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Quality Analysis on Indoor Thermal Comfort and Energy-Saving Improvement Strategy of Slate Dwellings, China

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Abstract: Slate dwellings are known as the "living fossil of primitive dwellings" in China. Energy-saving strategies are crucial to slate dwellings for sustainability as well as maintaining thermal comfort. In this research, a subjective satisfaction analysis on the indoor thermal environment in Daziliang village, China, was conducted. It was found that neutral temperature is 20.92 °C in summer, 8.92 °C in winter, and the actual operating temperature in winter is too low to meet the 80% acceptable range. Therefore, a series of improvement strategies in winter were proposed. The results showed that adding external thermal insulation material—expanded polystyrene board with a thickness of 80 mm on the roof and outside walls—and sunspace depth of 1.5 m are better in terms of energy-saving effects. In addition, the slate dwelling's daily energy-saving rate of the heating day is 44.26% lower than the original state through these strategies. The air temperature of Bedroom D in winter non-heating days increases by 3.82 °C after improvement and the mean radiant temperature increased by 2.54 °C. Our approach puts forward specific energy-saving improvement measures and provides feasible suggestions for the protection and development of slate dwellings in this area.

Keywords: slate dwellings; thermal comfort; energy-saving improvement measures; thermal environment

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1. Introduction

The building sector accounts for approximately 40% of energy consumption and 36% of carbon dioxide emissions [1]. Facing the energy and climate crises, reducing building energy consumption has become a consensus among researchers [2,3]. Most modern architecture requires high energy consumption to maintain a comfortable indoor environment. Heating and cooling of residential buildings consumes about 10% of the world's energy [4]. In this context, vernacular architecture, adapted to local climate and materials, has been considered as a potential approach to reduce energy consumption while maintaining a comfortable indoor thermal environment [5,6]. However, most vernacular buildings are self-built based on traditional experience without scientific and technical guidance and still cannot meet residents' requirements according to some research [7–9]. Therefore, energy-saving design strategies that could improve thermal comfort in combination with the current vernacular residential buildings have gained the attention of scholars.

1.1. Previous Studies

The majority research has analyzed improvement in energy performance in urban historic buildings [10]; whereas there is much less research on rural areas [11]. Zhang et al. found that adobe dwellings hold poor indoor thermal comfort and heat transfer coefficients of walls and roofs, and conducted three different schemes for improving thermal comfort and reducing energy consumption [12]. Similarly, Alev et al. proposed three renovation strategies: minimal influence on appearance, improvement of thermal comfort, and improvement in building service systems to achieve energy-saving targets in historical dwellings. Additionally, the authors also found that insulation of external walls has the largest energy-saving potential due to the high thermal conductivity and large area [12].

In conclusion, the measures commonly used in rural areas could be summarized as follows: (1) Envelope renovation: the improvement in thermal performance of rural residential buildings is an effective method, but the cost is higher and the energy-saving rate is lower [13–15]. (2) Shape coefficient: it has a certain influence on thermal environment and energy consumption [16,17]. (3) Sunspace: it could minimize the use of fossil fuels and increase the utilization of solar, etc. [18–21].

However, residents have strong climate adaptability and could improve indoor thermal comfort by adaptive behavior [22–24], resulting in different energy consumption. Therefore, quantification of thermal adoption is the basis for the study of energy-saving-oriented thermal environment enhancement in traditional rural dwellings. In recent years, many studies have explored the energy-saving potential of buildings through adaptive thermal comfort studies [19,25]. Nevertheless, most of them proposed systems setting temperatures based on neutral temperature and lack building improvement strategies based on actual situations, which is indispensable due the rare use of HVAC systems in rural areas [15,26].

1.2. Motivation

China, a large agricultural country with 45% of the population and 60% of the built-up areas in rural areas [27], whose vernacular architecture and people adapt to local climate in their own unique way [28]. With the resident living standard improving, the requirement for thermal comfort is increasing which is reflected in energy consumption per unit floor area rising from 3.02 kWh/m^2 in 2001 to 13.23 kWh/m^2 in 2017 [4,29–31].

Slate dwellings located in the mountainous area of southern Shaanxi are examples of Chinese material cultural heritage with strong artistic and preservation values. The earliest and best-preserved ones in this area were built in the Yuan Dynasty [32]. Most of the current research on slate dwellings focuses on ecological concepts and construction methods [33,34]; however, there is still a lack of quantitative analysis on thermal comfort and energy-saving strategies. Through field investigation, unfortunately, it is found that low temperature and high humidity are common problems of slate dwellings in winter. For sustainable development of slate dwellings, as well as livable indoor environments of local people, energy-saving strategies based on quantification of thermal adaption is necessary.

Therefore, the purpose of this study is to conduct a thermal comfort field study in slate dwellings to investigate the current state of the local thermal environment and put forward energy-saving improvement strategies. This research contributes to improvement of living quality in mountain areas and could guide the development of traditional dwellings.

2. Thermal Comfort Investigation and Research

2.1. Geographical Location and Climatic Characteristics

The slate dwelling is located in the Daziliang village, Shipo Town, Luonan County, Shangluo City, Shaanxi Province, China. It is between 33°52′00″ and 34°25′58″ north latitude and between 109°44′10″ and 110°40′06″ east longitude. This area shows a mountainous landform in the connection of river and hills. Figure 1 shows the location, layout, and the surrounding environment of the slate dwellings. The Luonan County has remarkable mountainous climatic characteristics, belonging to the cold region in China, with an annual average temperature of 7.8~13.9 °C, maximum air temperature of 37~40.8 °C, and minimum air temperature of −11.8~−21.6°C. The average annual precipitation in this area is 710~930 mm. The annual mean sunshine duration is 1860~2130 h. The temperature is suitable in spring and autumn, high in summer with large quantities of precipitation, and cold in winter with high air humidity.

