Study on indoor thermal environment of rural dwellings in Northwest China in winter

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Abstract. In order to study the status of the indoor thermal environment of the northwest rural dwellings in winter, the thermal performance and the residents' adaptability are investigated and the indoor and outdoor thermal environment parameters are measured in Zhongwei region of Ningxia, the indoor thermal environment is analyzed and evaluated by the operating temperature. The results show that the northwest rural residents have strong adaptability to the cold indoor thermal environment in winter. In this area, the cold and daily temperature difference in winter is large, but the solar energy is rich, and it has the geographical advantage of developing passive solar building. The thermal performance of existing rural dwellings is poor and the indoor thermal environment is not ideal. It is necessary to enhance the thermal performance of building's heat collection, thermal storage and enclosure structure.

1. Introduction
With the development of new socialist countryside construction, the living standard of rural residents has been greatly improved, at the same time, the residents' demand for indoor environment is also getting higher and higher [1].

According to the climate regions of architecture in China, most areas in Northwest China are in cold and rigour climate zone with horrible natural conditions with fragile ecological environment and lagging economic development. As a result of the large number of rural residents, the total amount of rural buildings is large and widely distributed, but due to the lack of scientific theory guidance for the design and construction of rural dwellings, it is still an indisputable fact that the indoor thermal environment in winter is poor [2]. Therefore, it is very important to understand the types of rural residential buildings, the thermal performance of building envelopes and the residents' subjective reactions to indoors in Northwest China to improve the indoor thermal environment quality of local rural dwellings in winter [3].

Ningxia autonomous region, located in the hinterland of Northwest China and located in the intersection zone of Ningxia, Gansu and Mongolia provinces, its climate characteristics and dwellings forms have are representative of Northwest China. In this area, the heating period is 137 days, the average temperature is - 0.5 C, the relative humidity is 30%, the annual average sunshine hours is 3796.1 h, and the annual average solar radiation is about 6000 MJ·m⁻²·a⁻¹ in this area [4]. Taking rural dwellings in Zhongwei area of Ningxia as the research object, this paper makes a questionnaire survey

on the thermal condition and residents’ adaptability, and tests the indoor and outdoor thermal environment parameters of rural dwellings, which effectively explores the indoor thermal environment of local residential buildings in winter, and gives corresponding improvement measures.

2. Survey scheme

2.1. Survey purpose
To understand the building types, thermal performance of exterior walls and windows, and residents' subjective adaptability to indoor thermal environment of rural dwellings in Northwest China, so as to provide the basis for improving the indoor thermal environment of rural dwellings in this area.

2.2. Survey content
In this field survey, a total of 170 questionnaires were developed and 143 copies were effectively recovered. The contents of the questionnaire include: building type, external wall, external window thermal performance, residents' subjective thermal sensation and behavioral adjustment ability to the indoor thermal environment. The thermal sensation vote adopts the 7 scale of ASHRAE. (-3 cold, -2 cool, -1 is slightly cooler, 0 is moderate, 1 is slightly warmer, 2 is warm, 3 is hot) [5].

2.3. Survey results and analysis
The survey found that there are two major types of rural dwellings in the area, raw-soil dwellings and brick-concrete dwellings, brick-concrete dwellings accounted for 88%, raw-soil dwellings accounted for 12%, raw-soil dwellings far less than brick-concrete dwellings, so this paper takes brick-concrete dwellings as the research object.

2.3.1 Resident behavior adjustment.
According to the theory of thermal comfort, people usually adapt to the thermal environment through behavioral adjustment. In this paper, the behavior adjustment methods of local rural residents are investigated. The results are shown in Fig. 1.

