Impact of Lofts in Traditional Dwellings on the Thermal Environment in Wenxian, Gansu, China

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Abstract. Through field research and measurements of traditional dwellings in Wenxian, Gansu Province, three types of lofts were identified: open-style, board-sealed, and wall-sealed. Models were established using Design Builder software, and indoor thermal environment simulations were conducted. The results showed that: 1) The difference in the average indoor air temperature of the living room in August between the open-style loft and the sealed lofts (board-sealed and wall-sealed) was 0.12°C and 0.19°C, respectively, with no significant difference; 2) CFD simulations revealed vertical temperature differences in the living room cross-section of 1.72°C and 2.47°C between the three conditions, with significant differences. Sealed lofts provide a more stable indoor thermal environment and higher space utilization. The "enclosed" loft design enhances thermal stability, space utilization, and energy efficiency, making it ideal for broader adoption.

Keywords: Wenxian; traditional dwellings; loft; thermal environment; numerical simulation

1 Introduction

Guided by green building policies and "dual carbon" goals, China's construction industry is shifting toward low-carbon development. However, recently, energy consumption and carbon emissions of residential buildings continued to rise[1], with many rural dwellings' thermal environments remaining unstudied and unoptimized. But research on building thermal environments in China has mainly focused on urban areas. Notable research includes studies by Yan Haiyan and Sun Zhen on office and residential buildings[2-3], and by Xu Yanan on rural dwellings using field measurements and simulations[4]. Existing studies mainly focus on envelope structures and spatial layouts, with limited attention to specific spaces. The unique attics of Wenxian County's traditional dwellings lack sufficient research. Thus,this study uses field research and Design Builder software to analyze the impact of three types of attics on the indoor thermal environment of these dwellings.

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2 Research Objects

Wenxian, located at the southern tip of Gansu Province, is at the junction of Gansu, Sichuan, and Shaanxi. Its unique geography and climate have shaped a regional dwelling style, the "tile house".

The first floor of the dwelling typically includes rooms like the living room, bedroom, and kitchen, while the loft's function varies. Most households seal the mountain and rear faces with rammed earth walls, leaving the front open or sealed with wooden boards, while a few use brick walls to divide the loft into rooms. The three types of lofts in the dwellings are shown in Figure 1. A total of 103 surveys were obtained through field research, and the statistical results are shown in Table 1.

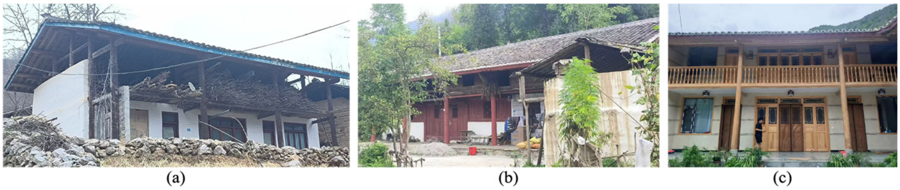

Fig. 1. Photos of Local Residences: (a) Open Type; (b) Boarded Type; (c) Walled Type

Table 1. Statistics of Loft Types in Traditional Residences of wenxian

Loft Types	Number of Households	Percentage
Open Type	63	61%
Board-Enclosed Type	34	33%
Wall-Enclosed Type	6	6%

3 Model and Parameter

The survey shows Wenxian's traditional dwellings have 660mm rammed earth walls and a 33mm wooden floorboard between the first floor and loft. According to local construction practices, simplified models were created with loft type as the variable, as shown in Figure 2.Due to the lack of meteorological data for Wenxian, Wudu District's meteorological data is used, with no cooling or heating applied during the simulation for accuracy.

