The effect of temperature on thermal sensation: a case study in Wuhan city, China

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Abstract

Thermal comfortable level is one of the most important factors that affect human health and living performance. Maintaining thermal comfort for residents in buildings or other enclosures has been not only a continuously persuade objective for heating, ventilation and air conditioning (HVAC) engineers, but also a theoretical interest for research scientists. A total of 4712 questionnaires were collected in the long-term thermal sensation survey in Wuhan city that was one of the hottest places in China. Most of subjects (80%) are not using air conditioners when the outdoor temperature ranges from 7.5 °C to 25 °C. With the polynomial regression, the calculated temperature zone was from 18.1 °C to 31.9 °C while the mean thermal sensation was between -0.5 and +0.5.

1. Introduction

Human thermal comfort is defined in ASHRAE Standard 55 as ‘the condition of mind that expresses satisfaction with the thermal environment’ [1]. Thermal comfortable level is one of the most important factors that affect human health and living performance. Maintaining thermal comfort for residents of buildings or other enclosures is a principal purpose of heating, ventilation and air conditioning (HVAC) engineers [2]. Fanger has related comfort data to physiological variables and given a single thermal comfort equation [3]. Moreover, thermal comfort and thermal sensation in buildings could be predicted with Fanger’s PMV and PPD equations [3-5]. With Fanger’s equations,

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more and more thermal comfort studies have been carried out all over the world in the past decades to build more comfortable air conditioned (AC) space [6,9]. However, most results are developed from laboratory studies and do not well consider the effects of building type. Particularly, in naturally ventilated (NV) buildings those results are found not to fit very well. For the NV buildings, recent field thermal comfort study guided by adaptive approach is found very usefully [10-14]. It has been a long-term necessity of human sustainable development for keeping thermal comfort with low energy consumption or in a low-carbon building.

Wuhan city is one of the hottest places in China. It belongs to hot-summer/cold-winter climate zone. Do the thermal comfort sensation in Wuhan city is the same as that in other cities in China? How about the neutral temperature in cold and hot season? Those are main aims of this survey.

2. Background descriptions

2.1. About Wuhan city

Wuhan city was situated in the middle of Hubei Province of China, the middle intersection of the Yangtze River and Hanshui River. In Wuhan city, the mean temperature in the hottest month is about 29.8 °C and the maximum temperature can reach 39.4 °C. The humidity in the hottest month in Wuhan is high and the mean relative humidity is 79%. The mean temperature in coldest month is 3.0 °C and the maximum temperature can reach -18.1 °C. The mean annual heating degree-days in Wuhan City are 856 days that is calculated at the 5 °C base temperature.

2.2. Instruments and measurement

There were four indoor environmental parameters, including indoor air temperature, mean radiant temperature, air velocity and relative humidity, could influence on thermal comfort. Air velocity in buildings was small and it was often less than 0.5 m/s [11,15]. It was measured by a thermal-bulb air velocity device (KANOMAX 6004). Air temperature and relative humidity were measured with a dry and wet bulb thermometer (WQG-11, Ruimin Laboratory Instrument Co., Changzhou City, China), with a measuring range of -35°C to +45°C and an accuracy of ±0.2°C. The mean radiant temperature was measured with a 150 mm diameter black globe thermometer, with an accuracy of ±0.1 °C. The accuracy of the instruments conformed to ISO 7726. Measuring height in this study is 1.1 m or 1.7 m above the floor.

Table 1. Scale of thermal sensation vote.

<table>
<thead>
<tr>
<th>Thermal sensation</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>+3</td>
</tr>
<tr>
<td>Warm</td>
<td>+2</td>
</tr>
<tr>
<td>Slight warm</td>
<td>+1</td>
</tr>
<tr>
<td>(Comfortably warm)</td>
<td>(+0.5)</td>
</tr>
<tr>
<td>Neutral or comfortable</td>
<td>0</td>
</tr>
<tr>
<td>(Comfortably cool)</td>
<td>(-0.5)</td>
</tr>
<tr>
<td>Slight cool</td>
<td>-1</td>
</tr>
<tr>
<td>Cool</td>
<td>-2</td>
</tr>
<tr>
<td>Cold</td>
<td>-3</td>
</tr>
</tbody>
</table>

2.3. Questionnaire and subjects

The long-term thermal survey carried out for about three years in a university. The questionnaire includes general thermal sensation vote and background of subjects. As shown in Table 1, scale of thermal sensation vote in this survey is according to ASHRAE 55 and ISO 7730 [1,17]. The background includes age, gender, clothing and other contents of demography. The questionnaires were filled by subjects after they stay in room at least for 20 minutes. A total of 4712 returned questionnaires were collected in the study. Most of subjects are university students with an
average age of 22 years and half of them are female. All of them had lived in Wuhan city more than 2.5 years and they already adapted the climate in this city. The subjects read book or operated computer in the room during the testing. Metabolic rates of the subjects were about 1.0-1.2 met (60-70 W/m²), which represents the value for sedentary or office activities [1].