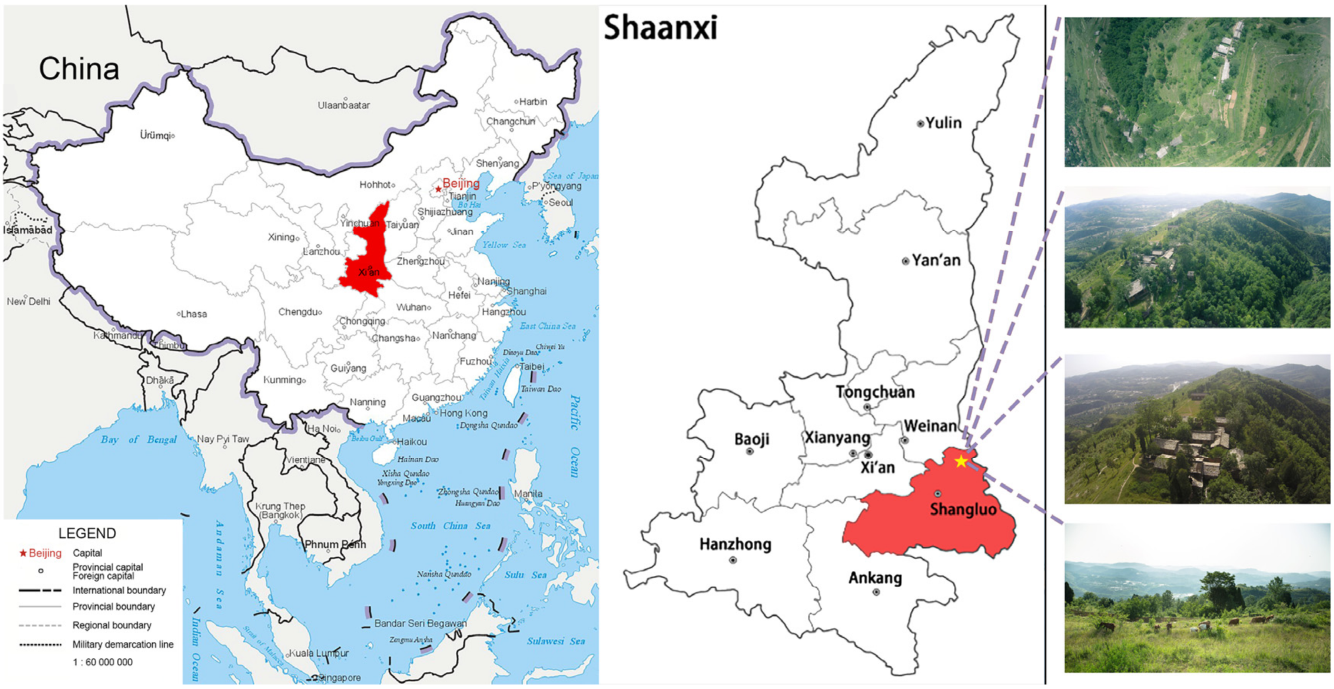


Figure 1. The location and the environment of slate dwellings in China.

The mountains around the village show an "s" shape, with the slope of 60–70 degrees. The slate dwellings are located at altitudes between 800 and 1200 m above sea level. Due to the regional cultural exchanges, the architectural form in this area was influenced by Qin Culture, Bashu Culture, Jinchu Culture, and Han River basin architectural forms. In addition, due to its geographical isolation and abundant slate resources, this area completely preserved its village features and the slate dwellings with regional characteristics. The slate dwellings show the result of a harmonious coexistence between local residents and the natural environment, having unique cultural and historical values.

2.2. The Characteristics of Slate Dwellings

The slate dwellings evolved according to local conditions by heavily using the stone materials in the surrounding mountains. The stone contains powder material which could be peeled into thin slices along the texture of the slate. Although the size, thickness, and shape of the slates are different, the hardness is moderate [35]. Residents polished the large stone slabs into the dwellings' foundation, wall, roof, and other parts according to the required size. The roads, stairs, and various public facilities in the village are also made of stone slates. The slate dwellings have significant advantages of warmth in winter and cool in summer compared with other rural dwellings. Table 1 shows the characteristics of the slate dwelling.

2.3. Questionnaire Survey

Since the number of existing slate dwellings is small, and some of them are in the same condition, this study conducted a questionnaire survey on the existing 72 slate dwellings. The questionnaire was designed to obtain the thermal sensation data of residents, and included basic information questions such as age, sex, clothing level, and thermal adaptation behavior. It also included the requirements of residents for the use of various functional spaces.

Table 1. The characteristics of slate dwellings.

Walls	Doors and Windows	Roof
		
The walls are generally made of thick stone slates, with the thickness of 370 mm, have good windproof and heat preservation performance. The exterior wall is directly decorated with stone, or with mud covered by straw and earth. The interior wall is decorated with the mixed slurry of straw and earth. The walls have good insulation property for several reasons. (1) The thickness and materials of the exterior walls are conducive to insulation. (2) The gable walls are paved with increasingly thinner stone slabs from bottom to top and are bonded with loessial slurry. (3) There is usually an air vent between the gable wall and the roof.	The doors are made of single-layer wooden material, without coating on both internal and external surfaces, some which have door lighters. The windows are wooden frames with single-glass, plastic paper, or gauze. There is an only one-side small window on the exterior walls facing the courtyard, causing poor indoor lighting and ventilation. The thermal insulation performance of the exterior window is poor, as the solar radiation entering through the exterior window is less than the heat lost by heat conduction and air infiltration.	The roofs are supported by column and tie wooden construction, covered by 2 cm slates paved layer by layer. The attic is formed by the sloping roof and the floor slab could serve as warehouses for storage and air space for summer insulation. The eaves were held by the purlins placed at the pediment head protruding from both sides of the gable walls. The veranda is between 600 and 1000 mm, acting as the climate buffer zone, effectively prevented the condition of excessive heat gain in summer and excessive heat dissipation in winter, making a better indoor thermal environment.