![Figure 1. The distribution frequency of residents' behavior adjustment methods](image)

As can be seen from Fig. 1, there are many ways for northwest rural residents to adapt themselves to the thermal environment through behavior adjustment. Use heated kang and coal furance are the main ways. Increasing and decreasing activity and the amount of clothing and opening and closing doors and windows are the secondary ways. A small number of residents do not think it is necessary to adjust or other ways. It can be seen that there are many ways for northwest rural residents to actively adapt to the thermal environment, and they have the ability to adapt to the cold indoor environment in winter.

2.3.2 Thermal performance of enclosure structure.
The exterior window is the weakest part of the envelope structure in terms of thermal performance, and it is also the aggregate of the building heat collecting parts and the heat losing parts. Improving the thermal performance of the outer window can obviously improve the indoor thermal environment quality [6]. In this paper, the types of exterior
windows of local dwellings are surveyed. The results are shown in Fig. 2.

The types of exterior windows

| Type   | Distribution frequency (%) |
|--------|---------------------------|
| I      | 37.6                      |
| II     | 19.1                      |
| III    | 28                        |
| IV     | 15.3                      |

Notes: Type I ——Aluminum alloy single frame single glass; Type II ——Aluminum alloy single frame double glass; Type III ——Plastic single frame double glass; Type IV ——Plastic single frame single glass

Figure 2. The distribution frequency of residences exterior windows types

As can be seen from Fig. 2, there are four types of exterior windows in local dwellings, of which there are two types of window frames and two types of glass. According to the literature [3], comparing with the influence of window frame materials on the indoor temperature of northwest rural residential rooms, the influence of glass layer number on indoor thermal environment is more obvious. Fig. 2 also shows that nearly 70% of the local dwellings use single glass windows, which is an important reason for the unsatisfactory indoor thermal environment. It is suggested that single frame double glass should be used instead of single frame single glass to improve indoor thermal environment quality in winter.

The exterior wall is the main part of the envelope structure, the material and insulation have a significant impact on the indoor thermal environment [4]. In this paper, the materials and insulation conditions of the exterior walls of the local dwellings are surveyed. The results are shown in Fig. 3.

The condition of exterior wall materials and insulation

| Material/Insulation | Distribution frequency (%) |
|---------------------|---------------------------|
| Sand-lime bricks    | 34                        |
| Solid clay brick    | 52.5                      |
| KPI perforated bricks | 13.5                    |
| No heat insulation  | 78.6                      |
| Have heat insulation| 21.4                      |

Figure 3. The distribution frequency of exterior walls materials and thermal insulation

From the Fig. 3, we can see that most of the exterior walls of rural dwellings in Northwest China adopt solid clay brick and lime-sand brick, accounting for about 85%, only a small part of which adopt KPI perforated brick, accounting for only 13.5%. From Figure 3, we also can see that the wall structure without thermal insulation accounts for nearly 80% of northwest rural dwellings. It can be seen that the thermal performance of the exterior wall of local dwellings is poor, which is an important reason for the unsatisfactory indoor thermal environment of local dwellings.
2.3.3 *Residents' subjective sensation.* Thermal Sensation Vote (TSV—Thermal Sensation Vote) is expressed by the 7 scale of ASHRAE. When the voting value is -1, 0, and 1, the residents can accept the thermal environment at this time. In this paper, the statistics on the voting results of residents, as shown in Fig. 4.

![Figure 4](image-url)

**Figure 4.** The distribution frequency of residents' heat sensation vote

Fig. 4 shows that the local rural residents voted -2 (cool), -1 (slightly cool) and 0 (moderate) samples accounted for 50%, 20.1%, 11.3% respectively, accounting for 81.4% of the total sample, while the residents who felt cold accounted for only 12.7%. The main reason is that rural residents have strong adaptability to the indoor cold environment.

3. Test content

3.1. Test objects

The outdoor air temperature, solar radiation intensity, indoor air temperature and humidity, indoor wind speed and inner wall temperature of a brick-concrete dwelling in Heilin Village, Zhongwei city, Ningxia were measured from January 18 to January 19, 2015. During the test, the weather was fine, and only the bedroom was heated by heating kang or coal stove. The exterior walls of the single building are made of 370 mm solid clay brick with 10 mm thick white tiles on the outside and 240 mm solid clay brick on the Interior walls. The exterior window is aluminum alloy single glass, the roof is a double-slope roof, only the bedroom roof with 5mm plasterboard ceiling, the roof covered with red tiles.

