Field Investigation on Indoor Thermal Environment at a Rural Passive Solar House in Severe Cold Area of China

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Abstract

This paper focuses on a field investigation on indoor environment at a rural passive solar house in Yushu City, Jilin Province in the severe cold region of China. The air temperature and relative humidity at the solar house were monitored from Dec. 15th, 2014 to Mar. 15th, 2015. During the period, the authors went to the solar house every 3 or 4 weeks, manually measuring the air temperature, relative humidity, air speed, globe temperature and surface temperatures of exterior window and Kang. Besides the solar house, three energy-saving houses and two old rural houses were investigated. Peasants’ thermal responses were surveyed by questionnaires at the meantime.

The results showed that the mean indoor air temperature of the solar house was 13.7°C, close to the design temperature of 14°C for rural houses in the severe cold areas of China. And the mean temperature of an old rural house monitored was only 10.5°C. The average relative humidity was 65.3% at the solar house, while it was 90.9% at the old rural house. Peasants in the solar house and energy-saving houses commonly felt warm, while peasants in the old houses mostly felt neutral or cool. So the solar walls had a positive effect on improving indoor thermal environment. The mean indoor air temperatures in the energy-saving houses and the solar house are higher than in the old houses. Peasants adapted to a relatively poor indoor environment by behavioral adjustments and mental preferences.

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Keywords: Solar house; Thermal environment; Thermal adaptation; Field survey; Severe cold area

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1. Introduction

For the construction of new socialist country in China, building energy saving and indoor environment in rural areas has become a hot spot. In severe cold areas of China, it is cold and long in winter, with a heating period of six months. Peasants mainly apply Chinese Kang for heating, which causes a great amount of energy consumption and pollutes indoor and outdoor air. Therefore, more efficient and cleaner energy with advanced heating modes are required. In recent years, some scholars have done researches on indoor environment at passive solar houses. Chen et al. [1] studied thermal comfort and air quality in a passive solar house in Dalian.

A passive solar house is an effective approach for energy saving and heating. Now, there are few national design standards for passive solar houses in China, with inexplicit requirements on indoor environmental conditions. In addition, only a few studies on indoor environment at passive solar houses in severe cold areas have been conducted. Because Kang is mainly used for heating in the rural, studies on coupled pattern of passive solar-collected wall and Kang are rather few. As a result, it is necessary to do researches on indoor environment at rural passive solar houses.

2. Methods

2.1. Subject

The passive solar house is located in Jilin, a city in northeast China. Figure 1 shows the floor plan of the solar house. It’s a single storey house with a dimension of 12m×8m×3m. There are two bedrooms, one kitchen and one storeroom. It is noted that a solar-collected wall coupled with Kang is applied for heating at Room 1, which was mainly occupied by peasants, while an application of solar-collected wall alone is for heating at Room 2, commonly uninhabited. The solar wall is set to the southern exterior wall. The area of the solar-collected wall is 16.8 m². The energy-saving walls (500mm) with large thermal insulation were used, made of non-clay bricks (120mm+240mm) and polystyrene board (100mm) with internal and external layers of lime plaster (20mm+20mm), and double glazed windows were adopted. The floor (110mm) consisted of polystyrene board (50mm), gypsum board (50mm) and surface layer. The roof adopted polystyrene board (100mm), gypsum board, cement mortar and felt. Figure 2 shows the south facade of the solar house.

In addition to the solar house, three new energy-efficient houses and two old rural houses were investigated. The envelopes of the three new houses were as same as the solar house, with only a new type of Kang available for heating. Clay bricks were used for the envelope of the old rural houses, with the traditional Kang for heating. One rural house has a much longer history than the other. The six houses had a similar size, about 100m².
2.2. Measurement

The field measurement was divided into continuous monitoring and manual tests. Besides a self-recorded thermometer monitoring outdoor temperature and relative humidity with careful protections from direct solar radiation and snow, three self-recorded thermometers were placed in the kitchen and two bedrooms respectively in every house, and the data were recorded in every 5 min. We went to the rural houses every 3~4 weeks, measuring the air temperature, relative humidity, air speed, globe temperature and surface temperatures of exterior window and Kang. Considering that peasants were usually sitting on the Kang, all the instruments were placed at the height of about 1.0 m above floor.

At the meantime of the field measurement, two peasants of each house were asked to fill in the questionnaires, which included background information (age, gender, height, weight and etc.), clothing, thermal sensation, expectation, comfort and acceptability, adjustments, and etc. A total of 58 valid questionnaires were collected.