This study adopted a seven-point ASHRAE scale to identify subjective thermal sensation (cold/−3, cool/−2, slightly cool/−1, neutral/0, slightly warm/+1, warm/+2, hot/+3). Additionally, Operative temperature (T_{op}) was used as the main evaluation index of thermal comfort.

$$T_{op} = A \times t_a + (1 - A) \times t_r \quad (1)$$

where t_a is the indoor air temperature (°C); t_r is the mean radiation temperature (°C); A is a coefficient determined by the numerical value of the wind speed: A = 0.5 (air speed < 0.2 m/s), A = 0.6 (0.2 < air speed < 0.6 m/s), A = 0.7 (0.6 < air speed < 1.0 m/s).

The field investigation was conducted from 9:00 to 21:00 each day during January 2019 and July 2019, and there were 104 sets of valid data for summer, 114 sets of valid data for winter. In addition, the environmental data were monitored simultaneously as subjects filled out questionnaires. The technical specifications of the corresponding instruments, including the measurement range, accuracy, and resolution, are shown in Table 2.

Table 2. The technical specification of the instruments' parameters.

Instrument Content	Instrument Name and Parameter
Temperature and humidity indoor and outdoor	NZ95-2G Automatic temperature and humidity recorder (Sensor range of temperature: −40−−70 °C, Accuracy ±0.2 °C; Sensor range of humidity: 0~100%RH, Accuracy: ±2%RH)
Wind velocity, wet bulb and black globe temperature	Thermal comfort instrument (CASSLER: Sensor range of black bulk 1–60 °C, Accuracy ±0.2 °C; Sensor range of air velocity 0–30 m/s (0–600 ft/min), Accuracy ±0.03 m/s)

2.4. Measurement Setup

The research group collected data both in summer and winter continuously for 2 days from 16 July at 6:00, 2019 to 17 July at 6:00, 2019 and from 15 January at 6:00, 2019 to 16 January at 6:00, 2019. We presented the outdoor parameters, including the air temperature, relative humidity, and wind velocity through field measurement in this research. In order to understand the indoor thermal conditions in extreme periods, we measured environmental values in unheated rooms, including the air temperature, relative humidity, indoor wind velocity, and operative temperature. These indoor test points were centrally located at a height of 1.5 m. The air temperature, operative temperature, and relative humidity were automatically recorded every 30 min by setting the auto temperature and humidity instrument sampling time. The wind velocity was recorded manually every 30 min at the same time during the measurement. The technical specifications of the corresponding instruments, including the measurement range, accuracy, resolution, and response time, are shown in Table 2.

2.5. Subject Investigation—Basic Information of Subjects

The information of the subjects is presented in Table 3. The subjects were all able to describe their state well and the population difference between summer and winter is due to Chinese Spring Break Holidays. There is no central heating in Daziliang village and air conditioning is also used less frequently. Clothing adaptation is one of key approaches for maintaining thermal comfort [36]. According to the findings, the clothing insulation of females in winter is greater than that of males. As shown in Figure 2, local residents spend more time in bedrooms both in summer and winter, as they go to bed earlier than city dwellers and most of them have a lunch break. In addition, the average time spent outside and in the living room during summer is similar due to more pleasant outdoor wind conditions and rich vegetation.

Table 3. The basic information of subjects.

Age Range	**-**	**10–20**		**21–30**		**31–50**		**51–60**		**Above 60**		**SUM**	
Season	**-**	**Win**	**Sum**	**Win**	**Sum**	**Win**	**Sum**	**Win**	**Sum**	**Win**	**Sum**	**Win**	**Sum**
Age/%	-	19.30	13.46	9.65	4.81	33.33	38.46	23.68	26.92	14.04	16.35	-	-
Gender/%	M	54.56	42.86	36.36	60.00	34.21	35.00	55.55	46.43	37.50	41.18	43.86	41.35
	F	45.45	57.14	63.64	40.00	65.79	65.00	44.44	53.57	62.50	58.82	56.14	58.65
Clothing insulation	M	2.03	0.24	2.09	0.20	2.15	0.32	2.14	0.32	2.33	0.42	2.13	0.32
	F	2.06	0.24	2.09	0.22	2.17	0.31	2.22	0.33	2.40	0.44	2.19	0.33

Key: F = female; M = male; Win = winter; Sum = summer; SUM = summary.