3.2. Test instrument

The solar radiation intensity is measured by JTDL-4 solar radiometer with a measuring accuracy of ±0.2%. The measuring points are arranged in the open outdoors and no shelter around. See Fig. 5“□”. The air temperature and humidity were measured by TESTO175-H type temperature and humidity auto-recorder. The measuring accuracy was ±0.1°C. The measuring point of outdoor air temperature was located in the shade of outdoor back. The measuring point of indoor temperature and humidity was located in the middle of the room and 1.5 m away from the ground. See Fig. 5“△”. The inner wall temperature is measured by JTNT-C type on-site testing instrument for heat transfer coefficient of envelope structure, and the measuring point is located at the center of the inner wall. See Fig. 5“○”. The measuring accuracy is ±0.5°C. The indoor wind speed test is based on ZRQF-30 hotline anemometer with a precision of ±0.01%. See Figure 5“▽”. The monitoring period of all the above points was 24 h, and the time interval was 10 min.
3.3. Test results and analysis

3.3.1 Outdoor thermal environment test. During the test period, the changes of outdoor temperature and solar radiation intensity are shown in Fig. 6 and Fig. 7 respectively.

As can be seen from Fig. 6, the average outdoor air temperature is -2.7 ℃, the temperature range is -7.6～2.5 ℃, and the temperature fluctuation range is 10.1 ℃. It can be seen that the area is cold in winter and large in temperature difference. As can be seen from Fig. 7, the solar radiation peak appeared around 4:00 p.m., the total radiation intensity was 544.8 W/m², and the scattering radiation intensity was 124.9 W/m². The average solar radiation intensity is 286 W/m², and the direct radiation intensity is larger, accounting for 80% of the total radiation intensity. It can be seen that the region has longer sunshine time and higher solar radiation intensity, and has the advantage of developing passive solar energy buildings [7].

3.3.2 Indoor thermal environment test. During the test period, the indoor temperature and humidity
Changes are shown in Fig. 8.

**Figure 8.** The changes curves of indoor temperature and humidity

As can be seen from Fig. 8, the indoor temperature and humidity vary greatly, and relative humidity decreases with increasing temperature, and vice versa. The highest relative humidity of indoor air is 51.7%, the lowest is 34.1%, which meets the requirements of human thermal comfort [9]; while the lowest temperature is 6.4, the fluctuation of temperature is 8.6 and the average temperature is 9.5 when the highest indoor temperature is 15, the average temperature is much lower than that in the “Technical Guidelines for Energy Saving of Rural Housing in Cold and Cold Areas” (trial) prescribed the computational temperature of indoor design for main function rooms in winter is 14~18°C[9], and the average temperature is much lower than the indoor design calculation temperature of winter in GBT/50824-2013 of Rural Residential Energy Saving Design Standard, which is 14~16.[10]. It can be seen that indoor temperature is low and fluctuating in winter, and the indoor thermal environment is poor.

For indoor wind speed test, because the hotline anemometer can not be placed in the respondent's home for a long time, so it can not be recorded continuously. However, through many household sampling tests, it was found that the indoor air flow is very weak, the wind speed is only 0.04 m/s, that is to say, which means that the air velocity has little effect on the local human thermal comfort [11].

During the test, the temperature changes inner surface temperature of bedroom are shown in Fig. 9.

