Investigation of indoor thermal environment, heating and cooling behaviors at rural residential buildings in Jiangsu, China

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Abstract
In China, with the economic development and the implementation of the rural revitalization policy, the demand for thermal comfort in rural residences has gradually increased. In this study, to comprehensively understand the long-term variations of indoor thermal environment of rural residences in hot summer and cold winter regions, one-year continuous field measurements in 9 dwellings and 47 households questionnaire survey were performed in Chenzhuang Village, Jiangsu Province. Indoor and outdoor temperature and humidity changes at different seasons were discussed. And the thermal comfort of rural residents together with their winter heating and summer cooling behavior were analyzed. The results indicated that residents were subjectively more tolerant of harsh winter conditions. We also found that the outdoor thermal environment was better than indoor at most of the time during summer nights. Residents prefer fans and natural ventilation over air conditioning. Enhanced ventilation may be an effective means to achieve indoor thermal comfort in summer night of rural areas.

Highlights

- One-year continuous investigation of indoor temperature and humidity were performed in 9 dwellings.
- Rural residential buildings in hot summer and cold winter regions were studied.
- Both field measurement and questionnaire survey were conducted.

Introduction
China's rural economy has risen quickly since 21st century due to the implementation of the Rural Revitalization Strategy. The acceleration of urbanization and the growth of population are considered to be the reasons of increasing demands for construction, life quality and energy consumption (Juan et al., 2019). The Chinese government reported that China's rural residential building area had surpassed 23 billion m2 and rural residential energy consumption had accounted for 22% of the national building energy consumption (Tsinghua University Building Energy Research Center, 2020). Over the past three decades, people's living standard in China has been greatly improved (He et al., 2014). China is now facing the challenge of meeting the increasing needs of a large population while controlling the total amount of energy consumption. The rural thermal environment has an important impact on both human well-being and rural-buildings energy consumption which deserves much attention.

In terms of thermal engineering of buildings, China is categorized into five climate zones: severely cold zone (SC), cold zone (C), hot summer and cold winter zone (HSCW), hot summer and warm winter zone (HSWW), and mild zone (M) (Ministry of Housing and Urban-Rural Development of China, 2016). A number of scholars have already carried out investigations and studies on the thermal environment in rural China. Shao and Jin (Shao & Jin, 2020) investigated the thermal environment and thermal comfort in three cities of SC zone and found that the neutral temperature, the size of the acceptable range and the expected temperature increased with increasing latitude. Zhang et al. (H. Zhang et al., 2019) conducted a 7-day field study on the indoor living environment of elderly people in urban and rural areas of SC zone and found that the thermal performance of existing rural dwellings in northwest China is poor and residents have strong adaptability to the cold indoor thermal environment in winter. Huang et al. (Huang et al., 2017) evaluated the indoor environment of rural dwellings from four aspects through field measurements. Zhang et al. (H. Zhang et al., 2017) conducted an annual analysis of temperature and humidity and found that the thermal performance of these houses was low due to poor air tightness and a lack of thermal insulation of the building envelope. Yoshino et al. (Yoshino et al., 2006) compared the northern and southern part of China and pointed that energy use for space heating and cooling in the southern China will increase in the near future because of occupants’ requirement for comfortable indoor environment.

Indoor thermal environment and thermal comfort of residents showed a lot of differences between urban and rural areas (Han et al., 2009; Yang et al., 2022; H. Zhang et al., 2017) or climatic zones (Yoshino et al., 2006). Most of studies have concentrated on SC and C zones. Field measurements in current studies about HSCW zone are always short-term (Li et al., 2018) or irregular (Xiong et al., 2019), making it impossible to capture the seasonal and annual variations of thermal environment in rural area. However, because of the particular climate in HSCW zone, people must contend with the harsh conditions in both the winter and the summer without central heating. HSCW zone will undoubtedly have a
difficult time keeping up with the rising energy demand (Z. Zhang et al., 2018). In previous study of urban residential buildings, the indoor thermal environment of HSCW zone was even considered as the worst among five climate zones (Li et al., 2020). Therefore, it is urgent and necessary to carry out continuous long-term environmental monitoring in HSCW zone and further analyze the thermal comfort status of rural residents in this region.