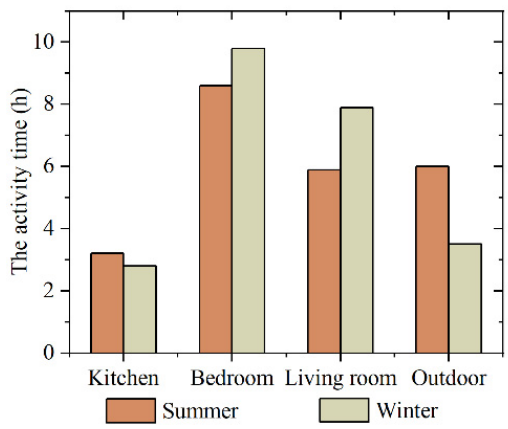
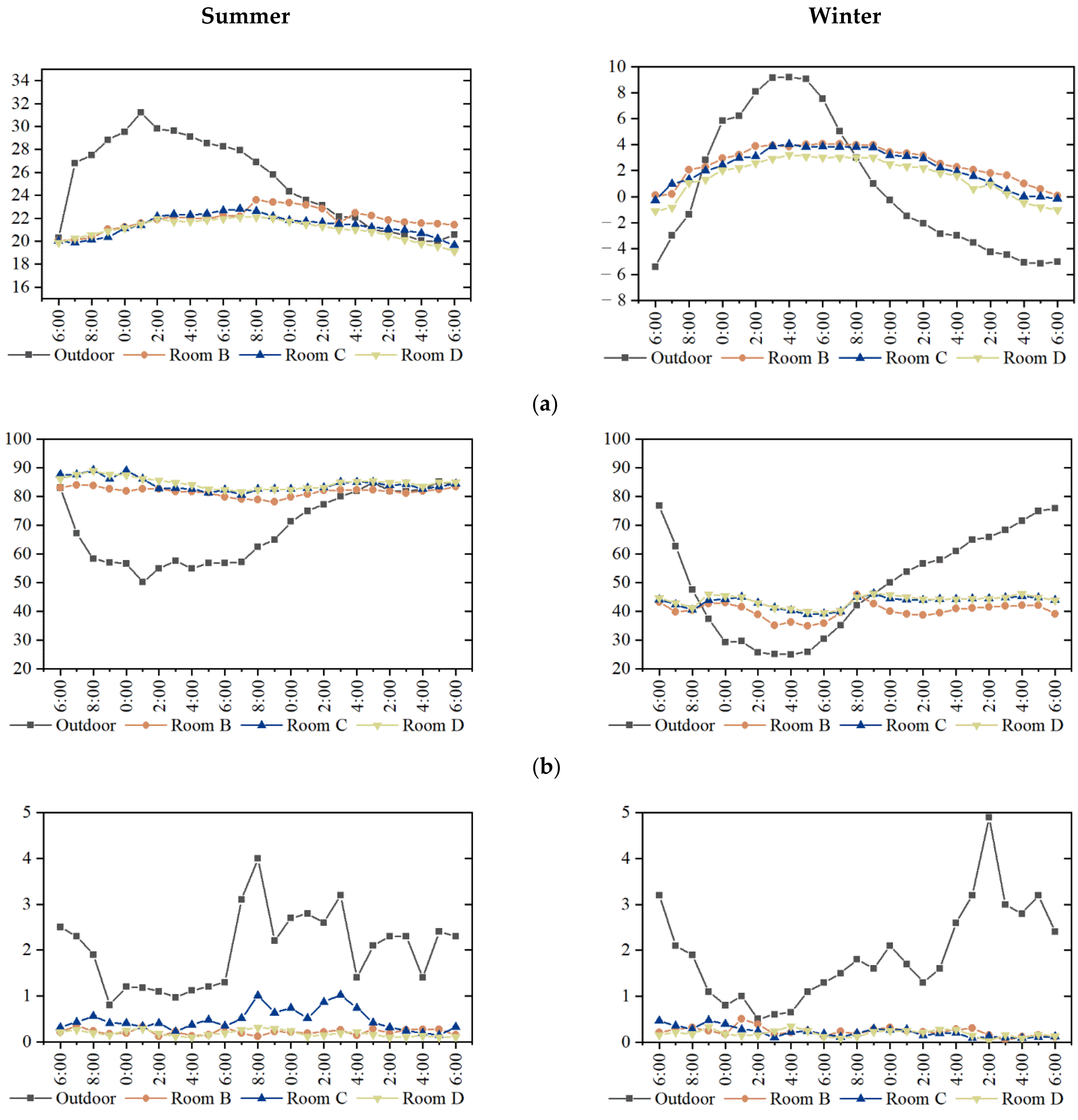


Figure 2. Daily use time in different rooms.

2.6. Objective Measurement—Indoor Thermal Environment

Figure 3 shows the indoor and outdoor environments of studied dwellings in winter and summer. Fluctuation in outdoor temperature is relatively significant in summer (from 19.98 to 31.24 °C). During this time, the mainly used rooms are quite stable from 20.05 to 23.56 °C. The relative humidity ranges from 78.11% to 89.24%, with an average value of 83.54% which is higher than ASHRAE Standard 62.1 (2019) [37].



(c)

Figure 3. Measured outdoor and indoor thermal environment parameters. (**a**) The indoor and outdoor air temperature (°C), (**b**) The indoor and outdoor humidity (%), (**c**) The in-door and outdoor wind speed (m/s).

In winter, outdoor temperatures are higher during the day and lower at night, with the opposite change to humidity. As shown in Figure 3, the temperature difference between day and night outdoors is large, but there is little change in indoor temperature fluctuations, from −1.12 to 4.06 °C. Although the indoor thermal environment is stable, the temperature value is far from the 12 °C required by code for non-heated rooms. Lower indoor humidity values were found in winter compared to summer. In conclusion, the indoor temperatures and relative humidity are not significantly better than outdoors. However, slate dwellings have good thermal stabilization which has been demonstrated by small indoor temperature fluctuations.

2.7. Indoor Thermal Comfort

The linear correlations between mean thermal sensation votes (MTS) and operative temperature in winter and summer is shown in Figure 4. Regression of MTS and operative temperature shows a significant linear relationship. According to the PMV-PPD equation, when the mean thermal sensation voting value is 0, t_{op} is the neutral temperature. When MTS = ±0.5, the satisfaction rate is 90%, and when MTS = ±0.85, the rate is 80% [38,39]. Results showed that, in summer, the neutral temperature is 20.92 °C. The 90% and 80% acceptable operative temperature range is from 18.99 to 22.84 °C and 17.64 to 24.19 °C, respectively. Additionally, in winter, the neutral temperature is 8.92 °C. The 90% and 80% acceptable range is from7.53 to 10.31 °C and from 6.56 to 11.28 °C, respectively.

