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Taguchi Method-based Optimization Design of Indoor Thermal Environment of Traditional Dwellings in Cold Regions

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Abstract:

Exploration into optimization design scheme for the indoor thermal environment of traditional dwellings in cold regions carries great significance for the inheritance and development of traditional architecture. With traditional dwellings in Qingcheng Ancient Town in Lanzhou as an example, through actual measurement of temperature and humidity and Ecotect Analysis software simulation, the main factors affecting indoor thermal environment were identified and used as the basis for selecting the optimization factors of Taguchi test. After selecting the appropriate optimization target and optimization factor, the optimization factor was subject to level analysis to determine appropriate optimization level and then establish factor level table. The appropriate orthogonal table was selected for Taguchi test based on the number of factors and levels, and the average value of the test results was analyzed to finally derive the optimization design scheme. According to simulation verification, the Taguchi method-based optimization design scheme reduces the annual energy consumption per unit area by 67.7%, which can provide a reference for the optimization design of the indoor thermal environment of traditional dwellings in cold regions.

Keywords*: Traditional dwelling; Indoor thermal environment; Taguchi method; Cold region; Software simulation.*

I. INTRODUCTION

Owing to the cold winter, great temperature difference throughout the year, and rich loess resources, traditional dwellings with rammed earth as the main material are gradually dominant in cold regions. In recent years, however, under vigorous development of rural areas, new-style dwellings constructed with new materials and techniques have gradually grown in number, posing a great threat to the inheritance of traditional dwellings. With the proposal of rural revitalization strategy, inheritance of traditional architectural culture has become the key to rural construction, while optimizing the indoor thermal

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environment is an effective measure to protect traditional architectural culture. So far, relevant researches have achieved certain results: Jin Guohui et al. optimized the indoor thermal environment of residences [1] and grassland dwellings[2] in western Inner Mongolia based on software simulation; Zhang Lili et al. designed and renovated farm houses in southwest of Shandong province, and compared the indoor thermal environment before and after renovation based on Ecotect and Airpak simulation [3]; Wu Zhongqi et al. proposed a passive renovation strategy for Quanzhou stone dwellings based on Design-builder [4]; Jin Ling et al. simulated and optimized thermal insulation, ventilation and shading of the newly built farm houses based on Energy Plus[5]; Yang Min et al. used Ansys Fluent to improve the felt system of the traditional yurt [6]; Liu Shichen et al. proposed optimization suggestions based on actual measurement and analysis of traditional stilt style dwellings in Southwest of Hubei province [7]; considering the coupling effect of shading and natural ventilation on the indoor thermal environment of traditional dwellings in Qinba Mountains, Wang Xianling et al. optimized the building shading components [8]; T.R. Pokharel et al. studied nine dwellings in three climate zones in Nepal, finding that indoor thermal environment can be significantly improved by optimizing the thermal insulation of the building envelope and reducing building energy consumption [9]. The above studies have extensively discussed the optimization of indoor thermal environment of rural dwellings, but the overall optimization of the indoor thermal environment of rammed-earth dwellings in cold regions of China is insufficiently studied. In view of the dry and hot summer and cold winter in cold regions, better indoor thermal environment is of great significance to the inheritance of traditional dwellings.

The traditional dwellings in Qingcheng Ancient Town, Lanzhou are selected as the research objects, the main factors affecting the indoor thermal environment are mastered through actual measurement and software simulation, and Taguchi method widely used in industry and product fields is used to formulate the optimization design scheme for the indoor thermal environment of traditional dwellings in cold regions. Taguchi method is a multi-factor, multi-level, low-cost and high-efficiency quality engineering design method proposed by Dr. Taguchi based on orthogonal tables in order to improve the quality of Japanese communication products. After comprehensive promotion in Japan, product quality is generally improved. It emphasizes that product quality is not improved through inspection, but through design [10]. It is now widely used in various industries such as chemical industry [11][12],electronic machinery [13],biological culture[14];etc., to reduce costs, increase efficiency, improve quality, enhance robustness, and obtain optimal process solutions. Meanwhile, application of Taguchi method in multiple disciplines is verified.