In this study, a questionnaire study and field survey were conducted for rural houses in Jurong Village, Jiangsu Province. The temperature and humidity of living rooms and bedrooms of 9 households were monitored for one year. The change patterns and influencing factors of indoor temperature and humidity were analyzed. The current status of thermal comfort in rural houses was summarized based on the thermal sensation vote results. The behavioral habits of rural residents were obtained, which provided pre-analysis and data support for future simulation studies on residents’ behaviors.

Materials and methods

Basic information

Chenzhuang Village is located in the middle of the hot summer and cold winter region of Jiangsu Province in China. The village currently has 88 farming households with a resident population of 230 people and a total area of 2.15 km². The investigation of questionnaires and site visits included the building information, house heating/cooling and hot water supply equipment usage, residents’ living habits and expectations, indoor thermal comfort and energy consumption.

To comprehensively investigate the residential indoor thermal environment, 9 typical farm houses (as shown in Figure 1) were selected for continuous indoor temperature and humidity monitoring for a whole year, from June 2, 2021 to July 16, 2022. For the convenience of description in the following, we labeled the 9 farm houses as No. 1, No. 2, …No. 9. The construction years of these 9 houses ranged from 1972 to 2020. The window was all single-glazed except for No. 3, which was double insulated glass, and the shading position was all full shading except for No. 7. Table 1 shows the statistical details of the basic characteristics of the 9 houses. The year of construction and structural characteristics of the envelope of these 9 dwellings are common and representative in the village, thus the test results can reflect the thermal performance of the dwellings in the whole village.

<table>
<thead>
<tr>
<th>House</th>
<th>Construction year</th>
<th>Resident (Gender, Age)</th>
<th>Envelope structure</th>
<th>Window type</th>
<th>Shading position</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>2020</td>
<td>Female, 77</td>
<td>Porous brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 2</td>
<td>2016</td>
<td>Male, 60 Female, 57</td>
<td>Porous brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 3</td>
<td>1985</td>
<td>Male, 50 Female, 47</td>
<td>Solid clay brick</td>
<td>Double insulated glass</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 4</td>
<td>1994</td>
<td>Male, 75 Female, 71</td>
<td>Solid clay brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 5</td>
<td>1997</td>
<td>Male, 59 Female, 58</td>
<td>Solid clay brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 6</td>
<td>2008</td>
<td>Male, 60 Female, 57</td>
<td>Porous brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 7</td>
<td>1972</td>
<td>Male, 73 Male, 50 Female, 50</td>
<td>Black brick</td>
<td>Single-glazed</td>
<td>Both</td>
</tr>
<tr>
<td>No. 8</td>
<td>1992</td>
<td>Male, 71 Female, 69</td>
<td>Solid clay brick and External wall tiles</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
<tr>
<td>No. 9</td>
<td>1980</td>
<td>Male, 80</td>
<td>Solid clay brick</td>
<td>Single-glazed</td>
<td>Living room</td>
</tr>
</tbody>
</table>

Thermal environment measurement

Indoor temperature and humidity were measured by an automatic data logger (Tianjian Huayi WSZY-1 sensor, Beijing, China). The instrument measurement ranges were from -50–100 °C for temperature and 0–100% for RH with measurement errors of 0.3 °C for temperature and 3% for RH. Two sensors are placed in each household, one in the living room and the other in the bedroom. Placement position of the instruments was about 1 m above the ground, not against the wall or window, and protected from light and with good ventilation conditions. Besides, one instrument was placed in the outdoor about 1 m from the ground, for recording outdoor values. The sampling interval was 30 min.

Questionnaire survey

47 households living in Chenzhuang were randomly selected to participate in the questionnaire survey, which included building overview, occupant information and energy consumption, etc. The details are shown in Table 2. A total of 47 questionnaires were sent out, and 47 valid questionnaires were collected.