**Figure 9.** The change curves of each inner wall of bedroom

As shown in Fig. 9, the law of wall temperature changes is roughly the same. The maximum temperature of each wall appears at 19:00, and the average temperature of the east, south, west wall and roof is about 9.0, but the average temperature of the north wall is only 7.7. The main reason is that the north wall is not affected by direct solar radiation, its outdoor comprehensive temperature is lower, and the heat loss of the wall is greater. The inner wall temperature of the partition wall is close to that of the south facing wall. As can be seen further from Fig. 9, the temperature fluctuation amplitude of the inner surface of the roof is the largest, reaching 7.1 degrees Celsius, compared with the temperature fluctuation amplitude of the east, west, north and South wall. This is mainly because the thermal storage capacity of the roof gypsum board is far less than that of the solid clay brick wall, so the temperature fluctuation of the inner surface is the largest.
Air temperature and average radiation temperature have great influence on human thermal comfort. According to the measured surface temperature of the envelope structure, the average radiation temperature of the room is calculated, as shown in (1) [2].

$$t_r = \frac{t_s S_s + t_e S_e + t_w S_w + t_n S_n + t_r S_r}{S_s + S_e + S_w + S_n + S_r}$$ (1)

In the above formula: $t_s$ —— Mean temperature of inner surface of south wall (°C); $t_e$ —— Mean temperature of inner surface of east wall (°C); $t_w$ —— Mean temperature of inner surface of west wall (°C); $t_n$ —— Mean temperature of inner surface of north wall (°C); $t_r$ —— Mean temperature of inner surface of top surface (°C); $S_s$ —— The inner surface area of the south wall (m²); $S_e$ —— The inner surface area of east wall (m²); $S_w$ —— The inner surface area of west wall (m²); $S_n$ —— The inner surface area of north wall (m²); $S_r$ —— The inner surface area of top surface (m²).

The curves of indoor air temperature and indoor average radiation temperature are shown in Fig. 10.

Figure 10. The change curves of indoor air temperature and mean radiation temperature curves

As can be seen from Fig. 10, indoor air temperature and mean radiation temperature are not synchronous, and there are significant differences in peak and mean values between them. When the relative humidity and indoor wind speed are in the range of human thermal comfort, human thermal sensation will be affected by indoor air temperature and average radiation temperature. Therefore, this paper uses the operating temperature $t_0$ as the indoor thermal environment evaluation index [12], and its calculation formula is shown as (2) [10].

$$t_0 = \frac{h_c t_a + h_r t_r}{h_c + h_r}$$ (2)

In the above formula: $h_c$ —— Convective heat transfer coefficient, W/(m²·°C); $h_r$ —— Radiation heat transfer coefficient, W/(m²·°C); $t_a$ —— Indoor air temperature, °C; $t_r$ —— Indoor mean radiation temperature, °C; $t_0$ —— Operating temperature, °C.

When the convective heat transfer coefficient is equal to the radiation heat transfer coefficient, (2) is expressed as:

$$t_0 = \frac{t_a + t_r}{2}$$ (3)

During the test period, the operating temperature changes of the bedroom are shown in Fig. 11.
Figure 11. The change curves of operating temperature

As can be seen from Fig. 11, the indoor thermal environment of rural dwellings in this area is poor, the indoor temperature is low and the temperature fluctuation is large. In order to effectively improve the indoor thermal environment quality in winter, it is necessary to strengthen the heat collection and thermal storage of buildings and the thermal performance of enclosure structure.

4. Conclusion

By the study of the indoor thermal environment of rural residential areas in Northwest China in winter, the following conclusions are reached.

(1) There are many ways for rural residents in Northwest China to actively adapt to indoor thermal environment, and they have strong adaptability to indoor cold environment. (2) Northwest China in winter is cold and the daily temperature difference is larger. At the same time, the region is rich in solar energy resources and has the geographical advantage of developing passive solar energy buildings. (3) The thermal performance of existing residential buildings in Northwest China is poor, the indoor thermal environment is not ideal, the indoor temperature is low and the temperature fluctuation is large, so it is necessary to strengthen the heat collection and thermal storage of buildings and the thermal performance of enclosure structure.

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