>
<tr>
<td></td>
<td>$v_a$</td>
<td>0~1m/s</td>
<td>±0.1m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1~5m/s</td>
<td>±0.5m/s</td>
</tr>
<tr>
<td>WSZY-1A Self-recording thermometer &amp; hygrometer</td>
<td>$t_a$</td>
<td>-40~100°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td>0~100%</td>
<td>±3%</td>
</tr>
<tr>
<td>FB-1 Self-recording anemometer</td>
<td>$v_a$</td>
<td>0~10m/s</td>
<td>≤ ±5% of measured value</td>
</tr>
<tr>
<td>HWZY-1 Self-recording globe thermometer</td>
<td>$t_g$</td>
<td>-50~100°C</td>
<td>±0.4°C</td>
</tr>
</tbody>
</table>

Fig. 1. Questionnaire used in this study
The environment parameters were being recorded when people in the classrooms were doing individual studies or having a break between classes. Meanwhile, those occupants were investigated by using questionnaires. In this study, we mainly asked the occupants about their clothes they were wearing, and their thermal sensation, thermal preference, and thermal acceptance (Fig. 1).

### 2.3 Investigated occupants

The gender and age distributions of the investigated occupants are shown in Table 2. There are totally 740 valid feedback questionnaires, which show the amounts of males and females are not discrepant much from each other. The mean ages of Harbin, Beijing and Shanghai occupants were close to 21.5. All the participants in the investigations had lived in their cities for at least one year, thus they could be considered to have adapted to the local climates well.

<table>
<thead>
<tr>
<th>Amount of occupants</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>Harbin</td>
<td>101</td>
</tr>
<tr>
<td>Beijing</td>
<td>155</td>
</tr>
<tr>
<td>Shanghai</td>
<td>111</td>
</tr>
</tbody>
</table>

### 3 Results

#### 3.1 Environment parameters

The distributions of indoor and outdoor environment parameters are shown in Table 3 and Table 4. In Beijing, the $t_o$, $\bar{E}_r$, RH and $v_o$ were all measured by instruments. In Harbin and Shanghai, $\bar{E}_r$ was calculated by using $t_o$, $t_g$ and $v_o$ according to ISO 7726 (ISO, 1998). The $t_{op}$ in Harbin, Beijing and Shanghai was simplified as an average value of $t_o$ and $\bar{E}_r$ according to the conditions introduced in ASHRAE Standard 55 (ASHRAE, 2013).

<table>
<thead>
<tr>
<th>Environment parameters</th>
<th>Harbin</th>
<th>Beijing</th>
<th>Shanghai</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_o$ (°C)</td>
<td>21.1</td>
<td>26.4</td>
<td>27.1</td>
</tr>
<tr>
<td>$\bar{E}_r$ (°C)</td>
<td>21.4</td>
<td>28.2</td>
<td>24.8</td>
</tr>
<tr>
<td>RH (%)</td>
<td>18.4</td>
<td>35.1</td>
<td>25.9</td>
</tr>
<tr>
<td>$v_o$ (m/s)</td>
<td>0.01</td>
<td>0.06</td>
<td>0.027</td>
</tr>
<tr>
<td>$t_{op}$ (°C)</td>
<td>21.3</td>
<td>27.1</td>
<td>24.3</td>
</tr>
</tbody>
</table>
Table 4. The outdoor temperature range of the three cities during the investigation periods

<table>
<thead>
<tr>
<th></th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harbin</td>
<td>-18.4</td>
<td>2.0</td>
<td>-8.9</td>
</tr>
<tr>
<td>Beijing</td>
<td>-2.0</td>
<td>10.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Shanghai</td>
<td>5.0</td>
<td>14.5</td>
<td>7.9</td>
</tr>
</tbody>
</table>

During the period when the study was conducted, Harbin experienced the coldest weather among the three cities. The lowest $t_{out,d}$ in Harbin reached -18.4°C, while the $t_{out,d}$ in Shanghai never fell below 0°C. However, the indoor temperature in Shanghai was the lowest, due to the lack of space heating indoors. Harbin and Beijing had apparently higher indoor temperatures than Shanghai did. The RH was low in Harbin and Beijing, and was moderate in Shanghai. The $v$ in all three cities were very low, which was not sensible and might not have influence on thermal comfort.