II. MEASURED OBJECTS, SCHEMES AND RESEARCH METHODS

2.1 Measured Objects

Qingcheng Ancient Town, a relatively well-preserved national historical and cultural town in Gansu Province, is located in Yuzhong County, Lanzhou City. The local dwellings are typical rammed earth buildings. Through the preliminary investigation, two representative traditional dwellings in the village were selected as the research objects. The status quo photos are shown in Fig 1. Building A faces south

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from the north, and building B faces east from the west, which are both slotted bays. Where, room A1 is the master bedroom and living room, which is the owner's resident room; room A2 is the secondary bedroom with smaller usage frequency; building B has the same functional design as building A, but it is actually used for storing sundries, with a low usage frequency. The two buildings are typical in shape and structure, both are well preserved as a whole. The building shape and structure is shown in Fig 1, and the main components of the building are shown in TABLE I.

(a) Building A

(b) Building B

Fig 1 Building photos measured

TABLE I Main building component parameters

Building component		**Component construction**
Wall	Front envelop structure	Wood, 50mm thick
	The remaining three sides of the envelope structure	420mm thick rammed earth
	Sill wall	250mm thick masonry
	Partition wall	200mm thick rammed earth
Roof		Wooden roof truss+50mm wood board+5mm waterproof roll+100mm loess
Floor		1500mm sand + 110mm brick
Doors & Windows	Window	Wooden window frame, 1.5mm plastic
	Door	Wood, 50mm thick

2.2 Actual Measurement Scheme

In order to analyze the status quo and influencing factors of the indoor thermal environment of local traditional dwellings, the indoor and outdoor temperature and humidity were measured. The measured samples are room A1 and room A2 of building A, and room B1 and room B2 of building B, a total of four rooms. The room layout and measurement point layout are shown in Fig 2. Based on local temperature analysis over the years, considering the actual temperature of the current year, the summer measurement time was from 9:00 on July 27, 2019 to 9:00 on July 28, and the winter measurement time was from 19:00

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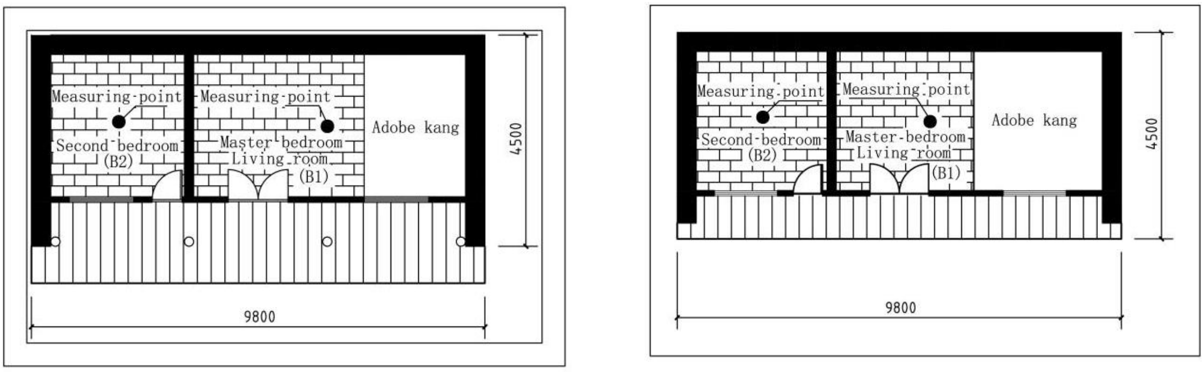
on December 25, 2020 to 19:00 on December 29, 2020. This measurement adopted 24-hour uninterrupted measurement, and the measurement time interval was 15 minutes. The instrument was calibrated before the measurement to control the relative error.



(a) Building A

(b) Building B

Fig 2 Layout of building and measuring points

2.3 Research Methods

With Qingcheng Ancient Town in Lanzhou as an example, the main factors influencing indoor thermal environment of traditional dwellings in cold regions were mastered through field measurement and software simulation analysis of typical traditional dwellings. Afterwards, an appropriate optimization objective was selected, and optimization factor was determined based on the main factors influencing indoor thermal environment. Through level analysis of the optimization factors, appropriate optimization level was selected to establish the factor level table. According to the established factor level table, appropriate orthogonal table was selected for Taguchi test, and average value of the test results was analyzed to formulate the optimization design scheme for the indoor thermal environment. Finally, through simulation test of the optimization scheme, the applicability and effectiveness of the Taguchi method in the indoor thermal environment optimization of traditional dwellings in cold regions were verified. The overall research idea is illustrated in Fig 3.

