DOI: https://doi.org/10.14256/JCE.3870.2024

Primljen / Received: 25.9.2023.
Ispravljen / Corrected: 6.6.2024.
Prihvaćen / Accepted: 10.6.2024.
Dostupno online / Available online: 10.8.2024.

Effect of advanced insulation materials and passive optimization strategies on interior thermal comfort of traditional houses in winter

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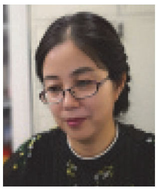

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Professional paper

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This study proposed an interior thermal comfort test to enhance the interior thermal comfort of traditional houses in the Guan Zhong region of the Shaanxi Province during winter. The study was conducted in Xiaoliu village by employing field tests and a questionnaire survey. The field tests and analysis revealed that the thermal comfort of traditional houses in this region is poor, the spatial layout of the houses is unsuitable for conserving heat, the thermal properties of the enclosure walls are inadequate, and the mode of heating is inefficient. The heat transfer parameters, heat lost and gained through fabrics, and thermal properties of nanomaterials have been used to improve the thermal comfort analysis. Combined with the local economic conditions, passive design strategies such as optimizing the spatial layout, improving the thermal insulation performance of the enclosure walls, and using solar energy were implemented. The simulation results indicate that energy consumption can be significantly reduced, and the indoor thermal comfort of traditional houses can be enhanced by reasonably dividing the indoor space, increasing the thermal insulation performance of the enclosure walls, and making better use of solar energy and natural ventilation. Therefore, to improve thermal comfort and reduce the energy load of traditional houses in the Guan Zhong region, it is necessary to adopt passive optimisation strategies.

Key words:

traditional house, indoor thermal comfort, thermal simulation, passive design strategies, nanomaterials

Stručni rad

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Učinak naprednih izolacijskih materijala i strategija pasivne optimizacije na toplinsku udobnost u tradicionalnim kućama tijekom zime

U radu je prikazano istraživanje toplinske udobnosti interijera kako bi se poboljšala toplinska udobnost interijera tradicionalnih kuća u regiji Guan Zhong u provinciji Shaanxi tijekom zime. Istraživanje je provedeno u selu Xiaoliu koristeći terenske testove i upitnike. Terenska ispitivanja i analize pokazali su da je toplinska udobnost tradicionalnih kuća u ovoj regiji loša, prostorni raspored unutar kuća neprikladan za očuvanje topline, toplinska svojstva vanjskih zidova neadekvatna, a način grijanja neučinkovit. Za poboljšanje analize toplinske udobnosti korišteni su parametri prijenosa topline, gubitak i dobitak topline kroz tkanine i toplinska svojstva nanomaterijala. U kombinaciji s lokalnim gospodarskim uvjetima primijenjene su strategije pasivnog dizajna kao što su optimizacija prostornog rasporeda, poboljšanje toplinske izolacije vanjskih zidova i korištenje solarne energije. Rezultati simulacije pokazuju da se potrošnja energije može značajno smanjiti, a osjećaj toplinske udobnosti u tradicionalnim kućama može se poboljšati razumnijom podjelom unutarnjeg prostora, povećanjem učinkovitosti toplinske izolacije vanjskih zidova i boljim iskorištavanjem Sunčeve energije i prirodne ventilacije. Stoga je za poboljšanje toplinske udobnosti i smanjenje energetskog opterećenja tradicionalnih kuća u regiji Guan Zhong potrebno primijeniti strategije pasivne optimizacije.

Ključne riječi:
tradicionalna kuća, unutarnja toplinska udobnost, toplinska simulacija, strategije pasivnog dizajna, nanomaterijali

1. Introduction

Traditional houses in the Guan Zhong region, a region located in the Shaanxi Province with an area of 55500 square kilometres and a population of approximately 24 million, have formidable thermal comfort issues during cold, snowy winters caused by stinging winds and precipitation. These houses are sensitive to heat loss and drafts because they are made mostly of mud, brick, and wood, making winter living conditions unpleasant for occupants. Finding creative solutions that combine current technologies with traditional designs is crucial to properly address these difficulties. Modern insulation materials and passive optimisation techniques have been successful in milder climates; however, their effectiveness in the traditional houses of Guan Zhong is still largely unknown. Adapting these innovations to meet the unique requirements of traditional houses in the region is mostly unexplored in the existing literature, which deals with contemporary construction techniques and Western architectural environments.

The number of urbanised areas worldwide has increased, and according to the United Nations, more than 70 % of the world's population is expected to be located in urban centres by 2050. According to World Development Indicators, 85 % of the population will be in developing countries by 2030. This growth has led to an increase in the urban density of buildings, especially in city centres, thereby influencing the characteristics of indoor environments that increasingly rely on artificial systems for satisfactory operation. Additionally, the time spent indoors has increased significantly in recent years. As architects and engineers consider ways to improve indoor comfort and building performance, they must consider that people spend 80–90 % of the day indoors. In developed countries, the building sector (residential, commercial, and public) consumes between 20–40 % of their total national consumption [1]. Buildings consume approximately 70 % of their energy through air conditioning systems and artificial lighting [2]. The high energy consumption of air conditioning is largely due to the uniform control of the indoor temperature regardless of the building location; however, as demonstrated in the literature, it is unnecessary to ensure strict thermal comfort temperatures [3]. Significant energy savings can be achieved by allowing air conditioning systems to exhibit a wider range of indoor temperature fluctuations. Specifically, multiple studies have focused on thermal comfort and energy efficiency [4]. In recent years, the field of research in thermal comfort has attracted the attention of many researchers worldwide, partially owing to the increased public discussion on climate change. Overall thermal comfort and indoor environmental quality assessments do not depend solely on physical parameters. The physiological and psychological responses of humans to the environment are dynamic and integrate various physical phenomena that interact with space such as light, noise, vibration, temperature, and humidity.

Energy problems are becoming increasingly prominent in the context of global warming. Therefore, sustainable energy development is of great significance [5]. As a large energy consumption country, China's building energy consumption has accounted for about 30 % of the national consumption [6]. The construction areas of rural residential buildings account for more than half of newly built houses in China [7, 8]. Therefore, decreasing building power consumption, particularly in rural areas, is critical. The government proposes that the strategic goal of rural revitalisation is to build a beautiful countryside and improve the rural living environment, which is crucial for harmonious living with nature. Consequently, there is an urgent need to study traditional houses for sustainable development.

It is undeniable that traditional rural architecture provides rich ecological experiences. Owing to rapid economic development, living standards have continuously improved, and the requirements for indoor thermal environments are also increasing. China has a large amount of traditional houses. Limited by economic conditions, the design standards of these houses are low, and most traditional rural houses do not meet thermal requirements. To date, rural self-built houses lack design specifications and blindly imitate urban buildings, leading to low thermal performance and significant heating energy consumption problems that are costly and environmentally unfriendly.

In the Guan Zhong region, the average outdoor air temperature of the coldest period (January) is approximately -1.2 °C. Most rural buildings in this region have a three-bay layout, resulting in a space layout that is inadequate for achieving thermal comfort. Additionally, the enclosure walls do not meet the standards, only one mode of heating is used, and the indoor thermal environment is poor. Winter indoor thermal problems in residential buildings have long been prominent worldwide, and related issues have continuously been investigated by academic circles. Figure 1 shows the Guan Zhong region.