Fig. 2 presents the measured indoor and outdoor temperatures of each city. According to the distribution of data dots, the chart could be divided into four areas:

- **Area I**: $t_{op} \geq t_{out,d} + 25$
- **Area II**: $t_{out,d} + 10 \leq t_{op} < t_{out,d} + 25$
- **Area III**: $t_{out,d} \leq t_{op} < t_{out,d} + 10$
- **Area IV**: $t_{op} < t_{out,d}$

It is obvious on Fig. 6 that no data dot is in Area IV, which means $t_{op}$ was always higher than $t_{out,d}$ on the day when a measurement was conducted. Furthermore, it is easy to find that most data from Harbin fall into Area I, while the Beijing data are mostly in Area II and the data from Shanghai fit Area III. If considering a situation that the $t_{out,d}$ is the same in these three cities, then it is very likely that the $t_{op}$ in Beijing would be lower than Harbin, meanwhile higher than Shanghai. Having this difference between the three cities, it is interesting to explore how people evaluated and reacted to their thermal conditions.
3.2 Clothing condition

\[ I_{cl, Shanghai} = -0.0507t_{op} + 1.8605 \]  \hspace{1cm} (1)  
\[ I_{cl, Beijing} = -0.0477t_{op} + 2.1442 \]  \hspace{1cm} (2)  
\[ I_{cl, Harbin} = -0.0573t_{op} + 2.3547 \]  \hspace{1cm} (3)

Fig. 3 and Eqs. (1) - (3) present how indoor \( t_{op} \) influences occupants’ clothing amount. The regression results of Harbin and Beijing almost overlap with each other. The mean values of \( I_{cl} \) in the three cities were 0.96clo (Harbin), 1.1clo (Beijing), and 0.99clo (Shanghai). People in Shanghai wore similar amount of clothes as people in Harbin did, although the mean \( t_{op} \) in Shanghai was 8°C lower than Harbin. Within the same temperature range of 17~22°C, the \( I_{cl} \) in Shanghai was about 0.3clo lower than it was in Beijing regarding a same temperature level.

3.3 Thermal comfort

Fig. 4. Relationship between TSV and indoor operative temperature
The relationship between TSV and indoor $t_{op}$ is presented in Fig. 4. By using Eqs. (4) - (6), the $t_n$ could be calculated, which were 22.45°C (Shanghai), 22.39°C (Beijing), and 21.58°C (Harbin) respectively. The slope of Eq. (5) is greater than those of Eqs. (4) and (6), which shows the Beijing occupants were more sensitive to the temperature changing than occupants in Harbin and Shanghai. When the temperature was lower than neutral, the mean TSV values in Shanghai were a little bit higher than Beijing, even though people in Shanghai wore few clothes than people did in Beijing.

$$TSV_{Shanghai} = 0.0973t_{op} - 2.185 \quad (4)$$

$$TSV_{Beijing} = 0.149t_{op} - 3.3359 \quad (5)$$

$$TSV_{Harbin} = 0.1059t_{op} - 2.285 \quad (6)$$

Regarding the thermal acceptance votes, we consider all the votes which fall between “+0” and “+1” as acceptable. Fig. 5 shows the percentage of thermal acceptance in the three cities. In Harbin, the percentage was always over 70%, and reached 80% when temperature was between 20°C and 26°C. In Shanghai, although there was no space heating, the percentage of acceptance was close to, or even exceeded 80% in the temperature range of 16~22°C. Obviously, people in Shanghai adapted well to cold environment in winter. The percentage of acceptance in Beijing was lower than those in Harbin and in Shanghai. People in Beijing were neither as adapted to cold environment as people in Shanghai, nor as adapted to warm environment as people in Harbin.

According to the thermal preference votes, a higher percentage of people in Beijing than in Shanghai hoped the indoor environment to be warmer, when indoor temperature was lower than neutral. When indoor temperature was higher than neutral, the percentage of people who would like to maintain the thermal condition was higher in Harbin than in Beijing, showing people in Harbin were more used to the warm indoor environment during winter.
4 Discussion: The warmer, the better?
It is always arguable that how “warm” is enough for winter. In this study, it appears that the
coldest city (Harbin) enjoyed the warmest indoor environment, meanwhile the warmest city
(Shanghai) seemed not be warm enough indoors.