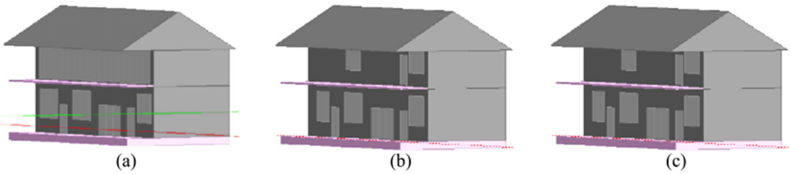

Fig. 2. Simplified Model Diagrams : (a) Open Type; (b) Board-Enclosed Type; (c) Wall-Enclosed Type

The models for the three scenarios were established based on the three types of lofts, each reflecting different envelope structures and heat exchange characteristics. The specific settings for each scenario, including the corresponding design parameters and assumptions, are presented in Table 2.

Table 2. Condition Settings

Conditions	Loft Types	Envelope Structure	Thickness
1	Open	No	0
2	Board-Enclosed	Wooden Board	50mm
3	Wall-Enclosed	Brick Wall	240mm

4 Simulation Analysis

Due to differences in envelope structures, lofts exhibit varying levels of heat exchange with the outdoor air, which has a significant impact on the indoor thermal environment. This variation directly influences the thermal comfort experienced by occupants. As air temperature largely determines thermal comfort[5], this study selects the indoor air temperature of the living room as the primary indicator for evaluating thermal performance. To ensure the analysis reflects real-life conditions, the schedule is designed to align with the villagers' typical summer routine. In particular, 2 PM is identified as the peak usage time for the living room, representing the period of highest activity. Furthermore, no air conditioning is applied during the simulation to maintain the authenticity and reliability of the results.

4.1 Temperature Analysis of the Living Room

The simulation was conducted for August data under three different conditions, focusing on the air temperature at 14:00 as the key analysis time. The results, highlighting temperature variations among the conditions, are illustrated in Figure 3 for comparison.

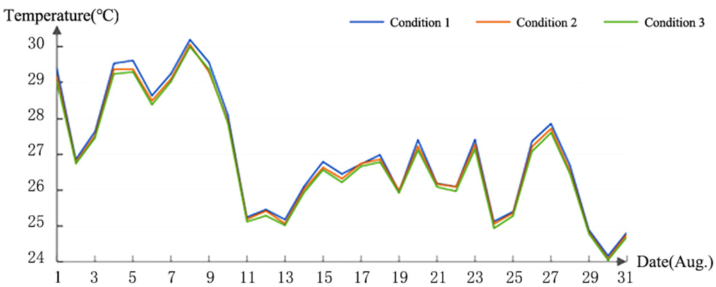

Fig. 3. Average Indoor Air Temperature in the Living Room

As shown in Figure 3, the air temperature of the living room reaches its highest under Condition 1, is slightly lower under Condition 2, and is the lowest under Condition 3. The temperature differences between these three conditions vary depending on the day, ranging from 0.07°C to 0.18°C. These differences clearly highlight the impact of structural variations on the indoor thermal environment, demonstrating how changes in envelope design influence the heat exchange with the outdoor air, ultimately affecting the living room's thermal performance.

In Condition 1, the lack of envelope structure allows outdoor hot air to enter the loft, increasing its temperature, which then transfers to the living room. In Conditions 2 and 3, envelope structures reduce heat transfer, resulting in lower indoor temperatures. The thicker 240 mm brick wall in Condition 3 offers more thermal resistance than the 50 mm wooden board in Condition 2, keeping the living room cooler. Weather conditions also affect the temperature differences—higher outdoor temperatures increase the differences, while lower temperatures reduce them. Statistical analysis of the monthly simulation data was conducted to determine the extreme and average indoor air temperatures for each condition,the results are shown in Table 3.