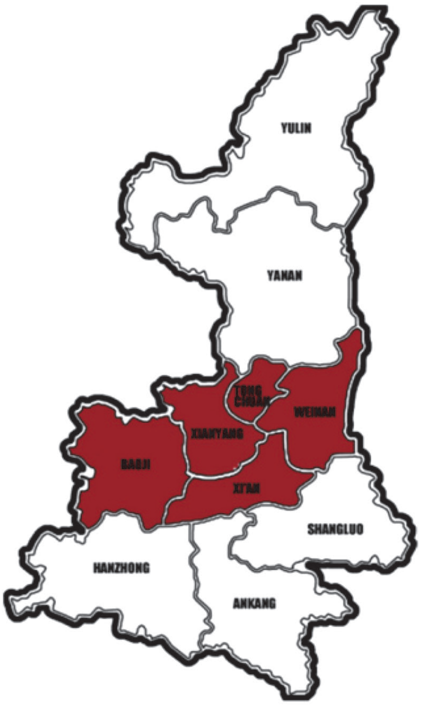

Figure 1. Guan Zhong Region in China

From January 10, 2020, to January 14, 2020, the research group conducted research and tests in Zhouzhi County, Guan Zhong area. Thermal-comfort-related research in the Guan Zhong region has been conducted. Liu et al. analysed problems in the spatial layout of typical rural houses in Guan Zhong [9]. Yang et al. analysed defects in the thermal design of residential building envelopes [10]. Shao et al. implemented optimisation measures such as increasing solar space to save energy [11]. To improve thermal comfort, Yu et al. proposed optimisation measures such as optimising the enclosure structure and designing doors and windows [12]. The authors [13] highlighted the importance of providing users with control over the indoor conditions to improve their thermal comfort. Notably, users of naturally ventilated buildings are more tolerant of indoor thermal conditions compared with those of air conditioned buildings. Most scholars have focused on the causes of thermal discomfort. Optimisation measures are empirical analyses from a certain aspect or angle. Few studies have systematically and quantitatively examined the thermal environment, matching the relevant factors that enhance the thermal comfort of traditional houses.

Maintaining thermal comfort during winter is a major challenge for traditional houses in the Guan Zhong region. To improve thermal comfort within these houses, this study investigates the effects of using passive optimisation techniques and sophisticated insulation materials, such as expanded polystyrene (EPS). The geographical and climatic setting of the Guan Zhong region is crucial for understanding the significance and consequences of this study. The region has a continental monsoon climate marked by clearly defined seasons and substantial temperature differences between summer and winter.

According to [28], this study should improve the characteristics of an office building's building envelope using a simulation-based multi-objective technique. To examine the different options, we used the particle swarm optimization technique. Subsequently, the optimisation outcomes were examined using a sensitivity analysis based on regression. According to the optimisation findings, the annual heating and cooling energy savings for the optimised building were 70 and 40 %, respectively, and the expected proportion of user discontent was 9 %. Gaši et al. examined the impact of perforations and slits on the diffusion of water vapour through expanded polystyrene (EPS) and how the thermal conductivity of the EPS board is affected by the size and quantity of perforations and slits [29]. Variations in the sample thickness, slit spacing, and depth and diameter of the perforations were tested using numerical models (control volume approaches). A numerical model used to compare perforated and non-perforated EPS boards demonstrated that water vapour diffusion may be improved by up to 42.18 % using non-perforated EPS boards. Additionally, this study reveals that the effective vapour diffusion coefficient is thickness-dependent for perforated EPS samples.

The cold weather and distinctive features of traditional homes in the Guan Zhong region, which often use materials such as mud bricks and wood, have been recognised as significant problems in existing studies. Research has often concentrated on recording these architectural traditions and their cultural importance while evaluating fundamental thermal performance traits such as energy consumption and heat loss. Nevertheless, there is a clear lack of knowledge regarding the efficient use of passive optimisation tactics and sophisticated insulation materials to improve the thermal comfort of older homes. Adapting such treatments to the unique requirements and limitations of the Guan Zhong region has received little attention, in contrast to their thorough examination in other settings such as contemporary structures or warmer climates.

A house in the Guan Zhong region was analysed to determine passive design guidelines for traditional houses in the region. Field tests were used to assess the thermal performance of the houses and the willingness of occupants to renovate their homes. A simulation was performed to assess the effects of different passive strategies. These passive design guidelines regarding the thermal satisfaction of occupants led to better thermal performance and reduced energy consumption. Our results align with those of other studies, showing that the thermal comfort of conventional homes may be significantly enhanced by using passive optimisation methodologies and modern insulation materials. Although our analysis adds to the current body of knowledge, it also highlights gaps in the literature regarding the socioeconomic consequences and long-term performance of passive techniques and insulation in traditional houses.

2. Methodology

This study used field measurements, questionnaires, and a simulation software. Passive design strategies were used in the simulation process, such as optimising the space layout, adding thermal insulation to the envelope structure of the building, and using solar energy and natural ventilation. Subsequently, the software compared the original building with the optimised building to determine the differences in thermal comfort. The control variable method systematically compared the effects of each optimisation measure. The simulation results demonstrated that the thermal performance of the traditional houses can be improved by employing various passive design strategies in Guanzhong, China. This study used EnergyPlus, a well-regarded and innovative building energy simulation program. By replicating the physical processes and interactions of a building, EnergyPlus enables an in-depth evaluation of the thermal comfort, HVAC performance, and electric power usage. This simulation program is useful for studying the effect of different materials, division schemes, and passive optimisation strategies on the interior climate and energy consumption.

2.1. Research objectives

An original brick and concrete house, which is a typical local three-bay self-built house in the Guan Zhong region, was selected for study because of its representative architectural style and climate conditions. It was built in 2008 and has two main floors. The heights of the first and second floors are 3.8 and 3.6 m, respectively. The depth of the bay is shown in Figure 2. The wall is a solid clay-brick wall with a thickness of 240 mm. The inside and outside of the walls are plastered without a thermal insulation layer. The heat transfer coefficient is $k = 2.04\ W/(m^2 \cdot K)$. The roof of the house has a double slope without a ceiling or layer for heat preservation. The shape coefficient of the house is approximately 0.52, and the house is north–south oriented. The Window-to-Wall Ratio (WWR) of the south and north walls is 0.27. All the windows are single-glazed wood windows. There is no curtain on the door. A carbon furnace is used for heating. Nanomaterials were added to the walls and roofs of the proposed building. Insulation reduces heat loss well, yet finding an appropriate roof insulation thickness is key to saving money and energy, according to the research. There must be a balance between the insulation thickness and other considerations, including material cost, installation difficulty, and long-term maintenance. The integration of state-of-the-art insulation materials and technology may improve thermal efficiency, leading to more sustainable building designs. The main objectives of this study are as follows:

- To compare the thermal conductivity, resistance, and other pertinent characteristics of modern insulating materials, including aerogels, vacuum-insulated panels, and phase-change materials to more conventional building materials and methods used in the Guan Zhong region.
- To determine the efficacy of advanced insulation materials to prevent heat loss and increase thermal comfort compared to more conventional options such as mud, bricks, and wood.
- To perform an experimental simulation based on metrics such as energy consumption and indoor thermal comfort to improve the indoor space layout, thermal insulation performance of the enclosure structure, and use of solar energy and natural ventilation.

2.2. Questionnaire results

From January 10, 2020 to January 12, 2020 approximately 100 houses were visited in Zhouzhi County in the Guan Zhong region, and information was collected concerning local building form, heating method, transformation willingness, perceived indoor temperature, and perceived humidity through questionnaires and interviews. Eighty-two valid questionnaires were administered. The results of the survey are shown in Figure 2.