Regarding considerations from aspects such as comfort, health, cost, and feasibility of
technologies, people may hold different opinions towards the above issue. The indoor
environment should indeed be kept warm during winter to meet a basic thermal comfort
demand. However, the problem is if “comfort” has been “over provided” in some cases. Take
Harbin, one of the studied cities in this paper, as an example. Wang et al (2003, 2006, 2011,
2012) found the winter indoor temperature in Harbin had been consecutively increasing
during the past 20 years. As Table 5 shows, in 1990 the mean level of measured indoor $t_a$ was
17.47°C, which then rose to 20.1°C in the year 2000, and further reached 22.8°C in 2010.
While the $t_a$ increased by more than 5°C during the 20 years, the $t_a$ in 2010 was also nearly 5°C
higher than it was 20 years ago.

Table 5. Changing of indoor thermal conditions during the past 20 years

<table>
<thead>
<tr>
<th>Year</th>
<th>$t_a$ (°C)</th>
<th>$t_c$ (°C)</th>
<th>$l_c$ (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>17.47</td>
<td>17.69</td>
<td>1.74</td>
</tr>
<tr>
<td>2000</td>
<td>20.1</td>
<td>-</td>
<td>1.37</td>
</tr>
<tr>
<td>2009</td>
<td>21.6</td>
<td>20.4</td>
<td>0.88</td>
</tr>
<tr>
<td>2010</td>
<td>22.8</td>
<td>22.6</td>
<td>1.04</td>
</tr>
</tbody>
</table>

This was not just accidently happened in China. Nicol and Humphreys (2002) presented a
comparison using the data collected from various field studies, as shown in Fig. 6. The chart on
the left side shows the field results in 1970s, and the right one presents data in 1990s. If
comparing these two charts, it could be easily found the regression lines for free running
buildings (A) stay almost the same, however for HVAC buildings, the distributions of data dots
and regression lines (B) differ a lot between the two charts. In 1990s, the mean level of indoor
$t_c$ during the cold season was 2°C higher than it was in 1970s, and even tended to be as high as
the $t_c$ in summer.

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Fig. 6. Relationship between indoor comfort temperature and mean outdoor air temperature ((a)-1970s,
(b)-1990s)
While the indoor temperature increased, people do not have to wear heavy clothes during winter, which brings them comfort and convenience. However, Yu et al (2013) announced that constantly staying in a warm heated environment might weaken people’s thermoregulatory, so that might cause discomfort or even health problem when experiencing a cold stress. The over relying on heating prevents people from exercising their acclimatization to cold environment, which they should have inherited through generations. It is necessary to arouse some vigilance on this trend.

5 Conclusions
The authors conducted a comparative thermal comfort field study during winter. Having analyzed the field data from Harbin, Beijing and Shanghai, some conclusions could be drawn as follows.

(1) Among the three cities, Harbin was the coldest and Shanghai was the warmest during the study period. The mean level of $t_{\text{out},d}$ in Harbin was almost 17°C lower than that in Shanghai. However, due to the lack of space heating, the indoor temperature in Shanghai was much lower than those in Harbin and Beijing, where buildings had district heating supplied indoors.

(2) The mean values of $l_{cl}$ in the three cities were 0.96clo (Harbin), 1.1clo (Beijing), and 0.99clo (Shanghai). People in Shanghai wore similar amount of clothes as people in Harbin did, although the indoor temperature in Shanghai was much lower than Harbin.

(3) When the indoor environment was colder than neutral, the mean TSV values in Shanghai were higher than Beijing, even though people in Beijing wore more clothes. The $t_n$ in the three cities were 22.45°C (Shanghai), 22.39°C (Beijing), and 21.58°C (Harbin) respectively.

(4) In Harbin, the percentage of acceptance was always over 70%, and reached 80% when temperature was between 20°C and 26°C. In Shanghai, people showed strong adaptation to cold environment with their percentage of acceptance close to, or even exceeded 80% in the temperature range of 16~22°C. The percentage of acceptance in Beijing was lower than those in Harbin and in Shanghai.

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References