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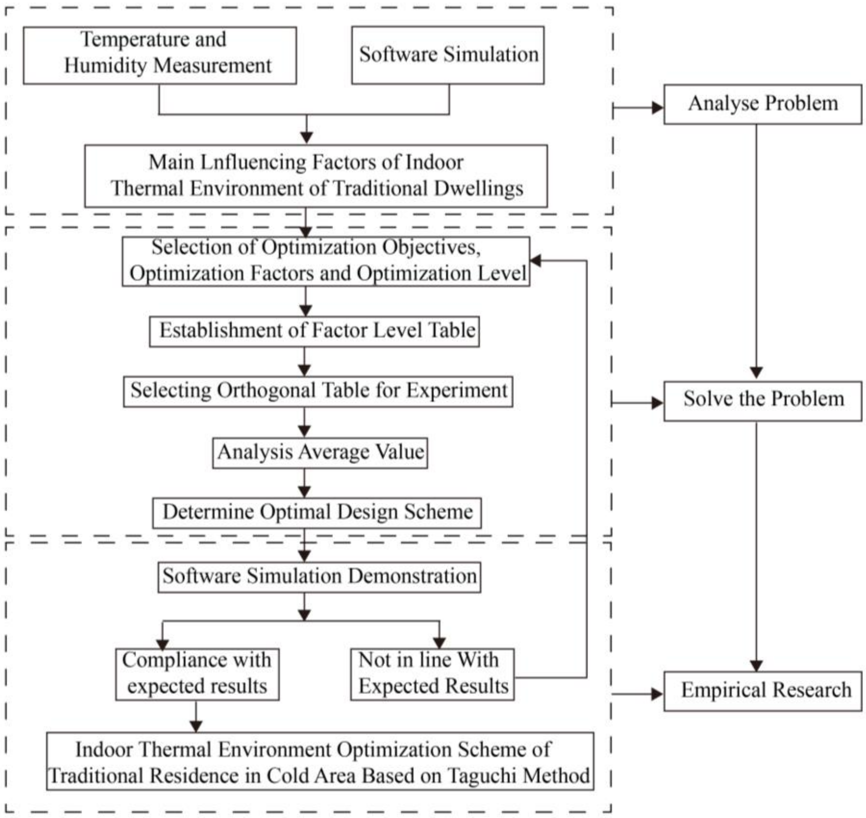

Fig 3 Research ideas

III. ANALYSIS OF FACTORS INFLUENCING INDOOR THERMAL ENVIRONMENT

3.1 Summer Data Analysis

According to the measured data, the maximum outdoor temperature during the summer measurement period is 38.9 °C, the minimum temperature is 23.0 °C, and the average temperature is 29.6 °C, which is at a level of relatively high annual temperature. The highest outdoor relative humidity is 59.1%, the lowest relative humidity is 24.1%, and the average relative humidity is 40.4%.

According to the overall indoor and outdoor temperature change in summer shown in Fig 4(a), the indoor temperature and humidity are more stable than outdoor. By analyzing the time corresponding to the maximum indoor and outdoor temperature, it is found that the maximum indoor temperature is delayed by about 4~6 hours compared with the outdoor, which proves that the local rammed earth buildings have good thermal stability and delay in summer. However, rooms A1, A2, B1, and B2 have an average temperature of 29.8°C, 29.4°C, 29.9°C, and 30.2°C, respectively, which are slightly higher than the somatosensory comfort temperature of the human body. Based on the actual building situation, it is mainly due to the poor building sealing performance and solar radiation in the preliminary analysis.