The survey results show that 2 % of the residents are unwilling to renovate their homes to improve thermal comfort. Although these residents are not pleased with the indoor thermal performance, some are concerned about the renovation cost and some are averse to damaging the aesthetic of the house. Conversely, 94 % of the residents are willing to improve their houses, which shows little resistance to optimizing the indoor thermal environment in Zhouzhi County. The research shows that 1 % of residents use solar heating, and most rely on non-renewable and environmentally unfriendly heating methods. In addition, the demand for the reduction of greenhouse gas emissions has increased in recent years; therefore, the use of firewood for heating has been restricted. This has led older people to abandon heating owing to poor economic conditions. The results of the indoor humidity analysis show that the perceived indoor humidity is high: 21 % of the residents think that the humidity is high, and 73 % think the indoor humidity is moderate. The analysis of the perceived indoor temperature shows that only 4 % of the residents think that the indoor temperature in winter is acceptable, indicating that the residents believe that the indoor thermal performance of their homes is poor and requires improvement.

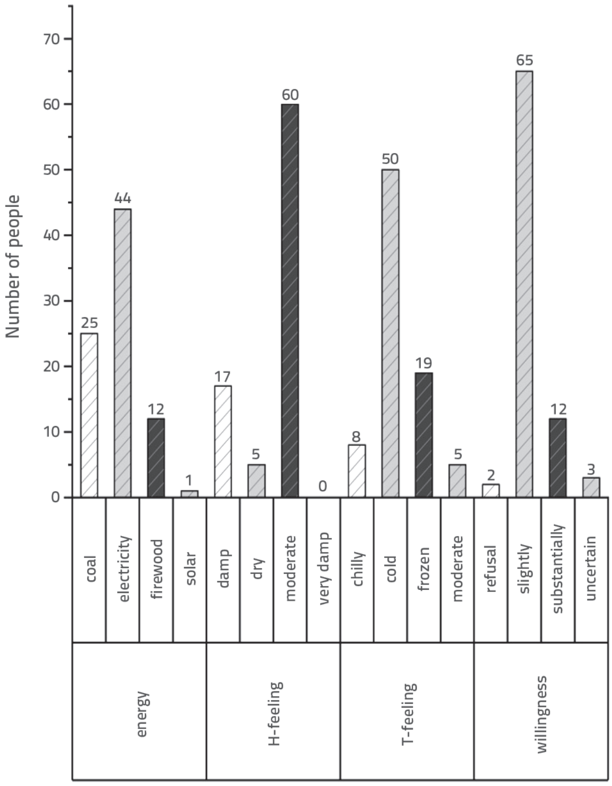

Figure 2. Survey analysis results

3. Field measurements

3.1. Measurements plan

The weather was sunny during the test period from 13 January 2020 to 14 January 2020. The test parameters included the indoor temperature, relative humidity, and outdoor solar radiation intensity during winter. A 175-h1 self-recording temperature and humidity meter with a measurement accuracy of ± 0.2 °C was used for 24 h with a data acquisition interval of 1 h. The measurement points were set in a first-floor bedroom. The height of the indoor measuring point was 0.9 m from the ground, and its distance from the wall was more than 1.0 m. The solar radiometer was set in an open space without shelter, and the data acquisition time interval was 1 h. The plan of the brick-concrete building and the measurement positions are shown in Figure 3.

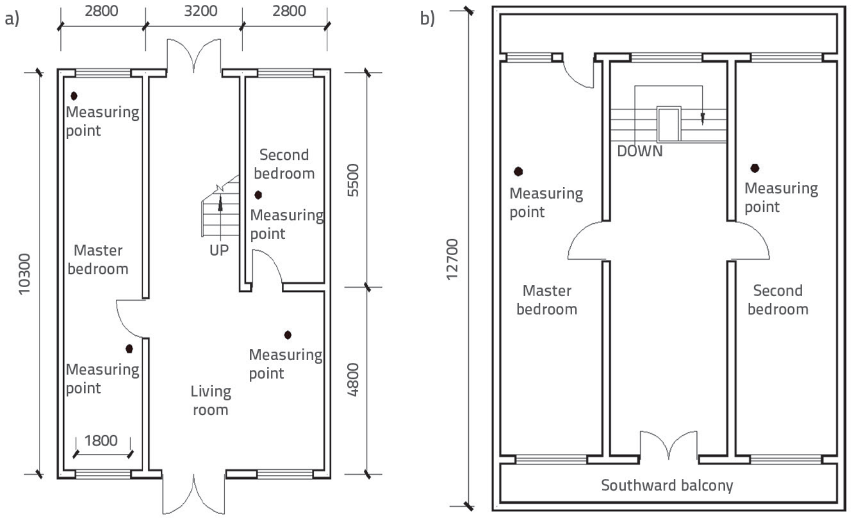

Figure 3. Original space division scheme [mm]: a) Spatial division of first floor; b) Spatial division of second floor

3.2. Intensity of solar radiation

The test lasted approximately 9 h, from 09:00 to 18:00. The maximum solar radiation intensity was 500 W/m². The average intensity was 237 W/m². The proportion of direct intensity was 77.8 %. Therefore, the solar radiation intensity in winter in this region is promising for the development of passive solar heating. The hourly variation curve of solar radiation intensity is shown in Figure 4.

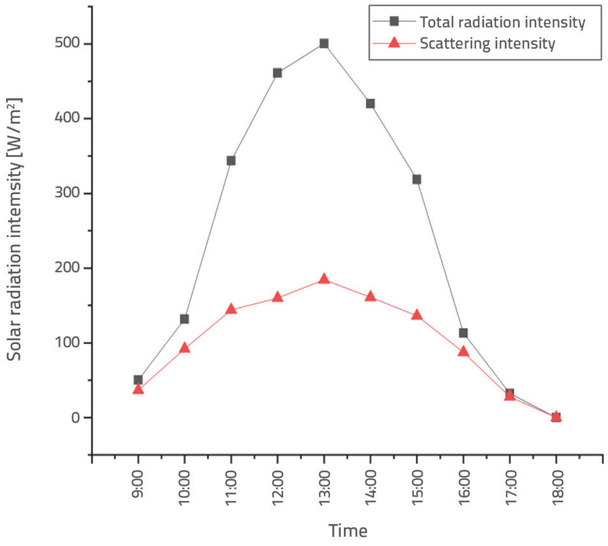

Figure 4. Variation curve of solar radiation intensity

3.3. Humidity and air temperature

The hourly variation curves are shown in Figure 5. The fluctuation range was large in the winter and the relative humidity decreased as the temperature increased. The average and maximum temperature of the first-floor master bedroom was 7.2 and 7.9 °C, respectively. The temperature variation range was 1.5 °C. The average and maximum temperature of the second-floor master bedroom was 7.2 and 8.3 °C, respectively. The temperature variation was 2.0 °C. The humidity distributions during the first and second periods were 47 and 46.5 %, respectively. However, this difference is not statistically significant. According to the test results of the second-floor master room, the maximum temperature was slightly higher than that of the first-floor master room, but the average temperature was the same. The temperature variation of the second floor increased, indicating that the thermal stability of the second floor is worse than that of the first floor. The hourly variation curves of temperature and humidity in the first- and second-floor master bedrooms are shown in Figure 5.

