Thermal Evaluation of Sloping Roofs on Indoor Environment of Traditional Rural Houses in Cold Areas

Weiihan Zou¹, Yeo Sok Yee*¹

¹ Department of Architecture, School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, China
*Corresponding author’s e-mail: yeosokyee@mail.xjtu.edu.cn

Abstract. In order to explore the influence of sloping roofs on the indoor thermal environment in cold regions in summer, the article takes the sloping roofs and flat roofs of traditional houses in a county in the cold region of Weinan City as the research object. A combination of theoretical and field measurements was used to analyse the effect of sloping roofs on the internal and external surface temperature of the floor level, indoor temperature and humidity, and comfort in summer. The results show that the existence of sloping roofs largely reduces the surface temperature of the roof and the heat transfer from outdoors to indoors, and can reduce the indoor air temperature by 1.3°C compared to flat roofs, which has a good effect of stabilising the temperature change and keeping the indoor thermal sense in a warm state, and the results of the study can provide a scientific basis for the construction and application of sloping roof houses.

1. Introduction

Traditional Chinese rural residential buildings have good thermal performance and climate adaptability [1]. The main reasons for this are related to the building materials, spatial form, and structural design of traditional rural dwellings, with sloping roofs as an important part of the structural design of dwellings, which largely reduce the amount of outdoor solar radiation input. And the mezzanine space between the roof and the floor slab blocks the transfer of heat to the interior to a certain extent, resulting in a lower indoor temperature level, which is a good inspiration for the construction and application of modern residential houses.

Researchers from different climatic zones have done a lot of research on the thermal environment of traditional houses, confirming the adaptability of traditional houses to their geographical environment and the thermal benefits they can achieve in winter and summer. For example, scholars such as Teng Shao and Liang dong have studied the thermal environment of traditional residential houses and the thermal comfort of rural residents in the cold regions of northeast China and confirmed that reasonable residential building structures and floor plans can achieve good thermal efficiency [2-3]. Besides, the thermal environment and its good thermal comfort achieved by traditional inhabitants of temperate, subtropical, and Mediterranean climate zones, among others, has been confirmed by relevant researchers [4].

However, there is still a lack of quantitative data to support the intrinsic relationship between sloping roofs and the indoor thermal environment of residential buildings in cold regions. Based on this, two residential buildings with sloping and flat roofs located in the cold region of Weinan City were selected for field measurement of environmental parameters such as internal and external surface temperature of the floor level, indoor and external air temperature and humidity, black-bulb temperature and wind speed during summer. To study the effect of the presence of sloping roofs on the temperature of the internal
and external surfaces of the floor levels of residential buildings, the temperature and humidity of the indoor air, and to explore the amount of solar radiation that can be reduced by sloping roofs. It also analyses the effect of sloping roofs on the indoor thermal comfort of residential houses, aiming to provide data support and provide a scientific basis for the design of traditional residential houses and their construction applications.

2. Methods

2.1. Experimental design

The measured site is located in Weinan City, Shaanxi Province, China (E110.15°; N35.24°), which is classified as a cold region according to the Chinese building thermal zoning standards (Figure 1), and according to the World map of koppen climate classification for 1901-2010, it is classified as BSK (B: Dry; S: Dry Summer; K: Cold arid). The measurement subjects were two traditional residential buildings with a sloping roof and a flat roof. The materials, window sizes, and floor heights of the two buildings were the same, and the orientation was the same so that other environmental parameters affecting the measurement results were controlled to the greatest extent possible. The measurement was conducted from 1 August to 8 August in the summer of 2020 and included the internal and external surface temperature of the floor slab layer, indoor air temperature, outdoor ambient air temperature, indoor black-bulb temperature and outdoor solar radiation for flat and sloped roofs (Figure 2). The measurement equipment mainly contains a thermometer, SMD temperature and humidity sensor, black ball thermometer, anemometer and solar radiometer, the relevant parameters are shown in Table 1, where the thermometer error is calibrated in a constant temperature and humidity chamber, and the temperature sensor is placed in an isolation enclosure for testing.

Figure 1. Research area.

Figure 2. Field measurement programs.
2.2. Evaluation indexes
PMV (Predicted Mean Vote) has been widely used for evaluating moderate indoor thermal environments and the results exhibit no severe deviations compared with other indexes, And the accuracy of PMV in thermal comfort studies has been proven [5]. The regression formula was obtained between human thermal sensation and human thermal load (Equation 1), and PMV has obtained seven levels of hot (3), warm (2), slightly warm (1), moderate (0), slightly cool (-1), cool (-2) and cold (-3) and their corresponding quantitative values are included, In order to facilitate the calculation of the variation of PMV at different periods, the article uses Rayman 2.1 software to simulate the indoor PMV study. Studies have confirmed that Rayman achieves good accuracy at calculating thermal comfort indicators [6].

\[
PMV = (0.303 \times \exp(-0.036M) + 0.0275)TL
\]  

(M is metabolic rate, W/m², TL is the difference between heat production rate and heat dissipation rate)