3. Results

3.1. Outdoor thermal environment

From Dec. 15th, 2014 to Mar. 15th, 2015, the mean daily outdoor air temperatures ranged from -22.1 °C to 1.1 °C, with an average of -11.3 °C. And the average relative humidity was 75.2%. Winter is cold and long here in severe cold areas.

3.2. Indoor thermal environment

The thermal parameters of the six houses are collected in Table 1.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Building</th>
<th>Temp. (°C)</th>
<th>RH (%)</th>
<th>Air speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>Solar house</td>
<td>20.5</td>
<td>7.6</td>
<td>13.7</td>
</tr>
<tr>
<td>2</td>
<td>Energy-saving House 1</td>
<td>20.4</td>
<td>6.0</td>
<td>13.1</td>
</tr>
<tr>
<td>3</td>
<td>Energy-saving House 2</td>
<td>30.9</td>
<td>10.9</td>
<td>19.5</td>
</tr>
<tr>
<td>4</td>
<td>Energy-saving House 3</td>
<td>22.2</td>
<td>5.5</td>
<td>14.6</td>
</tr>
<tr>
<td>5</td>
<td>Old house 1</td>
<td>24.1</td>
<td>5.84</td>
<td>10.8</td>
</tr>
<tr>
<td>6</td>
<td>Old house 2</td>
<td>20.7</td>
<td>4.0</td>
<td>10.5</td>
</tr>
</tbody>
</table>

It is seen that the indoor temperatures in the energy-saving houses and the solar house are higher than those in the old houses. This paper focuses on indoor environment at a rural passive solar house, and the analyses compared with the old house 2 are as the following.

Because Room1 in the solar house was mainly occupied, its temperature is analyzed. The in-door air temperatures at the solar house varied between 7.6 °C and 20.5 °C, with a mean of 13.7 °C, which was right near the design value of 14 °C [2]. And the relative humidity ranged from 23.8% to 100%, with an average of 65.3%. The average air speed was 0.08 m/s, a range of 0.05 m/s and 0.10 m/s.

While at the old rural house 2, the indoor air temperatures fell in the range of 4.0 °C and 20.7 °C, with an average of 10.5 °C. The relative humidity ranged from 54.6% to 100%, with a mean of 90.9%. The average air speed was 0.06 m/s, between 0.05 m/s and 0.06 m/s. Wang et al. (2013) conducted a field survey on 10 rural houses around Harbin and found that the mean indoor air temperature was 12.3 °C, relatively similar to the environment in the old house 2.

As Figure 2 shows, in the solar house, there were 35 days when the mean daily air temperature met the design standard value of 14 °C, accounting for 39.3% of the general monitoring days. On the other hand, there were only two days in the old house 2, accounting for 2.2%. The mean air temperature in the solar house was 3.1 °C higher than that in the old house 2, which suggests that solar wall is beneficial for improving indoor thermal environment.
The variations of indoor air temperature in the coldest days are indicated in Figure 3.

Usually, peasants fuel Kang at 8:00 am and 4:00 pm, respectively. As seen in Figure 3, the indoor air temperature in the solar house started to ascend at 8:00 am and lasted for about 1 hour until a stable state. The temperature dropped suddenly since 9:00 pm. By comparing air temperatures in the solar house with those in the old house 2, the following differences are found: 1) The mean indoor air temperature in the solar house was approximately 2–3 °C higher than that in the old house 2; 2) The temperature fluctuations were apparently smaller in the solar house than in the old house 2, and especially there was a sharp increase of about 5 °C in the old house when fueling Kang in the afternoon while the air temperature in the solar house was relatively stable (Because a part of heat load of the solar house was supplied by the solar wall, less biomass energy like straw was consumed in the solar house. As a result, the indoor air temperature fluctuated small). On the other hand, the indoor temperatures dropped obviously in the solar house and
the old house 2 at night without fueling Kang while peasants in both houses kept warm with heat dissipated from the Kang when sleeping.

Figure 4 indicates the variations of mean daily relative humidity in the two houses. There were 68 days when the mean daily relative humidity below 70% [3] at the solar house, accounting for 76% of the general monitoring days, while the relative humidity was higher than 70% at the old rural house 2. The high value of relative humidity in old house 2 was probably caused by the low indoor air temperature and a large quantity of plants. Referring to the psychrometric chart, the average humidity content of the solar house and old house 2 was 6.3g/kg and 7.1g/kg, respectively. As shown in Figures 2 and 4, it was found that the humidity conditions got improved at the solar house with air temperature increasing. In general, the thermal environment at the solar house was better than the old house 2.