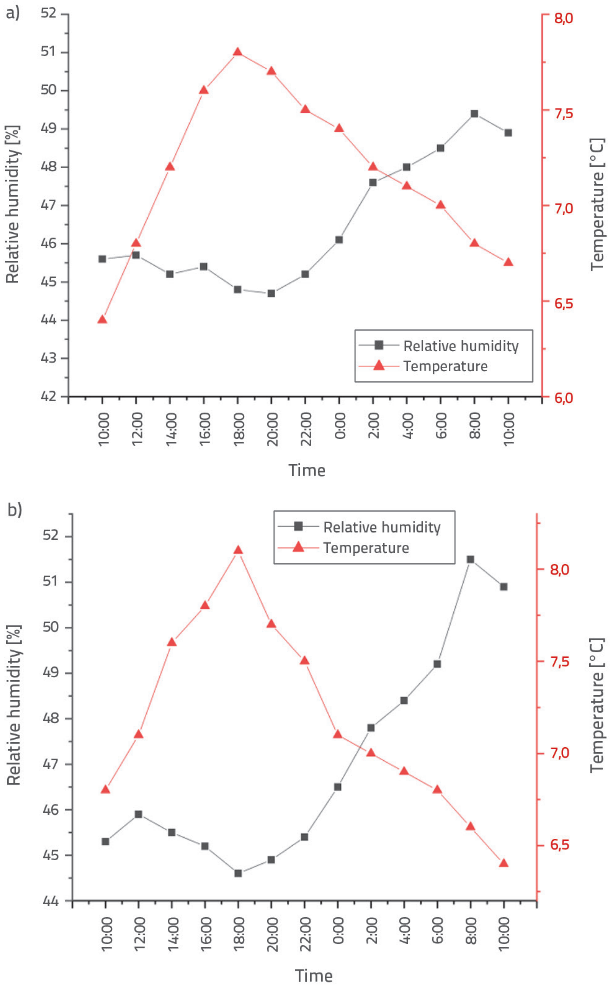

Figure 5. Hourly variation curves of temperature and humidity: a) First-floor room; b) Second-Floor room

The thermal data were collected from four strategically placed measurement locations. Locations near the outside walls, interior partitions, and floor centre were all considered when selecting these locations to depict different microenvironments. Two measurement units were placed on the second floor. These locations were chosen to track the temperature changes and thermal comfort at various elevations and orientations with respect to the outside walls and windows.

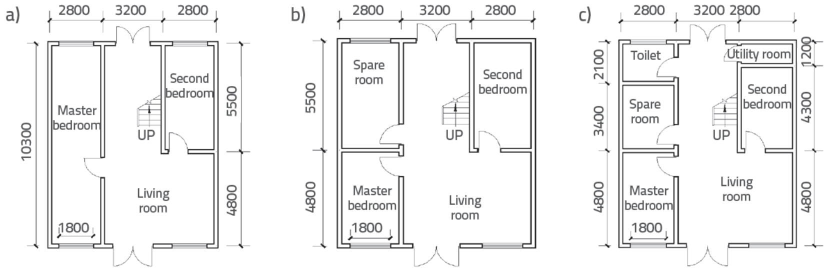

Figure 6. Division Scheme of the First Floor Space: Conditions A, B, and C

3.4. Analysis of existing problems

The original building is a typical three-bay building, which lacks a reasonable space separation scheme, and there is no north–south division of the bedrooms. The opening and depth of the rooms are very large, and the floor height is very high. Under these conditions, a comfortable indoor temperature is difficult to obtain. For the enclosure structure, the external wall comprises a 240-mm clay brick, and the inside and outside of the wall are plastered without thermal insulation. The roof is a double slope roof without a ceiling, and the wood and tile materials have poor thermal performance. The external windows are single glass windows, with poor airtightness and thermal insulation performance. The residents are accustomed to opening the door, and do not have a cotton curtain set up. The heat transfer coefficient of each link of the enclosure wall in cold areas is far less than the standard requirements, and substantial heat is lost through the wall, which is unfavourable for thermal insulation in winter.

A single mode of heating is used in this area, and solar energy cannot be used for passive heating under certain conditions. These houses rely heavily on electrical energy, coal, and firewood. However, these heating methods consume large amounts of energy, and are costly and environmentally unfriendly.

3.5. Optimization simulation analysis

3.5.1. Energy saving optimization scheme

An optimisation scheme was implemented to reflect the reality as closely as possible. The existing rural economic conditions was also accurately reflected and the optimisation measures were implemented according to these conditions. Because of the existing problems, this study proposed optimisation strategies based on three aspects: space division, thermal insulation performance of enclosure structure, and additional sunlight rooms.

The simulation software adopted was the mainstream thermal calculation software Ecotect 2011. Based on the control variable method, the advantages and disadvantages of the scheme were compared stepwise to ensure that the simulation results were reliable.

3.5.2. Optimization of spatial layout

Based on the basic space division of existing buildings in the Guan Zhong region, three suitable spatial division modes were determined, as shown in Figure 6. Condition A is the original layout of the building. Condition B contains a north–south division of the west main bedroom on the first floor, whereas condition C adds more auxiliary rooms in the north–south dimension. When the three schemes were simulated, the second floor was set according to Figure 2.b for comparison.

The simulation time set by the software was consistent with the test time, and the meteorological conditions in Xi'an, Shaanxi Province were selected. According to the clothing of the residents and [14], the average clothing thermal resistance value of indoor personnel in winter was set to 2.5 clo, and the indoor humidity was set to 47 %. The indoor air change frequency was set as 0.5/h, and under the default conditions of the weather tool, the human activity was set to sit. However, when the WWR was set to 0.5, the thermal insulation of the enclosure structure and solar-heating efficiency were to low levels. The specific operational processes and parameter settings were combined [15]. The simulation results of the building energy consumption under different space division modes are shown in Figure 7.

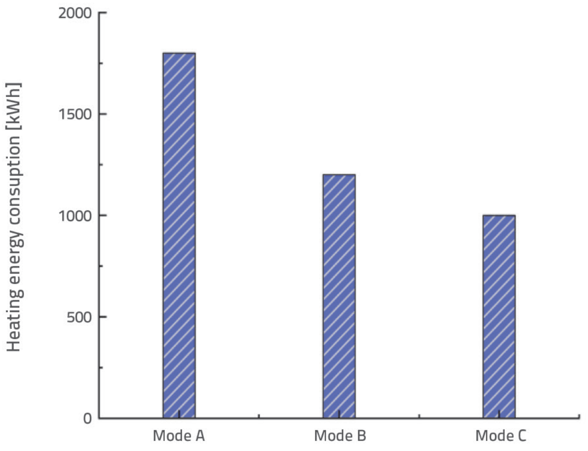

Figure 7. **Heating energy consumption simulations under various space-division schemes**

Table 1. Demographic information and thermal comfort indicators for traditional houses in the Guan Zhong region of Shaanxi Province

Participant ID	Age	Gender F/M	Occupation	Building type	Indoor temperature [°C]	Humidity [%]
1	45	Ž	Farming/Agriculture	Single-story mud-brick	18	50
2	30	M	Business	Multi-story wooden	20	45
3	55	M	Construction/Manual labor	Labor courtyard-style	16	55
4	65	Ž	Homemaker	Single-story mud-brick	17	60
5	20	M	Student	Multi-story wooden	19	40
6	35	Ž	Farming/Agriculture	Courtyard-style	18	55
7	50	M	Business	Single-story mud-brick	16	50
8	60	M	Construction/Manual labor	Multi-story wooden	17	45
9	40	Ž	Homemaker	Single-story mud-brick	21	42
10	35	Ž	Student	Labor courtyard-style	19	48

The researchers chose participants from the target population using a mix of a stratified selection and convenience sampling. Convenience sampling was used to identify individuals interested in participating in the study. This method allows useful data to be gathered while maintaining strict time and resource limits. Stratified sampling guarantees that all demographics, geographic regions, and typical home types (e.g. single story vs. multi story, north facing vs. south facing) are represented. The findings should be generalisable to a larger population, and this stratification aids in capturing variability. Table 1 shows the demographic information and thermal comfort indicators of the traditional houses in the Guan Zhong region of Shaanxi Province.