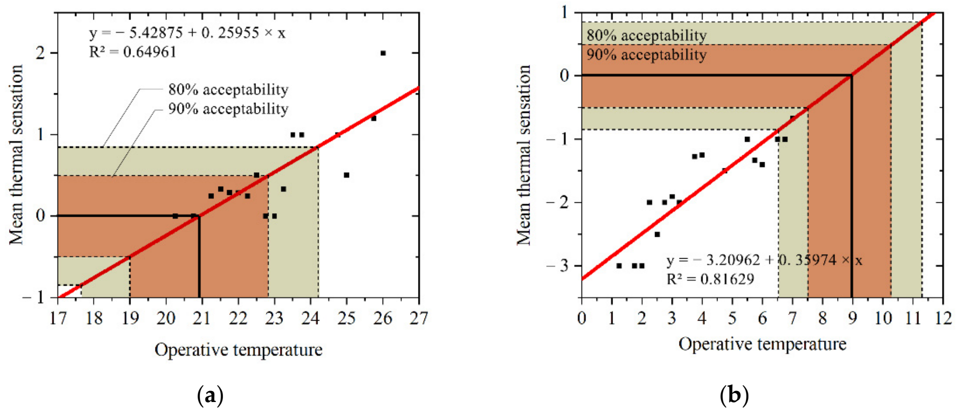


Figure 4. The relationship between MTS and the operative temperature. (**a**) Summer, (**b**) Winter.

It could be seen that the actual operating temperature in summer is moderate, which basically meets the 80% acceptable comfort range for the human body. However, in winter, the temperature is too low to meet the 80% acceptable range and well below requirements of 12 °C for non-heated rooms and 18 °C for heated rooms for indoor suitable temperatures (Thermal Design Code for Civil Buildings in China GB50176-2016) [40].

From the above data analysis, the indoor thermal environment of slate dwellings has some disadvantages in winter, which needs to be improved urgently.

3. Simulation and Results

3.1. Dwelling Description

In this research, the typical traditional "I" shape slate dwelling was selected as the energy-saving and comfort enhancement object, which was built in the 1940s due to the "I" shape having the simplest and most basic plan form and is the most common form in southern Shaanxi. Figures 5 and 6 present a typical example of the selected residential slate dwelling. The walls are made from thick slates, one overlapping another, with a thickness of 370 mm. The interior wall surfaces are made of mud mixed with straw and earth, covering the stone slates. The windows are single glazed solid wooden windows, with sizes of 0.9 by 0.9 m. There are two doors located on the south elevation, with the sizes of 0.9 by 1.8 m and 1.2 by 1.8 m, respectively. There are ventilation openings above each door, with sizes of 0.6 by 0.6 m. There are also two ventilation openings on the east wall and the west wall flush with the eaves, both of which are 0.6 by 0.6 m. The roof is a herringbone sloping roof, made of thin stone slates. The dwelling is 4.5 m in height, with four rooms, each of which is 3.3 by 6.0 m.

Figure 5. The typical example of the traditional slate dwellings.

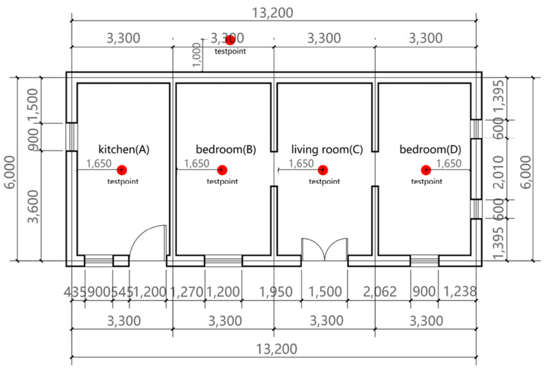


Figure 6. Layout of the traditional slate dwellings.

3.2. Simulation Method

Under the premise of architectural functions, the indoor thermal environment of the slate dwelling could be improved through the appropriate improvement strategy to achieve the effect of energy saving and meet the requirements of local residents for thermal comfort.

DesignBuilder was used as the simulation software for strategy validation and numerical simulation. DesignBuilder is a free, open-source program using Energyplus as its engine, commonly used in academic work due to its accuracy [41–43]. This study identified optimization strategies through quantitative simulations; then verified the improvement in energy consumption in heating state and indoor thermal environment in non-heating state for the final optimized solution. The accuracy of model has been demonstrated through simulations and previous research by the group.

3.2.1. The Parameter Settings of the Improvement Strategy

Taziliang Village was selected in the second batch of traditional villages in Shaanxi Province in 2017. Therefore, according to the relevant regulations, historical buildings should retain their original height, mass, external appearance, and color. Additionally, retrofitting should be conducted under the guidance of experts and local authorities. The following strategies are reasonable and acceptable to the local residents and experts.

1. The transformation of openings

The function layout of the slate dwelling is basically reasonable. Additionally, it is possible to alter the position of the door in living room to facilitate furniture arrangement. Figure 7 shows that, in addition, the improvement design transforms the openings in rooms A, B, and D which could reduce the impact of the dominant wind on the bedroom in winter and prevent the indoor heat loss, as well as improve daylight and the wind environment.

2. Attached sunspace

(**a**) (**b**)

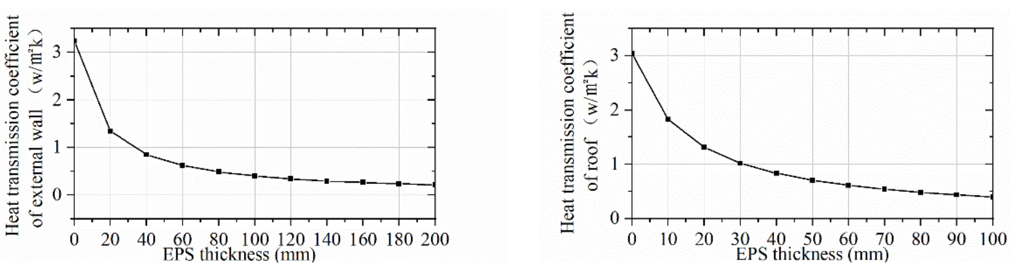
Figure 7. The improved model (**a**) plan of slate dwelling, (**b**) model of slate dwelling.