To further quantify the amount of solar radiation reduced by studying sloped roofs, the article introduces the Stefan-Boltzmann law (Equation 2), to approximate the total radiance of the external surface of the sloping roof under the floor level and the flat roof, and to indirectly reflect the difference between the amount of solar radiation absorbed by the external surface of the roof.

\[
M = \varepsilon \sigma T_s^4
\]  

(M is the radiation intensity of the object (W·M⁻²), \( \varepsilon \) is the radiation coefficient of the object (taken as 0.92 in this study), \( \sigma \) is the Stefan-Boltzmann constant \( (\sigma = 5.6697 \times 10^{-8} \text{ W·M}^{-2}·\text{K}^{-4}) \) and \( T_s \) is the surface temperature of the object.)

3. Analysis and results
The impact of sloping roofs on the thermal environment of traditional dwellings can be divided into direct and indirect thermal benefits, with the direct thermal benefit referring to the impact of the sloping roof on the internal and external surface temperature of the floor below, and the indirect thermal benefit on the indoor air temperature of the dwelling. In addition, based on the similar trend of three consecutive days, combined with this field measurement (Figure 3) and the outdoor ambient air temperature measured by the local meteorological station (Figure 4), it can be found that the temperature and humidity changes from August 2 to August 5 show a similar trend, so the article chose August 3 as a typical analysis day, the field test results are analysed as described below.

![Figure 3. Outdoor air temperature.](image)

![Figure 4. Outdoor air temperature.](image)
3.1. Direct thermal benefits of sloping roofs

The first observation of the change in temperature between the external surface of the floor slab layer under the sloping roof and the external surface of the flat roof (Figure 5) shows that the surface temperature of the broken roof is higher than that of the flat roof before 10:00 a.m. This is because the presence of the sloping roof makes the long-wave radiation from the floor slab layer under the roof reflected at night, resulting in a higher temperature. After 10:00 the solar radiation gradually increased and the temperature on the flat roof rose rapidly, reaching an extreme value (44.4°C) at 16:40, with a difference of 13°C from the sloping roof, and remained at a high level thereafter, while the temperature on the outer surface of the sloping roof floor layer was more stable and less fluctuating. Comparing the temperature changes of the inner surface of the sloping roof slab layer and the flat roof, it can be found that the inner surface of the sloping roof has been at a lower level with less fluctuation. The temperature of the inner surface of the flat roof, on the other hand, rises rapidly after 14:00 with the strengthening of solar radiation and reaches its maximum temperature difference of 2.6°C at around 21:20. At night the internal surface temperature of the flat roof is higher than the internal surface temperature of the sloping roof slab layer mainly because of the high inhalation of solar radiation during the day, which makes it difficult to dissipate in a short time at night, resulting in higher temperatures. The results of the analysis of the change in temperature of the internal and external surfaces of the sloping roof floor and flat roof confirm that the sloping roof has a significant cooling benefit on the internal and external surface temperatures of the floor.

Table 2 shows the extreme values, mean values, standard deviations and total surface radiation of the external surface temperature of the sloping roof floor and the external surface of the flat roof, where the external surface temperature of the sloping roof floor is 2.9°C lower than that of the flat roof and the average temperature difference reaches 8°C between 12:00 and 18:00 hours when the solar radiation is stronger. The fluctuations in temperature, expressed as a standard deviation, reveal that the external surface temperature of the sloping roof floor (2.1) is significantly more stable than the external surface temperature of the flat roof (7.5), and the total radiation at the external surface of the sloping roof floor is also lower than that of the flat roof at 48.5 W/m² during the 12:00-18:00 hours.

Table 2. External surface temperature test parameters and total radiation of the object.

| Type        | Highest temperature (°C) | lowest temperature (°C) | Average temperature (°C) | 12:00-18:00 average temperature (°C) | standard deviation | Radiation quality (W/m²) |
|-------------|--------------------------|--------------------------|--------------------------|--------------------------------------|--------------------|--------------------------|
| Sloping roof| 31.4                     | 25.5                     | 28.3                     | 30.3                                 | 2.1                | 441.4                    |
| Flat roof   | 44.4                     | 22.8                     | 31.2                     | 38.3                                 | 7.5                | 489.9                    |