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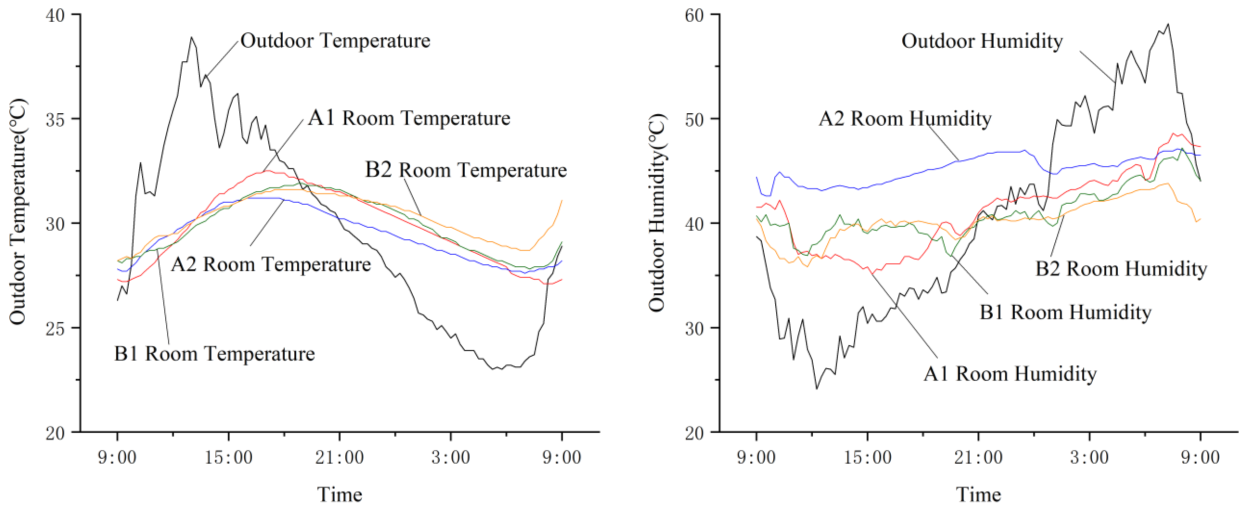
Analysis of the indoor and outdoor humidity changes shown in Fig 4(b) shows that the relative humidity of the four rooms fluctuates in the range of 35.1%~48.6%, and the average relative humidity is 41.1%, 45.2%, 40.9, and 40.2%, respectively. The overall fluctuation is relatively stable and the relative humidity has small difference in average value. It suggests that the indoor humidity environment of local traditional dwellings is relatively stable and comfortable in summer, and the difference between buildings exerts little effect on the indoor relative humidity.



(a) Temperature (b) Humidity

Fig 4 Temperature and humidity changes in summer

3.2 Winter Data Analysis

According to the measured data, the maximum outdoor temperature during the winter measurement period is 3.2 °C, the minimum temperature is -11.5 °C, and the average temperature is -5.9 °C, which is at a level of relatively low annual temperature. The highest outdoor relative humidity is 72.0%, the lowest relative humidity is 24.0%, and the average relative humidity is 43.1%.

A preliminary analysis of the indoor and outdoor temperature changes shown in Fig 5(a) indicates that the indoor temperature and humidity are relatively stable compared to the outdoor. According to calculation, the standard deviation of the outdoor temperature during the actual measurement period is 3.63, and the standard deviation of the indoor temperature in rooms A1, A2, B1, and B2 is 1.75, 1.67, 1.05, and 0.46, respectively, proving that indoor temperature fluctuation in winter is more stable than that of the outdoor. However, the indoor temperature of the four rooms is only 3.9°C at the highest and -3.7°C at the lowest. The average temperatures are -0.7°C, -0.7°C, -1.8°C, and -0.6°C, respectively, all below zero. Where, the window of room B1 has serious air leakage, and the average temperature is significantly lower than that of the other three rooms, indicating that the poor building sealing performance is also an important reason for the poor indoor thermal environment in winter.

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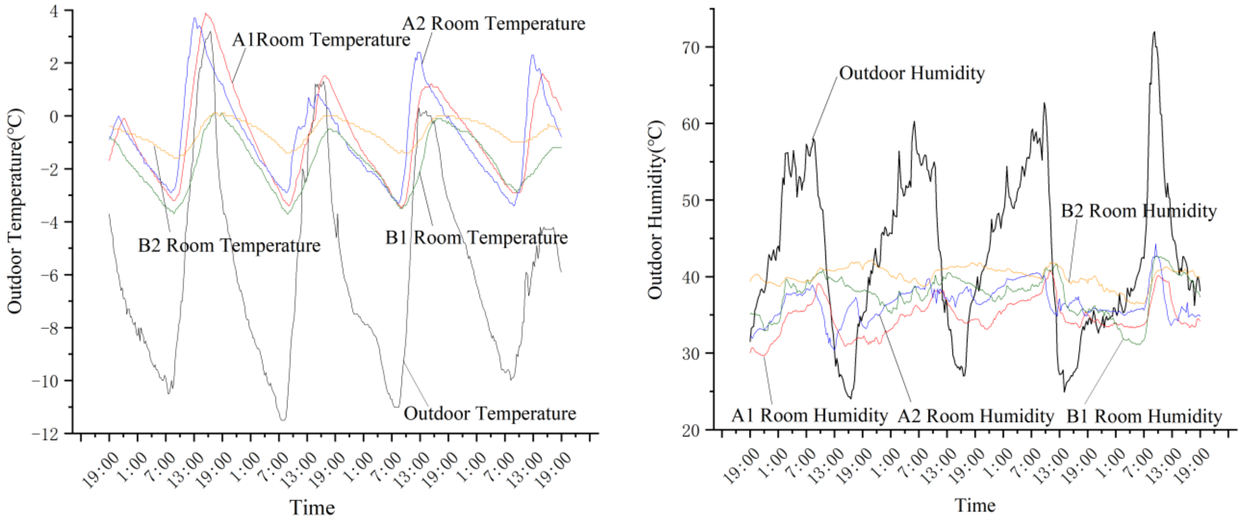
According to the indoor and outdoor humidity change in winter shown in Fig 5(b), the relative humidity of each room fluctuates in the range of 29.6%~44.30%, and the average relative humidity is 34.7%, 36.6%, 37.6%, and 40.1%, respectively. The overall indoor humidity is dry, but more stable than outside.