The simulation results revealed that multi-space division could significantly decrease the heating energy load. Reference [16] indicated that the indoor temperature of the main rooms can be improved by setting partition walls. The south-facing wall received solar radiation; therefore, the main room was positioned in the southern direction. A secondary room was arranged in the north to form a temperature buffer zone. The temperatures of the main rooms in the southern direction were maintained at high levels. The change from condition A to condition C increased the average hourly temperature of the first-floor master bedroom by approximately 1.2 °C. The simulation results show that condition C was the most heating energy efficient.

Dividing a building into several thermal zones allows targeted heating and cooling. One way to minimise the total energy required for climate management is to keep sections utilised less frequently at lower temperatures. Mechanical ventilation may be unnecessary in an open-floor design because of the improved air movement. However, energy consumption can increase in cramped, divided rooms because of the need for more ventilation and, perhaps, individual HVAC systems. Artificial lighting is minimised using division designs that optimise the entry of natural light. Spaces with heavy partitioning may require more artificial light, thus increasing the energy usage, whereas open layouts with strategically placed windows and skylights can maximise daylighting. The space-division scheme of the subsequent analysis adopted condition C. The final scheme is shown in Fig. 7. The original bedroom had no north–south divisions. The original master bedroom was divided into three parts, as shown in scheme C. The first floor retains its original function with

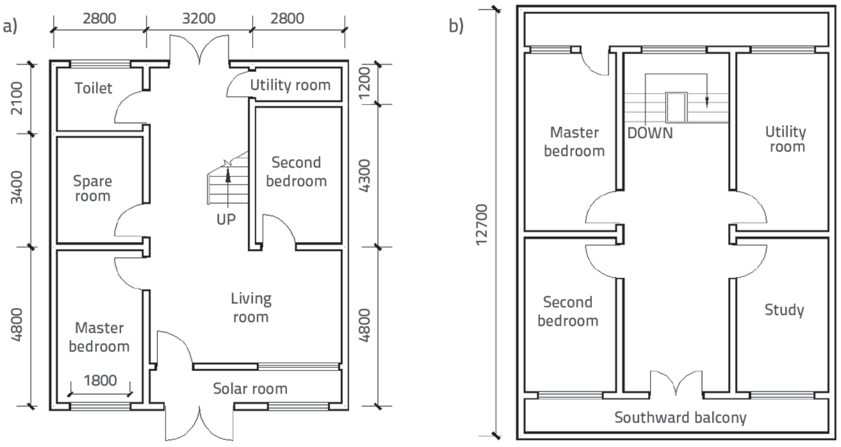

Figure 8. Optimized space division scheme [mm]: a) Plan of the first floor; b) Plan of the second floor

an additional kitchen, toilet, and storage room to improve functionality. To increase the differentiation of the small spaces and achieve thermal insulation, the concept of "room in room" is implemented as a temperature transition zone to prevent heat loss. Therefore, a reasonable indoor space division can improve the room temperature. In the architectural layout, the kitchen and Kang room are adjacent. A Kang room is a heat source that radiates and convects heat [17]. This type of space division scheme does not change the shape coefficient of the building and avoids concave-convex changes to the layout. The subsequent analysis was optimised based on the spatial division scheme shown in Fig. 8.

3.6. Optimization of enclosure structure

The enclosure structure included exterior walls, roofs, doors, and windows.

3.6.1. External walls

The wall is the main component of the building envelope, and its thermal performance significantly influences the heat loss and indoor temperature. According to [18], the equal heat transfer coefficient method should be used to simplify the exterior wall structure design. In schemes A, B, C, and D, the thickness of the insulation layer is gradually increased. Table 2 lists the calculation models of the exterior wall structure.

Note: The thermal parameters of the materials were obtained from [19], and the heat transfer coefficient was obtained from [20].

The four wall materials were inputted into Ecotect 2011 with unchanged model parameters. The results for the different wall structures are shown in Figure 9.

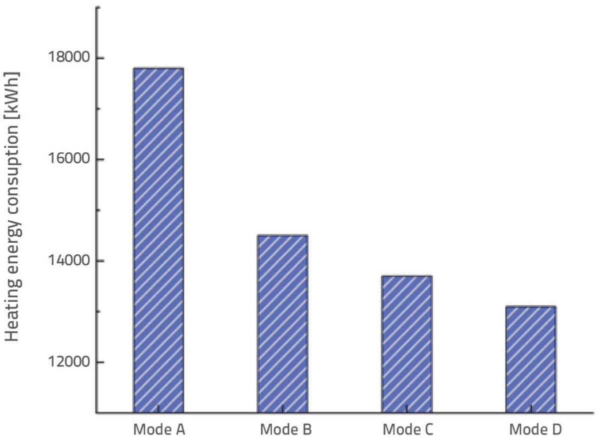

Figure 9. Simulation results of energy consumption for different wall structures

As the amount of insulation increases, the energy-consumption rate decreases. This indicates that the primary task should be to increase the wall insulation.

Table 2. External wall construction model parameters

Methods	Material	Thickness [mm]	Thermal conductivity [W/(m·K)]	Dry density [kg/m^3]	Specific heat [J/(kg·K)]	Thermal resistance [K/W]	Heat transfer coefficient [W/(m^2·K)]
Method A	cement mortar	20	0.930	1800	1.05	0.022	2.04
	clay brick	240	0.810	1800	1.05	0.296	
	cement mortar	20	0.930	1800	1.05	0.022	
Method B	EPS	50	0.041	20	1.38	1.220	0.59
	clay brick	240	0.810	1800	1.05	0.296	
	cement mortar	20	0.930	1800	1.05	0.022	
Method C	EPS	60	0.041	20	1.38	1.463	0.52
	clay brick	240	0.810	1800	1.05	0.296	
	cement mortar	20	0.930	1800	1.05	0.022	
Method D	EPS	80	0.041	20	1.38	1.951	0.41
	clay brick	240	0.810	1800	1.05	0.296	
	cement mortar	20	0.930	1800	1.05	0.022	

When selecting a structure, the cost should be considered simultaneously; thus, method B was selected for subsequent simulation calculations.

Method A represents a traditional wall structure with cement mortar and clay bricks without additional insulation. This model likely shows a higher heating energy consumption owing to its lower thermal resistance and higher heat transfer coefficient. Method B incorporated 50 mm of EPS insulation, which significantly improved the thermal resistance and reduced the heat-transfer coefficient. This model shows lower heating energy consumption than Method A, owing to improved insulation. Method C used 60 mm of EPS insulation, further enhancing the thermal resistance and decreasing the heat transfer coefficient compared to Model B. This results in an even lower heating energy consumption than that of Methods A and B. Method D incorporated 80 mm of EPS insulation, offering the highest thermal resistance and lowest heat transfer coefficient among all models. This model exhibits the lowest heating energy consumption owing to its superior insulation properties.

3.6.2. Roof

Based on the original roof, the energy consumption was simulated by changing the thickness of the thermal insulating layer. These parameters are listed in Table 3. The results are shown in Figure 10.