3.2. Indirect thermal benefits of sloping roofs

Comparing the change in indoor temperature between sloping roofs and flat roofs (Figure 7), it can be
seen that there is little difference in indoor air temperature between the two during the 5:00-10:00 hours when solar radiation is absent or low. However, after 10:00, the solar radiation gradually increases, while the indoor air temperature on the flat roof rises rapidly and remains at a high level until 23:00. On the other hand, the temperature on the sloping roof was always lower than that on the flat roof, with a slow increase and a gradual stabilisation after 16:00, with a maximum difference of 2.1°C at 22:20. Table 3 shows the comparison of the extreme, mean and standard deviation of indoor air temperature between sloped and flat roofs. It can be found that the average difference in indoor air temperature between the two is 0.6°C, but the average difference between the two reaches 1.3°C during the 12:00-18:00 hours, confirming that sloped roofs can significantly reduce indoor air temperature when solar radiation is strong. Comparing the changes in indoor air relative humidity between sloped and flat roofs (Figure 8, Table 3), it can be seen that the indoor air relative humidity is consistently higher on sloped roofs than on flat roofs, and the variation is stable (standard deviation of 0.47). On the other hand, the relative humidity of indoor air on flat roofs decreases significantly after 12:00 when solar radiation increases, with a large variation (standard deviation of 2.01), and the maximum difference between the relative humidity of indoor air on sloping roofs is 4%. Although there is a small recovery after 20:00, it is still at a low level. A comparison of the changes in the relative humidity of indoor air between sloped and flat roofs also confirms that sloped roofs have some humidifying effect on indoor air.

### Table 3. Air temperature and relative humidity test parameters.

| Type      | Highest temperature (°C) | Lowest temperature (°C) | Average temperature (°C) | 12:00-18:00 average temperature (°C) | Standard deviation | Average Relative Humidity (%) | Standard deviation |
|-----------|--------------------------|--------------------------|---------------------------|--------------------------------------|--------------------|-------------------------------|--------------------|
| Sloping roof | 28.6                     | 27.4                     | 28                        | 28.1                                 | 0.38               | 74.1                          | 0.47               |
| Flat roof   | 30.1                     | 27.2                     | 28.6                      | 29.4                                 | 0.97               | 70.1                          | 2.01               |

### 3.3. Thermal Sense Analysis

By calculating and comparing the variation in PMV over the day for sloping roofs and flat roofs (Figure 9), the results show that the indoor thermal perception of sloping roofs is between warm (1) and warm (2), while flat roofs are in the warm to the hot range (1-3). And the difference in heat perception between the two is small before 11:00 am, while the heat perception in the flat roof indoor environment gradually transitions from warm to hot phase as the solar radiation increases. The PMV of sloped roofs is significantly lower than that of flat roofs and remains in the warm to warm interval, and the difference in thermal perception between the two is greatest at 19:00 (0.4), confirming the significant moderating effect of sloped roofs on human thermal perception in indoor environments.
4. Conclusion
The article is a field measurement study of the thermal environment and thermal comfort parameters such as internal and external surface temperature of the floor level, indoor air temperature and humidity, PMV of two traditional houses with sloping and flat roofs in the cold region of Weinan City in summer, which mainly leads to the following conclusions: (1) Sloped roofs have significant direct thermal benefits in summer compared to flat roofs, stabilising the magnitude of changes in the internal and external surface temperature of the floor level and reducing the average daily temperature of the external surface of the floor level by approximately 2.9°C compared to flat roofs, achieving a thermal benefit of 8°C during the 12:00-18:00 time period when solar radiation is stronger, reducing the total radiation on the external surface by approximately 48.5W/m² and having a positive effect on the internal Surface temperatures also have a stabilising temperature fluctuation and direct thermal benefit. (2) Compared to flat roofs, sloping roofs also have significant indirect thermal benefits on indoor air temperature and relative humidity, with a daily average temperature difference of up to 1.3°C and a daily average relative humidity difference of up to 4%, and a stabilising effect on changes in indoor air temperature and relative humidity. (3) Similar to the indirect thermal benefits of the sloped roof, the sloped roof has a significant effect on the regulation of indoor thermal comfort when solar radiation is enhanced so that the thermal perception of people in the indoor environment is always in the warm to warm interval. The findings of the article provide scientific data to support the future application of sloping roofs in the construction of traditional residential houses and indirectly promote the construction of a rural ecological environment.

References
[1] Lili Zhang., Yan Yu., Jiawen Hou., Xi Meng. (2017) Qian Wang, Field Research on The Summer Thermal Environment of Traditional Folk Tibetan-style Houses in Northwest Sichuan Plateau. Procedia Engineering., 202: 438-445.
[2] Teng Shao., Hong Jin. (2020) A field investigation on the winter thermal comfort of residents in rural houses at different latitudes of northeast severe cold regions. China, Journal of Building Engineering., 32: 101476.
[3] Liangdong Ma., Nina Shao., Jili Zhang., Tianjiao Zhang., Meng Xu. (2016) A Study on Indoor Thermal Environment of Rural Residence in South Liaoning Province. Procedia Engineering., 146: 366-374.
[4] Haiying Wang., Chonggen Shi., Wenyu Li., Lin Wang., Jie Wang., Gang Wang., Songtao Hu. (2021) Field investigation on thermal environment and comfort of people in a coastal village of Qingdao (China) during winter. Building and Environment., 191: 107585.
[5] Toby Cheung., Stefano Schiavon., Thomas Parkinson., Peixian Li., Gail Brager. (2019) Analysis of the accuracy on PMV-PPD model using the ASHRAE Global Thermal Comfort Database II. Building and Environment., 153: 205-217.
[6] Matzarakis., F. Rutz., H. Mayer. (2010) Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. International Journal of Biometeorology., 54 (2): 131-139