Also, a questionnaire survey on indoor thermal sensation of residents in the area was conducted from June 1 to June 6, August 28 to August 30, October 12 to October 15, 2021 and January 2 to January 4, 2022. In total, 151 questionnaires were received, including 44 in summer, 58 in transition season and 49 in winter. In the survey, the subjects’ hot and cold sensations was evaluated corresponded to the ASHRAE 7-level evaluation index, expressed as cold (-3), cool (-2), slightly cool (-1),

![Figure 1: Overhead view of Chenzhuang.](image-url)
moderate (0), slightly warm (1), warm (2), and hot (3). Besides that, a thermal comfort vote (TCV) was applied to reflect the thermal comfort of residents, with four levels of indicators: comfortable (0), slightly uncomfortable (-1), uncomfortable (-2), very uncomfortable (-3) and intolerable (-4).

**Table 2: Details of questionnaire.**

<table>
<thead>
<tr>
<th>Items</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building overview</td>
<td>Year of construction, Window-to-wall ratio, envelope structure, window and door shading, etc.</td>
</tr>
<tr>
<td>Occupant information</td>
<td>Resident population, age, gender, cooling and heating method, cooling and heating period, etc.</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Average household electricity consumption, heating period, cooling period electricity consumption, etc.</td>
</tr>
</tbody>
</table>

**Results and discussions**

**Thermal environment analysis**

Figure 2 and Figure 3 shows the variation of the average daily indoor and outdoor temperature and RH over the measurement duration, respectively. The obtained measurement data were critically checked and a part of the data error points were removed. The results showed that the average annual outdoor temperature in Chenzhuang is 18.9 °C, with a fluctuation range of 6.6 °C to 43.4 °C. The average temperature in the living room is 20.3 °C, with a fluctuation range of 3.3 °C to 35 °C. The average bedroom temperature is 20.8 °C, with a fluctuation range of 4.7 °C to 34.8 °C. In terms of the range and magnitude of indoor temperature fluctuations, the thermal environment in the bedroom is better than the living room, and indoor is better than outdoor. The average daily temperature differences between the bedroom, living room and outdoor were 30.1 °C, 31.7 °C and 50 °C, respectively.

According to the Chinese National Climate Season Division Standard QX/T152–2012, the data from the nearest meteorological station (Nanjing Lukou Airport) were selected to calculate the starting date of the climate season of the year. The year was divided into four seasons: summer (May 25 to October 11), autumn (October 12 to December 1), winter (December 2 to February 28), and spring (March to May 22). Figure 4 and Figure 5 is box line diagram of temperature and RH in different room functions at different seasons. In this region, indoor temperatures during the transition season range from 10–25 °C and RH averages around 65%, which is relatively comfortable. Indoor RH and temperature is the highest in summer, indicating a hot and humid indoor environment. In winter, the indoor temperature is between 3–20 °C, and the average RH is between 66%-67%.
Figure 5: seasonal RH variation.

By comparison, it was found that in all season the average temperature of both the bedroom and the living room indoors was higher than that outdoors, which may be due to the living behavior of the residents. Specially, in summer, the average indoor temperature is even over 28 °C. Compared with the indoor high temperature and humidity environment, the outdoor thermal environment is better at most of the time during summer nights. While indoors, the heat and humidity environment in the living room is significantly better than the bedroom, probably because the living room as an open space has the advantage of better natural ventilation.

Figure 6: Indoor temperature and humidity changes and window opening behavior of residents in a day.

To further understand the effect of ventilation on the indoor environment in rural residences, the window opening and closing behaviors of household 6 on June 5, 2021 were recorded. And by comparing with the indoor and outdoor temperature and humidity data of that day, the following findings can be obtained. With the windows opened at 17:30, the indoor temperature dropped significantly. After 2 hours of ventilation, the indoor temperature decreased by 2 °C, and the temperature difference between indoor and outdoor decreased from 2.3 °C to 1.1 °C. When the windows are closed at 19:30, the room temperature and humidity hardly change anymore. This finding suggests that enhancing natural ventilation in rural dwellings during summer nights might be a way to reduce indoor temperatures and improve thermal comfort.

Indoor thermal comfort analysis

The monthly average temperature and humidity data measured were expressed on an enthalpy-humidity graph and compared to the comfort zone range specified by ASHARE, as shown in Figure 7 (ASHRAE, 2017). It was showed that the indoor thermal environment in Chenzhuang is uncomfortable in most of the time, except for part of the transitional season. In particular, it is extremely undesirable in summer and winter.