Table 3. Model of roof insulation thickness

Roof insulation thickness [mm]	**Energy consumption** [kWh]
0	13000
20	10000
40	9000
60	8800
80	7000

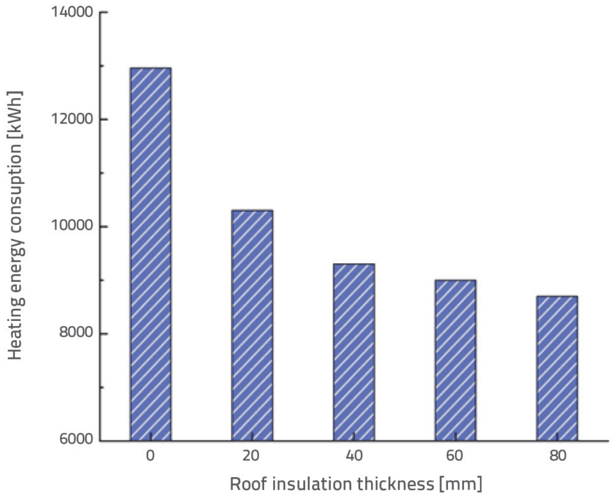

Figure 10. Simulation results of energy consumption for different roof insulation thicknesses

The results indicate that increasing the thickness of the roof insulation layer results in lower gains in the energy-saving rates. The final roof insulation method was a flat tile surface, 40-mm EPS extruded board, waterproof layer, cement mortar levelling layer, and roof panel. The heat transfer coefficient of the roof is approximately 0.590 W/(m²·K). A sloped roof panel can be combined with a light ceiling to form a closed-air interlayer, which is more conducive for winter insulation.

The lap joint of the ceiling has an opening that can be opened or closed. In summer, ventilation can be improved and indoor heat can be removed. The subsequent optimisation was based on the above contents. Several thicknesses of the EPS insulation were investigated to minimise the heat loss without compromising cost-effectiveness. Concrete, clay tiles, metal, and other roofing materials have been tested for their thermal performance and compatibility with EPS insulation. Researchers have examined the effects of reflective coatings on roofs to determine how well they lower heat absorption and increase energy efficiency. Roof vents, ridges, soffits, and gables were examined to determine how they affected the thermal comfort and energy use within the building. Furthermore, research has been conducted on the insulating qualities, heat loss mitigation capabilities, and interior temperature regulation possibilities of green roofs (roofs covered with plants).

3.6.3. Transparent enclosure

The transparent envelope in a building is an important source of solar radiation and the main way that buildings lose heat; therefore, their thermal performance is very important [21]. The thermal performances of three typical external windows are listed in Table 4. Single glass windows are used in most of the traditional houses. The energy loads of the three types of external windows were simulated using the Ecotect software. The WWRs of the south and north were set to 0.5 and 0.27, respectively. In terms of the exterior window materials, considering their comprehensive performance, plastic steel windows were selected from wood, plastic steel, and bridge-breaking alloys. Plastic steel costs significantly less, and its excellent heat preservation and airtightness can be achieved at a relatively low cost. The calculation model information for the different external window structures is presented in Table 4. Several glazing types were evaluated to determine their effects on the thermal insulation and solar gain. These include single-, double-, and triple-glazing. This study examined the thermal performances and energy efficiencies of several frame materials, including wood, aluminium, and uPVC. The thermal comfort was studied by placing windows on several faces (north, south, east, and west) to examine the effects of solar gain and shade.

Table 4. Calculation model information under different external window structures

External window structures	Single glass	Double glass	Low-E window
Methods	6 mm glass	6 mm glass	6 mm Low-E glass (Radiation rate 0.25, arranged inside)
		10 mm air layer	10 mm air layer
			6 mm glass
Heat transfer coefficient [W/(m²K)]	5.70	3.00	2.30

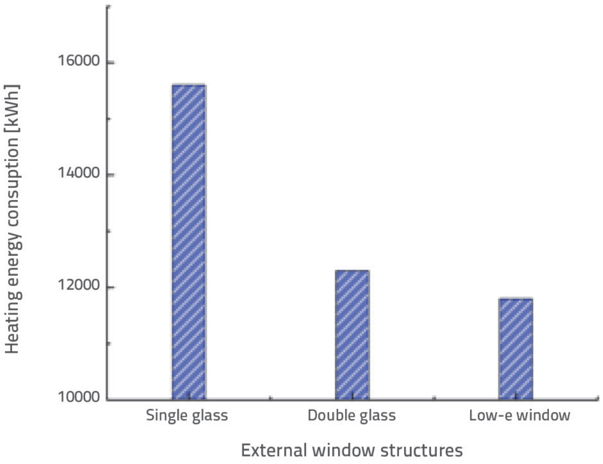

Figure 11. Simulation results of energy consumption under different external window structures

The simulation results for energy consumption under different external window structures are shown in Figure 11. The single-glass window had the worst thermal performance and highest energy consumption. A single-glass window has a large heat transfer coefficient and poor airtightness. In winter, the indoor heat loss through these windows is large. The energy consumption of double-glass windows is significantly lower than that of single-glass windows, and the energy consumption difference between glass windows and low-E windows is small; therefore, the thermal performance of windows can be improved to reduce cold air penetration and heat loss significantly, and the hollow structure can also improve the sound insulation performance. Therefore, the first energy-saving strategy for external windows involves the replacement of single-glass windows with double-glass windows. We can also consider hanging a cotton curtain on a door during the winter. Heat loss, which is a part of the indoor and outdoor heat exchange, can be effectively reduced in doors and windows through the above methods.

3.6.4. Window-to-Wall Ratio (WWR)

The original WWR was 0.27. Referring to [22] for rural residential buildings in cold areas, the south-facing window ground ratio was set to 0.5. To simplify the working conditions, the WWR in the north was set to 0.27. The results of the energy loads under various WWRs are shown in Figure 12. The results show that increasing the ratio of south-facing windows to the ground could significantly reduce energy consumption, and that a large area of south-facing windows could increase the temperature of the main rooms facing south.

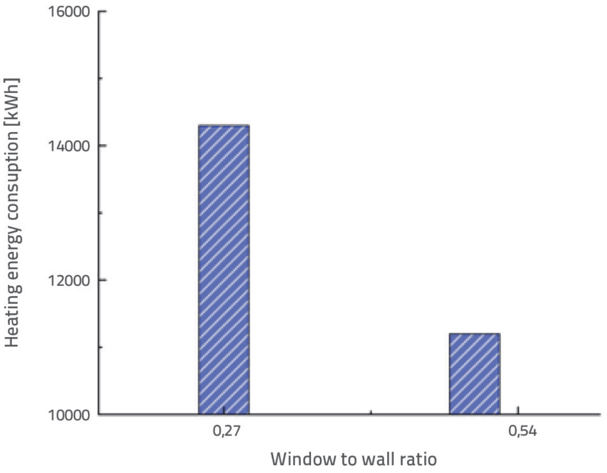

Figure 12. Simulation results of energy consumption under different window-to-wall ratios

3.7. Passive solar heating

The test results indicate that solar heating in this region is promising. Solar energy can reduce the dependence of the residents on firewood and significantly reduce non-renewable energy consumption [23, 24]. However, the survey results also show that only 1 % of residents used solar heating equipment. Considering the local economic situation, passive solar heating is the best choice for improving thermal comfort. Adding a sunlit room is the first choice for the development of passive solar heating [25, 26]. To do this, in the model, an additional sunshine room was set up in the living room, with a regular architectural shape that does not change the shape coefficient of the house. In addition, the depth of sunlight affects the heat collection effect and room use. In this study, energy consumption at different sunlight depths was simulated. A section diagram of the model is shown in Figure 13, and the marked position in the figure is a sunlit room. The calculation model information for different sunshine depths is listed in Table 5. The simulation results are shown in Figure 14.