The attached sunspace could be added on the south side of the living room. In winter, the attached sunspace could prevent the heat loss of the slate dwelling, maximize the use of solar energy, and avoid the cold wind directly entering the room, which could meet the requirements of energy saving and thermal comfort. The translucent cover plate or heat-absorbing glass with good thermal insulation quality could be covered on the attached sunspace, effectively increasing the heat collection area of the sunspace. According to statistical survey and simulation calculation, a sunspace with a depth of 1.5 m could not only meet the needs of production and could fit with the overall shape of original house, but also function better in terms of energy saving and thermal environment improvement.

3. The improvement of the enclosure structure

The envelope structure is the main object for the optimization of indoor thermal energy consumption of buildings. Due to the lack of thermal insulation in the external walls and roof of the slate dwelling, the indoor thermal environment is poor in winter. The indoor internal surface temperature is mainly determined by the heat transfer characteristics and thickness of the thermal insulation material of the structural layer. Under ideal circumstances, thicker material with lower heat transfer coefficients could make a better indoor thermal environment.

Figure 8 shows the relationship between the heat transfer coefficient and the thickness of the external wall and roof insulation material. As we could see from the general trend, as the thickness of the insulation material increases, the heat transfer coefficient decreases. External walls and roofs have a similar trend. When the insulation material increases from 0 to 20 mm, the heat transfer coefficient of both decreases the fastest. When the thickness increases to 80 mm, the downtrend of the heat transfer coefficient slows down.



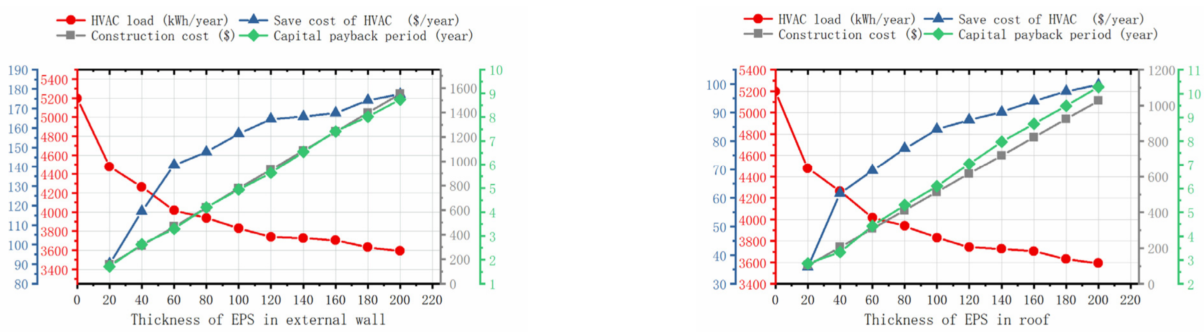
(**a**) (**b**)

Figure 8. (**a**) The relationship between the heat transfer coefficient and the thickness of external wall insulation material; (**b**) the relationship between the heat transfer coefficient and the thickness of roof insulation material.

However, excessively improving the building thermal environment will result in the increased costs of construction and waste of materials. Therefore, a reasonable solution within a suitable range is needed.

Figure 9 shows the construction cost, cost savings of cooling and heating, and capital payback period of different thicknesses of EPS in external walls and roofs. The premise of this analysis is shown below:

1. A tiered electricity tariff is used in residential buildings in Shangluo: 0.07818 USD/kWh for electricity consumption of 2160 kWh or less per year. The tariff is 0.08613 USD$/kWh for electricity consumption between 2161 and 4200 kWh and 0.1254 USD/kWh for electricity consumption above 4201 kWh.
2. The expanded polystyrene (EPS) is priced at USD 40.0169 per cubic meter.



(**a**) (**b**)

Figure 9. (**a**) The payback period of capital for different thicknesses of EPS in external walls; (**b**) The payback period of capital for different thicknesses of EPS in the roof.

As shown in Figure 9, according to an assessment of the actual situation, 80 mm was chosen as the thickness of the roof and external walls due to easy construction, and the capital payback periods are 4.2 and 5.31 years, respectively.

3.2.2. Simulation Parameter Settings

1. Modeling

In this research, by using DesignBuilder software, taking the actual size of the traditional slate dwelling in southern Shaanxi, Figure 7b shows the improvement model of the slate dwelling. In the numerical simulation of this research, we conducted two phases of study. The first is to analyze the energy consumption using heating and cooling systems. The second is analysis of the thermal environment without heating and cooling facilities. The main parameter settings are as follows:

2. Room parameters

In winter, the heating season is from November 15th to March 15th as required. The interior design temperature for heating main rooms in rural housing in winter is calculated at 14–18 °C [44]. Considering the living standards and economic conditions of this area, 14 °C could be set as the design temperature for heating rooms in winter. Therefore, the upper limit of the indoor tolerance temperature is 28 °C as required, and the lower limit is 14 °C. For the sake of uniform calculations, we chose electricity as the fuel for heating and cooling. Additionally, the coefficient of performance is 0.8. The air change rate is 0.5 ach. The dwelling is 4.5 m in height and the roof space is mainly used for storage. Therefore, it has no heating and cooling needs, as well as a kitchen.