According to the evaluation of residents' subjective thermal comfort and thermal sensation as shown in Figure 8, it is seen that residents are most satisfied with the indoor thermal environment during the transition season, with 63.9% considering the current thermal environment comfortable and 55.6% considering the thermal sensation as moderate (0). In contrast, residents were less satisfied with thermal environment in both summer and winter. In summer, the proportion of comfortable was 33.3%, only 23.1% of people had moderate thermal sensation (0), and most residents thought it was warm (2) or slightly warm (1). The percentage of winter comfort is 37.5%, only 10.0% of the residents think the current thermal sensation is moderate (0), and 40% think it is slightly cool (-1).

Comparing the results of thermal comfort vote (TCV) and thermal sensation vote (TSV), it was found that their general trends were highly consistent during the transition season and summer, while a large deviation was observed in winter. For the TSV, few people found it moderate (10% of the population), but for the TCV, lots of residents found it comfortable (37.5% of the population). Besides, compared to 20.6% find it uncomfortable or worse in summer, the number in winter is only 12.5%. This indicates that residents are subjectively more tolerant of harsh winter conditions, still consider them comfortable even if they feel colder, and hardly reach the level of intolerable.

Heating and cooling behaviors

In summer, all residents have cooling behavior, and it occurs centrally from July to August. 88.24% of residents used fans, 76.47% would choose natural ventilation, and 52.94% used air conditioners. Each household has 3 to 4 fans in the village, with an average of 0.9 ceiling fans and 2.4 floor fans. 95.5% of households have installed air conditioners, which are mainly used in summer. On average, each household has 2.14 units of air conditioners, including 0.34 vertical units and 1.8 wall-mounted units. However, 62.7% of residents use only one air conditioner, and 51.94% of them have their air conditioners set at a temperature greater than 26 °C.

Figure 10: Air conditioner use rate and Residents’ adaptive behaviors in summer.

In winter, only 37.65% of the residents had heating behavior, and the heating time was concentrated from December to the following February, among which 58.33% of the residents used electro-heating blankets, 18.67% used fire pits, 18.33% used air conditioners, and 11.45% used radiators. Although almost every household has an air conditioner, it is seldom used in winter. Residents are accustomed to turn on radiators and electric blankets for one to three hours at night before bedtime, which helps to save energy and maintain human thermal comfort.
Conclusion

In Chenzhuang, the yearly variation of outdoor temperature and humidity ranged from -6.6 °C to 43.4 °C and 15.6% to 94.7%. The yearly variation of living room and bedroom temperature ranged from 3.29 °C to 35.03 °C and 4.71 °C to 34.83 °C, RH ranged from 32.69% to 91.37% and 34.67% to 89.57%. In terms of the range and magnitude of indoor temperature fluctuations, the bedroom is better than the living room, and the indoor is better than the outdoor. In summer, the average indoor temperature is over 28°C, even higher than the average outdoor temperature. The outdoor thermal environment is way better than indoor at most of the time during summer nights.

Using the ASHARE comfort zone for comparison, the rural indoor environment is hardly ideal. Rural Residents are most satisfied with the indoor thermal environment during the transition season, over 50% consider it comfortable and moderate. General trends of TSV and TCV were highly consistent during the transition season and summer, while showed inconsistency in winter. The residents are subjectively more tolerant of harsh winter conditions, still consider them comfortable even if they feel colder.

Rural residents use air conditioner mostly from July to September and from December to February, and the use rate of AC in winter is less than 40%. People prefer to cool down by ventilation and using fans, and to warm up by using electric blankets.

Based on the practical measurement result and the behavior of rural residents, combined with the design concept of energy saving, enhanced ventilation may be an effective means to achieve indoor thermal comfort and partial district heating may be a more suitable heating method in rural areas.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (52278109).

References


**Figure 7:** Comparison of indoor thermal environment with ASHRAE comfort zone.

**Figure 8:** TSV result of different season.

**Figure 9:** TCV result of different season.