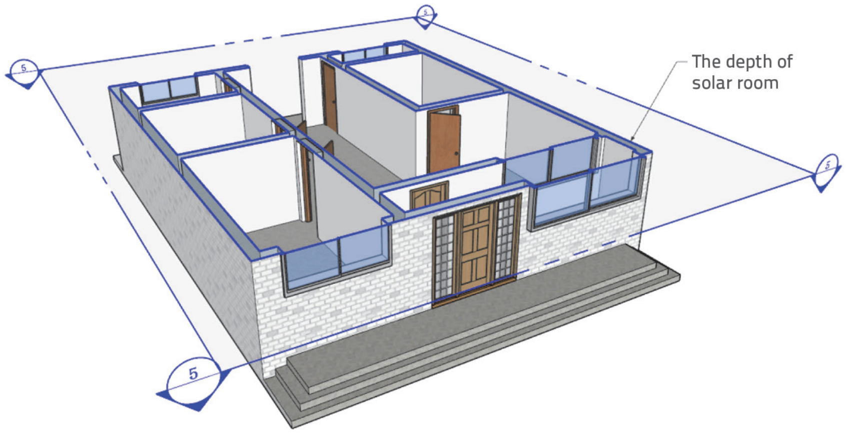

Figure 13. Location of additional sunlight in the section

Table 5. Model information for different sunshine depths

Window	The depth of solar house [m]				
Plastic steel double glass window	0	0,6	1,2	1,8	2.4

Table 5 and Figure 14 present the simulation results, which indicate that the energy load tends to be the lowest when the depth is 0.6 m. Increasing the depth of sunlight means that the heating energy consumption is no longer reduced, showing an increasing trend. When the depth was set at 1.2 m, the low energy consumption was maintained and the requirements of the function and cost were satisfied.

The wall between the additional sunlight space and the living room can play a role in heat storage. Trombe walls were used and openable vents were set at the bottom and top. The air in the sunlight room was then heated. The ventilation holes were opened during the day. When heated, the air is lifted and flows into the room through an airport. The cold air in the living room flows into the sunlight room through the lower vent, forming a cycle. The vents were closed at night, and the stored heat was released to heat the room.

To cope with overheating in a sunlight room in summer, the glass in the sunlight room can be opened as a vent. The pebbles can be removed in summer, and the louvres can be shaded to prevent overheating. In the optimised scheme, the relative positions of the doors and windows are conducive to natural ventilation and removal of indoor heat. Therefore, an openable vent was set on the external wall under the cornice, which can be opened in summer and closed in winter.

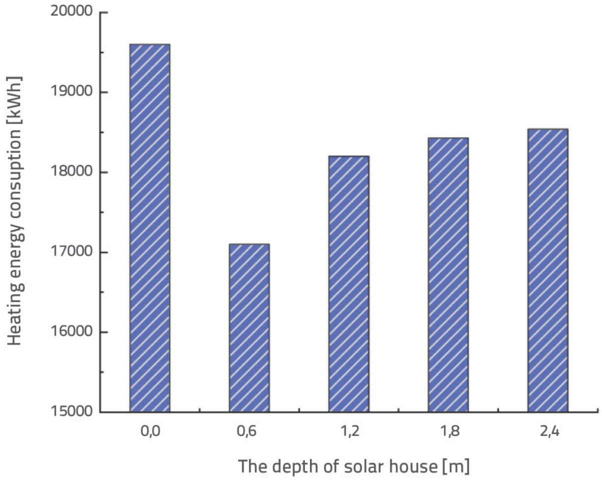

Figure 14. Simulation results of energy consumption under different depths of sunshine room

As the height of the first floor of the building is 3.8 m, a 10 mm PVC ceiling was placed at 3.0 m in the master bedroom to reduce the room volume and heating difficulty. A section diagram of the optimised brick-concrete residential building is shown in Figure 15.

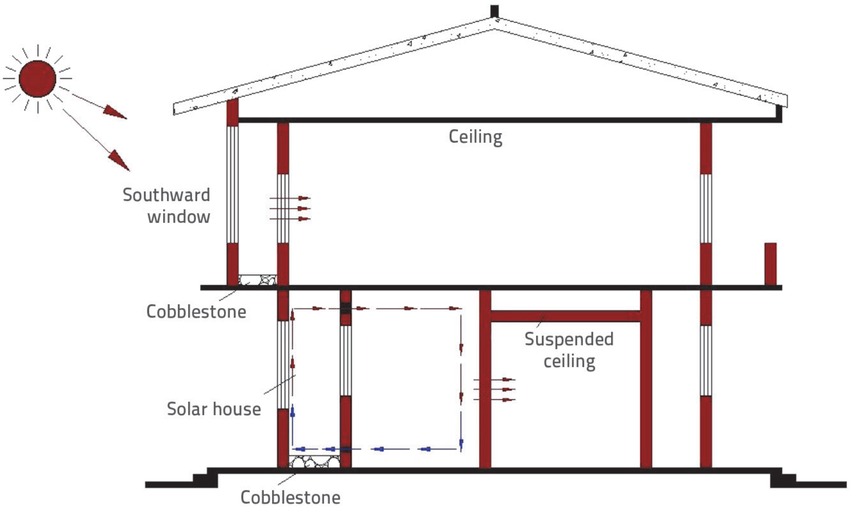

Figure 15. Sectional view and indoor ventilation of residences after optimisation

3.8. Simulation of final scheme

A summary of the improved model practice information is provided in Table 6, and the final rendered image is illustrated in Figure 16.

scheme could significantly enhance thermal performance. Simulations and comparisons were performed before and after optimisation. The simulation time set by the software was consistent with the test time, and the meteorological conditions in Xi'an of Shaanxi Province in the database were selected. The average clothing thermal resistance value was set

Table 6. Improved model information

Position	Summary of model setting information after optimizing
Space division	Multi-space division mode C / the main rooms are set in the south, and the secondary rooms are set in the north / "Stove with Kang" (A traditional heating method in North China)
Exterior wall	50 mm EPS + 240 mm clay brick+20 mm cement mortar, Heat transfer coefficient is 0.59
Window	6 mm glass + 10 mm air layer+6mm glass plastic steel double glass window, Heat transfer coefficient is 0.30
Window-to-wall ratio	South: 0.5; North: 0.3
Roof	Plain roofing tile + 40 mm XPS + waterproof layer + cement mortar levelling course roof slab, heat transfer coefficient is 0.59 Lightweight suspended ceiling under a sloping roof slab
Door	Add cotton curtain
Solar house	Depth:1.2 m / add Trombe wall/heat storage materials/set blinds
Master bed-room	10 mm PVC ceiling is set at 3.0 m

as 2.5 clo, the indoor humidity was set as 47 %, the indoor wind speed was set as 0.5 m/s, and the indoor air change frequency was set as 0.5 times/h.