3. Indoor parameters

The study set 3 people indoors with the per capita heat output of 53 W. The maximum power of the bulb indoors is 20 W. The interference parameters indoors were set according to the actual living habits of the local residents and the usage of electrical appliances, including the occupants, lights, and electrical appliances.

4. Envelope parameters

According to the characteristics and prices of insulation materials commonly used in southern Shaanxi, this study selected expanded polystyrene board (EPS) as the external wall and roof thermal insulation material for the improvement of the slate dwelling. Table 4 indicates the comparison of parameter values of the envelope before and after improvement.

Table 4. The comparison of envelope parameters of the slate dwelling before and after improvement.

Building Type	Envelope Structure	Structure before Improvement (mm)	Heat Transfer Coefficient (w/m^2·k)	Structure after Improvement (mm)	Heat Transfer Coefficient (W/m^2·K)
The slate dwelling	External wall	Untidy stone slate 370 Clay sawdust surface 20	3.238	Untidy stone slate 370 Cement mortar 20 Expanded polystyrene panel (EPS) 80 Polymer mortar 3	0.402
	Internal wall	Grass and clay walls 240	1.530	Cement mortar 20 Red clay brick 240 Cement mortar 20	1.537
	Roof	Plank 20 Untidy stone slate 40	3.783	Plank 20 Expanded polystyrene panel (EPS) 80 Cement mortar 20 Bituminous waterproof sheet material 3 Cement mortar 30 Untidy stone slate 40	0.415
	External window	Single wooden window frame with common glass 6	5.894	Aluminum insulating glass 6 + 9 + 6	3.124
	External door	Single solid wooden door 25	-	Single solid wooden door 25	3.316
	Internal door	-	-	Single solid wooden door 25	3.316
The sunspace	Door	-	-	Glass door 15	2.876
	External wall	-	-	Insulating glass wall 6 + 9 + 6	3.009

3.3. Numerical Simulation Results

3.3.1. Energy Consumption Result for Heating Condition

Table 5 shows the average values of the seven simulated energy consumption results, including four single measures and three complex measures. As shown in Table 5, under the condition of keeping the outdoor environmental parameters unchanged, this study carried out the energy consumption simulation by changing the four parameters separately, which are window, external wall material, roof material, and attached sunspaces. By only changing the external wall material, the energy-saving rate is 24.23% with the shortest payback period while the energy-saving rate of attached sunspaces is 1.52% with the longest payback period.

As for complex measures, combined single measures in the external walls and roof is the most economical and effective measure, whose capital payback period is only 4.88. Although all four measures combined could have a better HVAC energy-saving rate, it has a longer payback period. Even so, all four measures combined was chosen as the optimal measure in this research due to it not only having a better energy-saving rate, but it also could meet productive and living needs of local residents. Therefore, we conducted a two phases study based on all four measures combined.

Table 5. The energy consumption analysis for the simulation before and after improvement.

Improvement Measures		HVAC Total Load (KWh)	HVAC Total Energy Saving (%)	Save Cost of HVAC (USD/year)	Construction Cost (USD)	Capital Payback Period (Year)
Before Improvement		5197.69	-	-	-	-
After Improvement	Window	4449.49	14.39	93.82	825.07	8.79
	External wall	3938.16	24.23	147.66	620.67	4.20
	Roof	4580.37	11.88	77.41	410.70	5.31
	Sunspace	5118.83	1.52	9.92	1166.88	117.63
	External wall + Roof	3084.90	40.65	211.23	103.37	4.88
	External wall+ Roof + window	3127.44	39.83	207.57	1856.44	8.94
	All four measures combined	2897.33	44.26	227.39	3023.32	13.30

3.3.2. Thermal Environment Result for Non-Heating Condition

The simulation selected Bedroom D because it has the poorest indoor thermal environment compared with other rooms. Figure 10a shows that the average humidity of the Bedroom D after improvement is 39.74%, with the highest humidity of 43.86%, and the lowest of 36.43%, 3.96% lower than that before the improvement. Figure 10b shows that the average air temperature of the Bedroom D after improvement increased by 3.65 °C compared to before. Figure 10c shows that the indoor mean radiant temperature of Bedroom D after improvement is 2.12 °C higher than before. It is indicated that these measures could effectively improve the indoor thermal environment in winter under the present economic conditions of the countryside.

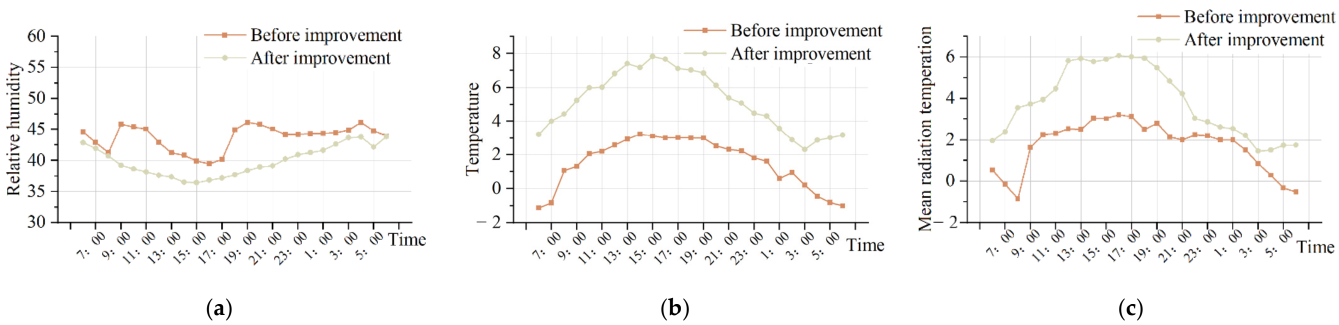
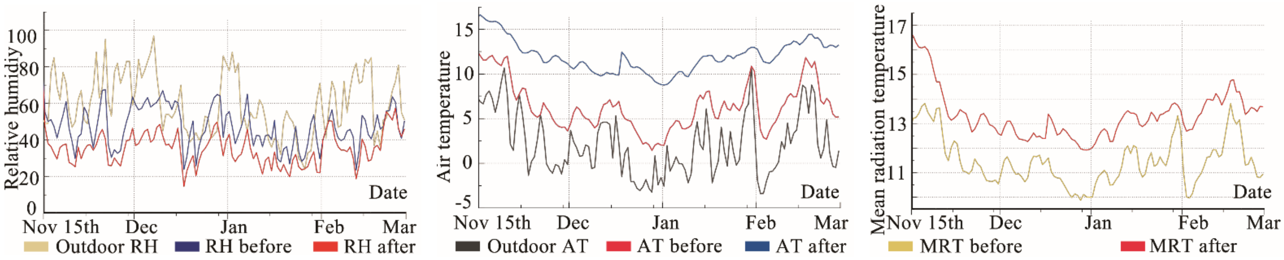