3. Results

3.1. Climate of Wuhan city

Mean monthly outdoor temperature in Wuhan city from 2007 to 2010 is shown in Figure 1. Standard value of climate in Wuhan city is obtained from China Meteorological Data Sharing Service System of China Meteorological Administration. The change of monthly outdoor temperature in these four years is small. The recorded temperature curves are similar to the standard temperature value (1971-2000) in Wuhan city. Therefore, the data of thermal sensation could be dealt with together for the whole year thermal neutral temperature. From Figure 1, January, February and December are three coldest month in Wuhan city and they could be taken as cold season. Similarly, June, July and August are hot season. March, April, May, September, October and November could be seen as transition season.

![Fig. 1. Mean monthly outdoor temperature in Wuhan city.](image)

3.2. Indoor and outdoor temperature

Subjects in residential buildings can open and close windows as they wish. Outdoor temperature has effect on the temperature in buildings. But the changes of indoor temperature are different to those of outdoor. As shown in Figure 2, the indoor temperature is lower than outdoor temperature in hot season and it is higher than outdoor temperature in cold season in Wuhan city. For example, indoor temperature is about 10 °C when outdoor temperature is 0 °C and it is about 34 °C when outdoor temperature is 35 °C.
3.3. Thermal neutral temperature

The result of thermal sensation vote in this survey is shown in Figure 3. The detail of thermal comfort vote is shown in Table 2. With linear regression model, the relationship between thermal comfort vote and indoor temperature is given in Fig. 3.

The thermal neutral temperature in Wuhan city could be different to that in other areas. The neutral temperature of whole year in Wuhan city is 24.0 °C according to Figure 3. It is 1.5 °C higher than that in Shanghai [11]. In tropical area, the neutral temperature occurred at 26.8°C in naturally ventilated classrooms and at 27.4°C in air-conditioned classrooms [18].

3.4. Clothing insulation

In generally, the clothing insulation and indoor environment perhaps are the main influence facts for thermal sensation vote. However, the adjustment of behavioral adaptive could not always follow the rhythm of environmental parameters completely. The thermal sensation of subjects could be different in the same temperature space. Therefore, large scale survey is needed to use for eliminate the deviation in the field study.

As we known, clothing is one of important influence factors in adaptive thermal comfort study. The clothing insulation of subjects does not rely on indoor temperature. People often adjust their clothing referring to weather forecast or outdoor climate before they go out in China. So it is also related with outdoor temperature. From Figure
4, the relationship between clothing insulation and outdoor temperature is given in Fig. 4.

<table>
<thead>
<tr>
<th>Range of temperature, °C</th>
<th>Number of vote</th>
<th>Mean</th>
<th>S.D</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2,5)</td>
<td>39</td>
<td>-2.3</td>
<td>0.9</td>
<td>-3</td>
<td>-1</td>
</tr>
<tr>
<td>[5,10)</td>
<td>74</td>
<td>-1.7</td>
<td>1.4</td>
<td>-3</td>
<td>1</td>
</tr>
<tr>
<td>[10,15)</td>
<td>556</td>
<td>-0.8</td>
<td>1.0</td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td>[15,20)</td>
<td>1027</td>
<td>-0.3</td>
<td>0.7</td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td>[20,25)</td>
<td>1204</td>
<td>-0.2</td>
<td>0.6</td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td>[25,30)</td>
<td>1075</td>
<td>0.1</td>
<td>0.6</td>
<td>-2</td>
<td>3</td>
</tr>
<tr>
<td>[30,35)</td>
<td>706</td>
<td>0.7</td>
<td>0.9</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>[35,36]</td>
<td>31</td>
<td>1.9</td>
<td>1.0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>4712</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Correlation of clothing insulation to outdoor temperature (The whole year).

4. Discussion

The linear regression is a common method used in thermal comfort research. Many studies showed that the results are acceptable [12-14,16,18]. It is useful to the study in a season or a temperature range. However, a simple linear regression could not be fit for the whole year thermal comfort study. There are many neutral temperatures obtained from thermal comfort studies in winter and in summer [18-27], as they shown in Figures 5 and 6. The neutral temperature of each study is different. The temperature difference could be 7.4 °C and 6.7 °C in winter and in summer, respectively. The use of simple linear regression without some limited conditions could cause large deviation, especially for whole year survey.

According to ISO 7726, the required and desirable accuracy of measuring instrument for air temperature are ±0.5°C and ±0.2°C, respectively. The accuracy of dry and wet bulb thermometer (WQG-11) used in this survey is ±0.2°C. So 0.4 °C was taken in the present study as the temperature zone and handle the whole year data. The result is shown in Figure 7. Obviously, the correlation between thermal sensation vote and indoor temperature could be polynomial regression curve or distribution curve rather than linear regression approximation. With polynomial regression, the temperature zone is from 18.1 °C to 31.9 °C when thermal sensation vote is between -0.5 and +0.5.
Fig. 5. The winter neutral temperature of thermal comfort researches in China.

Fig. 6. The summer neutral temperature of thermal comfort researches in China.

Fig. 7. Correlation of mean thermal sensation vote versus indoor temperature (Polynomial regression).
5. Conclusions

The survey was carried out to study comfort conditions in Wuhan city in the present study. It is found that there is a wide range of thermal accommodation conditions for people in buildings in Wuhan city. The whole year neutral temperature is 24.0 °C with a simple linear regression. The largest neutral temperature difference in those studies is 7.5 °C and 6.7 °C in winter and in summer, respectively. Thermal comfort zone of cities in China should be determined based on local climate zone for the reason of low energy consumption and low carbon emission.

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References