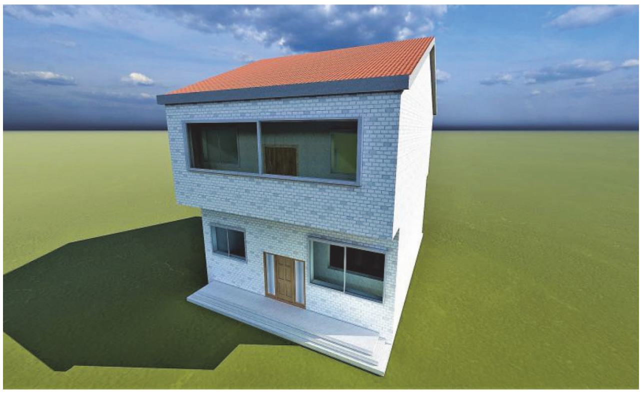

Figure 16. Rendering of optimised house

The Ecotect thermal model was established to verify whether the reconstruction

Under the default conditions of the weather tool, the human activity was set to sit still, south WWR was set to 0.5, north WWR was set to 0.27, envelope insulation was set to medium, and solar heating efficiency was set to high. The simulation results are shown in Figure 17. T-tests were used to compare the means of the two groups and ascertain whether there was a statistical difference between them. Using the given dataset, t-tests can be used to compare thermal comfort indicators (such as interior temperature, humidity, and comfort rating) across various demographic groups. One possible use of t-tests is to compare gender or age groups with respect to the mean indoor temperature.

Thermal comfort can be improved by adopting reasonable space division, optimising the thermal performance of the enclosure structure, and using proper passive solar heating. According to

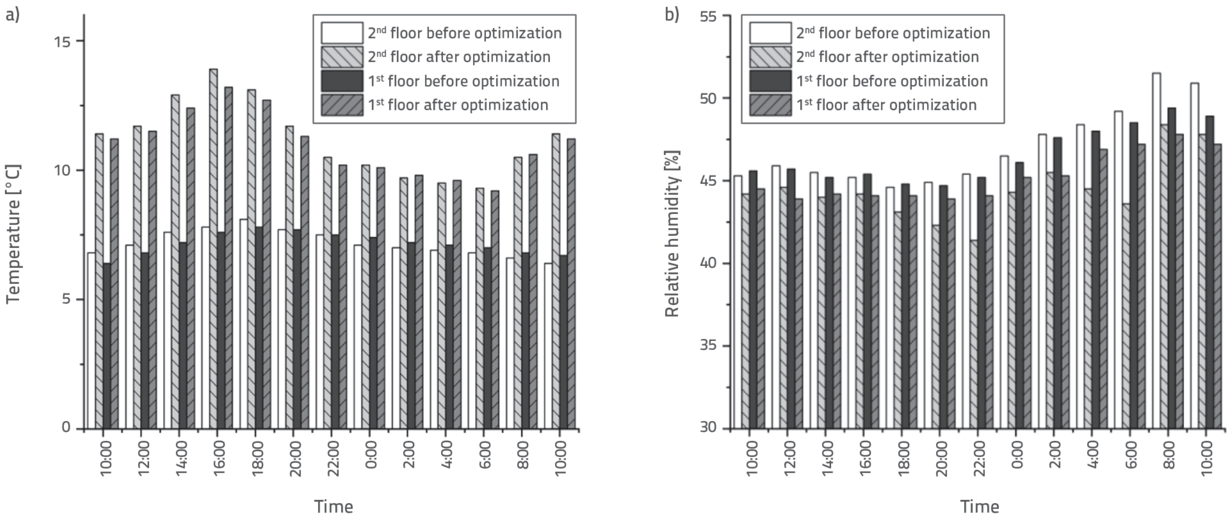

Figure 17. Comparison of temperature and humidity of master bedrooms before and after optimisation: a) Temperature comparison chart of master bedroom; b) Humidity comparison chart of master bedroom

the reference, this includes a direct-benefit solar house, a kang room, and an additional sunshine room in the living room. After calculation, the average temperature of the first- and second-floor master bedrooms were 11.0 and 11.2 °C, which increased approximately 4 and 4.2 °C, respectively. The room comfortable temperature in winter varies from 18 to 28 °C, and there is a gap between the above simulation results and the comfortable temperature. If passive solar heating is used and the heat source is supplemented, such as by considering the contributions of the kitchen stove and Kang, it may be easier to reach a comfortable temperature range. According to [27], the relative humidity for indoor comfort ranges from 30 to 70 %; thus, the relative humidity achieved is comfortable. Because temperatures often drop below freezing throughout the winter in this region, well-insulated and heated spaces are essential for year-round indoor comfort. However, owing to the large variations in temperature between the day and night, maintaining constant interior temperatures is more challenging.

4. Final discussion

To explore the effects of the design scheme, the control variable method was used to compare the effects before and after improvement. A passive design strategy was adopted based on field tests and questionnaire results. The best strategies were determined from the passive design strategy analysis, which included improving the space layout, enclosure structure, window-to-wall ratio, and ventilation, and constructing a sunshine room. Because the main problem in this region is heat preservation in winter, ventilation in summer is not discussed. However, the ventilation optimisation measures that were added to the passive design took into account heat protection in summer. The above measures aimed to improve the comfort of traditional houses based on the acceptable transformation willingness of residents. This scheme can provide references and tests for a new national rural construction process. The efficiency of the proposed method was compared with that of an existing simulation-based multi-objective technique (SMOT) [28]. The proposed method achieved a high efficiency of 98.4 %.

5. Conclusion

This study introduces a comprehensive passive optimisation strategy for traditional houses in the Guan Zhong region. Field tests and analysis revealed that the thermal comfort is poor, the spatial layout is inadequate, the thermal properties of the enclosure walls are unideal, and the mode of heating is inefficient. The questionnaire results show that the residential space division is simple, the envelope structure performance is poor, only one mode of heating is used, the room's thermal comfort does not meet the requirements, and the majority of residents have a strong desire to optimise the thermal comfort of their homes. The test results show that the solar radiation intensity is considerable in the Guan Zhong region in winter, and passive solar heating can be developed. The results also revealed that the thermal storage performance of the building envelope was unsatisfactory. During the test period, the indoor temperature remained far from the comfortable range of thermally heated rural residential living rooms in cold areas. Based on the control variables, the energy consumption simulation verified that a multi-space division, insulation of the exterior wall and roof, double-glass windows, and a Trombe wall-type additional solar room can significantly reduce the energy load and improve the room temperature. Simulations and comparisons were performed before and after optimisation. The simulation time set by the software is consistent with the test time, and the meteorological conditions in Xi'an of Shaanxi Province in the database were selected. The average clothing thermal resistance value was set as 2.5 clo, the indoor humidity was set as 47 %, the indoor wind speed was set as 0.5 m/s, and the indoor air change frequency was set as 0.5 times/h. Under the default conditions of the weather tool, the human activity was set to sit still, south WWR was set as 0.5, north was set to 0.27, the envelope insulation was set as medium, and the solar heating efficiency was set to high. The final scheme was simulated using computer software. The average temperature of the first and second floors increased by approximately 4 and 4.2 °C, respectively. The simulation results verified that the thermal performance of the proposed envelope and space division improved. When combined with an active heat source, the temperature was closer to the lower limit of the comfortable temperature range. Improvements in thermal comfort can be achieved via passive optimisation strategies and modern insulation materials in traditional houses. This can improve the thermal comfort of houses, which is particularly helpful in winter. Homeowners may reduce their environmental impact by maximising insulation and passive techniques, thus decreasing the need for heating systems. In addition to helping achieve broader energy efficiency targets, this has significant cost-saving implications.

This study analyses the indoor thermal comfort, thermal gain, and energy loads of traditional houses using building nanomaterials. However, factors such as microclimate changes, unexpected weather patterns, and distinctive architectural aspects of particular houses were generalised. Future studies should investigate the long-term durability and maintenance requirements of nanomaterials such as aerogels and phase change materials (PCMs) under varying environmental conditions.

Acknowledgements

This work was funded by NSFC (No. 52078419).

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