Figure 10. The 24 h simulation comparison of the physical environment before and after improvement in Bedroom D on the 15–16 January. (**a**) The 24 h simulation comparison of indoor humidity before and after improvement, (**b**) The 24 h simulation comparison of the indoor air temperature before and after improvement, (**c**) The 24 h simulation comparison of the mean radiation temperature before and after improvement.

The indoor thermal environment simulation of one day cannot represent that of the whole winter. Through environment parameters of a typical winter meteorological year, this study further simulated the air temperature, relative humidity, and mean radiation temperature of Bedroom D before and after improvement in winter. Our approach aimed to evaluate the effectiveness of renovation measures throughout winter.

Figure 11a shows that the value of relative humidity decreases by 6.13% after improvement. As we can see in Figure 11b,c, the air temperature and mean radiation temperature increase by 3.82 and 2.54 °C, respectively. After renovation, the indoor thermal comfort of the slate dwelling is improved compared with that before renovation.



(**a**) (**b**) (**c**)

Figure 11. The simulation comparison of physical environment before and after improvement in Bedroom D in winter. (**a**) The simulation comparison of indoor humidity before and after improvement in winter, (**b**) The simulation comparison of the indoor air temperature before and after improvement in winter, (**c**) The simulation comparison of the mean radiation temperature before and after improvement in winter.

4. Conclusions and Recommendations

4.1. Conclusions

In this study, the indoor thermal environment and energy-saving mode of a slate dwelling in southern Shaanxi were simulated and analyzed by DesignBuilder. The thickness of the thermal insulation materials was determined by comparing energy-saving rate and capital payback period. Moreover, the indoor temperature change and energy consumption variation were obtained by computer simulation. The main conclusions are as follows:

(1) Data analysis showed that in summer, the neutral temperature is 20.92 °C. The 90% and 80% acceptable operative temperature ranges are from 18.99 to 22.84 °C and 17.64 to 24.19 °C, respectively. In winter, the neutral temperature is 8.92 °C. The 90% and 80% acceptable range is from 7.53 to 10.31 °C and from 6.56 to 11.28 °C, respectively. It could be seen that the actual operating temperature in summer is moderate while the temperature in winter is too low to meet the 80% acceptable range and needs to be improved.

(2) In this study, the building envelope heat transfer coefficients of the thermal insulation material expanded polystyrene board (EPS) with different thicknesses were analyzed in winter. According to the analysis of energy-saving rate and capital payback period, it is reasonable to choose 80-mm-thick expanded polystyrene board (EPS) as the insulation material for the exterior walls and roof of the slate dwelling.

(3) The simulation of an energy-saving scheme after building improvement was made. After improvement, the slate dwelling's daily energy-saving rate of the heating day is 44.26% lower than before by adopting 80 mm EPS external insulation materials on the roof and external walls, and adding attached sunspaces with a depth of 1.5 m. The result shows that the slate dwellings in southern Shaanxi have great potential in terms of energy saving after improvement. In addition, the reconstruction of the envelope is the most economical and effective measure.

(4) In this research, by using the meteorological parameters in winter of a typical meteorological year, the simulation of the slate dwelling with additional insulation materials on the roof and external walls, and attached sunspaces, was made. Through the simulation of the building energy-saving scheme, the improved slate dwelling has a prominent performance in the thermal environment as the indoor mean radiant temperature increased by 2.54 °C. However, as it cannot fully meet the thermal demand of residents, heating facilities are also important measures for improving the indoor thermal environment.

4.2. Recommendations

Due to urbanization and COVID-19, relatively few local long-term residents were studied in this research, although every effort was made to find subjects in settlements.

However, our research data is reasonable based on a comparison of other vernacular dwelling studies, 8.6 °C in winter in Shangluo region and 22.95 °C in summer in Hanzhong region [45]. Our group will continue to improve the local database in future research.

The renovation of energy efficiency strategies based on thermal comfort enhancement allowed Bedroom D to significantly improve its indoor thermal environment under non-heating conditions, with its 24 h indoor operating temperature range rising from −0.765–3.135 °C (before improvement) to 1.88–6.86 °C (after improvement), which was calculated based on data in Figure 10 by using Equation (1). However, it still falls short of the acceptable temperature range for local population. Therefore, in this mountainous region, the renovation strategy does not fully satisfy the thermal requirements and heating facilities are still necessary to improve the indoor thermal environment. The simulation results fully illustrated that the energy consumption of the traditional slate dwelling in Shangluo could be reduced significantly through these measures such as adding 80 mm EPS insulation to the roof and external walls and attaching a 1.5 m deep sunspace to the south. In addition, the addition of EPS to the external wall and roof is the most economical and effective measure with better energy-saving rates and lower capital payback periods.

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