Table 3. Indoor Air Temperature in the Living Room under Three Different Working Conditions

Conditions	Max Value /°C	Min Value/°C	Average /°C
1	30.08	24.06	26.89
2	29.95	23.98	26.77
3	29.88	23.94	26.70

According to Table 3, the average indoor air temperatures are 26.85°C for Condition 1, 26.77°C for Condition 2, and 26.71°C for Condition 3. These results indicate temperature reductions of 0.12°C and 0.19°C, respectively, when comparing the "open" loft (Condition 1) to the "enclosed" lofts (Conditions 2 and 3). All recorded temperatures fall within the comfortable range defined by China’s thermal comfort standards, which set a maximum threshold of 30°C for summer conditions[6]. Among the three conditions, Condition 3 exhibits the most favorable thermal environment, providing the lowest average indoor temperature. To further investigate the indoor thermal environment, Computational Fluid Dynamics (CFD) simulations were performed using Design Builder. These simulations analyzed a vertical section of the model to provide detailed insights into air temperature distribution and thermal performance under different conditions.

4.2 Computational Fluid Dynamics Simulation

In the study of indoor thermal environments in buildings, CFD simulations can accurately model various parameters such as airflow paths, temperature distribution, relative humidity, and pollutant concentration. By utilizing the CFD simulation function in Design Builder software, the air temperature distribution at a specific section of the building can be obtained. CFD simulations were conducted for the residential models under three conditions, with 14:00 on August 21st as the simulation time. The center of the living room was selected as the section point for a vertical cross-section, and the resulting vertical air temperature distribution contour maps for the three models are shown in Figure 4.

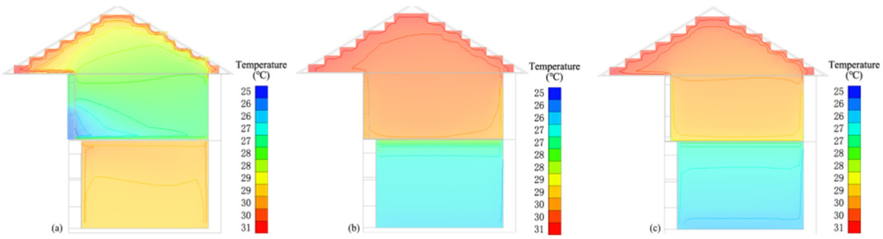

Fig. 4. Contour Map of Air Temperature: (a) Condition 1; (b) Condition 2; (c) Condition 3

Figure 4 illustrates that the indoor air temperatures along the living room's vertical cross-section show more variation compared to the overall room temperature, with the lowest temperature found at the floor and the highest at the ceiling. Within the typical human activity height, however, the temperature remains relatively uniform and comfortable, indicating a stable thermal environment for occupants. The average air temperatures on the vertical section are 29.18°C for Condition 1, 27.46°C for Condition 2, and 26.71°C for Condition 3. Notably, Condition 1 is 1.72°C higher than Condition 2, and 2.47°C higher than Condition 3. As a result, Condition 3 demonstrates significantly better thermal stability and comfort compared to the other two conditions, highlighting its superior indoor thermal performance.

5 Conclusion

Through field research and numerical simulations using Design Builder, the analysis reveals that the three types of lofts in traditional dwellings in Wenxian, Gansu, have varying degrees of impact on the indoor thermal environment of the building's main living space—the living room. The specific conclusions are as follows.

(1) Based on the average indoor air temperature of the living room throughout August, a gradual decrease is observed from Condition 1 to Condition 3. The temperature differences between Conditions 1 and 2, and between Conditions 2 and 3, are 0.12°C and 0.07°C, respectively, with no significant differences.

(2) According to CFD simulations, the air temperature distribution along the vertical section at the center of the living room shows significant differences between the three conditions. The temperature differences between Condition 1 and Conditions 2 and 3 are 1.72°C and 2.47°C, respectively. This demonstrates that the "enclosed" lofts in traditional dwellings create a more stable indoor thermal environment compared to the "open" lofts.

As the living conditions of villagers improve, some have chosen to build modern houses, which not only disrupt the overall aesthetic of the village but also lead to significant energy consumption and carbon emissions. However, by modifying the lofts in traditional dwellings, it is possible to enhance the living comfort of villagers while avoiding unnecessary energy consumption and carbon emissions.

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