![Fig. 4. Variations of the mean daily indoor relative humidity.](image)

### 3.3. Temperatures of cavity in the solar wall and the indoor

Figure 5 shows the variations of temperatures of Rooms 1 and 2 in the solar house, and the cavity from 9 am to 3:30 pm.

![Figure 5: Variations of temperatures in Rooms 1, 2, and cavity.](image)
As seen in the Figure, the indoor air temperature in Room 1 (so-lar-collected wall coupled with Kang) has a small fluctuation, and is less consistent with temperatures in the cavity, because both the solar-collected wall and Kang are responsible for heat load. In Room 2 (solar-collected wall alone for heating), the indoor air temperature varied obviously with temperatures in the cavity, and around 2:40 pm the temperature reached a maximum, which was two hours later than the time of the temperature in the cavity, for the heat load is alone undertaken by the solar-collected wall.

Comparing the two houses, there would be a large and rapid increase of air temperature for Room 1 at about 8:00, which was mainly due to burning Kang. However, the indoor air temperature of Room 2 peaked at around 2:40 pm with a slow response, which was primarily attributed to the solar-collected wall.

3.4. Thermal sensation

Figure 6 indicates that the distribution thermal sensation votes. As Figure 7 shows, peasants in the solar house all voted on warm or slightly warm and 79% of votes in the saving houses were warm, slightly warm or neutral. However, 74% of votes in the old houses were neutral or slightly cool. In general, peasants in the solar house and energy-saving houses commonly felt warm, while peasants in the old houses mostly felt neutral or cool.

3.5. Clothing insulation and activity level

Based on the subjective surveys of clothing insulation, it is found that the average clothing insulation of peasants in the solar house was 1.04clo, and in the old rural house 2 was 1.37clo, which indicated that peasants in the solar house wore fewer clothes. The activity levels of peasants were similar, equivalent to light physical activity (1.2met).

The clothing insulation of 12 peasants in six households ranges from 0.64clo to 1.71clo, with an average of 1.16clo, higher than that of urban residents of 0.88clo in Harbin [4]. This is commonly due to that peasants needed frequent access to a house and would seldom change clothes.

Figure 7 shows the five field survey of male and female clothing insulation comparison chart. It is found that average clothing insulation for six hosts was 1.31clo, while average clothing insulation for hostess was 0.98clo. As seen from the Figure, the clothing insulation of male is about 0.33clo higher than that of the female, equivalent to a thin sweater and a thin long underwear pants. This is because hosts need frequent access to the indoor and outdoor, while hostesses generally stay indoors with housework.
4. Discussion

Compared with the old rural house 2, the temperature fluctuations in the daytime at the solar house were smaller while at night they were similar. In the daytime, a part of heat was supplied by the solar-collected wall, which didn’t work at night. Therefore, the solar-collected wall has a positive effect on stability of indoor air temperature.

Although the indoor air temperature at the old house 2 was lower than that of the solar house, the peasants at the old house 2 can accept the poor environment with lower indoor temperature with a higher clothing insulation of 1.37clo. As a result, by changing clothes or applying Kang, the peasants can adapt the indoor environment and feel comfortable.

The mean air temperature in the solar house was lower than that in urban residential buildings. Due to a long thermal history, peasants in the severe cold region have got accustomed to a cold indoor climate with a lower economic level. Consequently, peasants prefer lower indoor temperature. As well, peasants do not like to change clothes for frequently getting in or out of houses. Therefore, with more clothing and the higher metabolic rate, peasants may adapt to a poor indoor environment with a lower indoor temperature. Besides, Kang could create a warm microclimate for local thermal comfort [5,6].

5. Conclusions

- The mean indoor air temperature at the solar house was 13.7°C, which was 3.1°C higher than that in the old house 2 with Kang for heating. The temperature fluctuations were small in the solar house.
- The mean daily relative humidity below 70% in 76% of the general monitoring days at the solar house, while the relative humidity was higher than 70% at the old rural house 2. The solar wall may improve indoor thermal environment.
- The mean indoor air temperatures in the energy-saving houses and the solar house are higher than in the old houses, which indicates a better thermal environment in the energy-saving houses and the solar house.
- Peasants in the solar house and energy-saving houses commonly felt warm, while peasants in the old houses mostly felt neutral or cool.
- By behavioral adjustments such as changing clothes or applying Kang, and expectation, peasants could adapt to a poor indoor environment.
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References