(a) Temperature (b) Humidity

Fig 5 Temperature and humidity changes in winter

3.3 Software Simulation Analysis

In order to further investigate the main factors influencing the indoor thermal environment of traditional dwellings in cold regions, the measurement model of building A was established in the Ecotect Analysis simulation software, and the passive component heat gain simulation was performed throughout the year to master the heat gain and loss of the building.

The simulation results are shown in TABLE II. The analysis shows that envelope structure has the largest proportion of heat loss in local traditional dwellings, followed by air infiltration heat loss and regional heat loss; comprehensive temperature heat gain and solar radiation heat gain account for a large portion of the building heat gain. The actual building analysis shows that the main reason for the high proportion of heat loss and comprehensive temperature heat gain of the envelope structure is the poor thermal insulation and sealing performance of the building front envelope and roof, so a thermal insulation layer should be added to improve material performance. Rammed earth wall is the main envelop structure of the local traditional dwellings, whose thickness will also exert a certain impact on the indoor thermal environment. The great cold air infiltration heat loss is mainly due to the simple plastic window material which cannot effectively block the outdoor air, so material with better sealing performance should be selected. Analysis of the relevant specifications in the "Energy-saving Design Standards for Rural Residential Buildings" [15] shows a great correlation between solar radiation heat gain in cold regions and

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building window area, so the window-wall ratio also exerts a great impact on the indoor thermal environment of the building. By summarizing the above analysis, it is concluded that the main factors influencing indoor thermal environment of local traditional dwellings include: front envelope structure, roof material, window material, window-wall ratio and rammed earth wall thickness.

TABLE II Building heat gain and loss

Heat gain and loss	**Heat loss**			**Heat gain**			
	Envelope structure heat loss	air infiltration heat loss	Regional heat loss	Envelope structure heat gain	overall temperature heat gain	solar radiation heat gain	air penetration heat gain
Percentage (%)	82.9	15.5	1.6	3.6	69.1	24.7	2.5

IV. OPTIMIZATION DESIGN SCHEME FOR INDOOR THERMAL ENVIRONMENT

4.1 Establish Factor Level Table

4.1.1 Select optimization objectives and optimization factors

The purpose of this Taguchi test is to explore how to optimize indoor thermal environment, so the annual energy consumption E_S per unit area is selected as the optimization target, which is calculated as follows:

$$E_s = E/S \quad (1)$$

Where, E_S is the annual energy consumption per unit area, KWh/m^2; E is the annual energy consumption value of the building, KWh; S is the total building area, m^2, S=35.28 m^2 in this paper. According to the building energy consumption simulation principle of the software, smaller E_S indicates better indoor thermal environment of the building, and greater E_S indicates worse indoor thermal environment of the building.

Based on the main factors influencing indoor thermal environment obtained from the above research, the optimization factors of this Taguchi test are selected as follows: A thermal insulation layer thickness of the front envelope structure, B thermal insulation layer thickness of roof, C window material, D window-wall ratio of front envelope structure, E rammed earth wall thickness.

4.1.2 Selected optimization level

Selection of the optimization level requires level analysis of the optimization factors. That is, there is need to study the corresponding numerical relationship between the different levels of each optimization factor and the optimization target value, and then select the appropriate level for the optimization test. The

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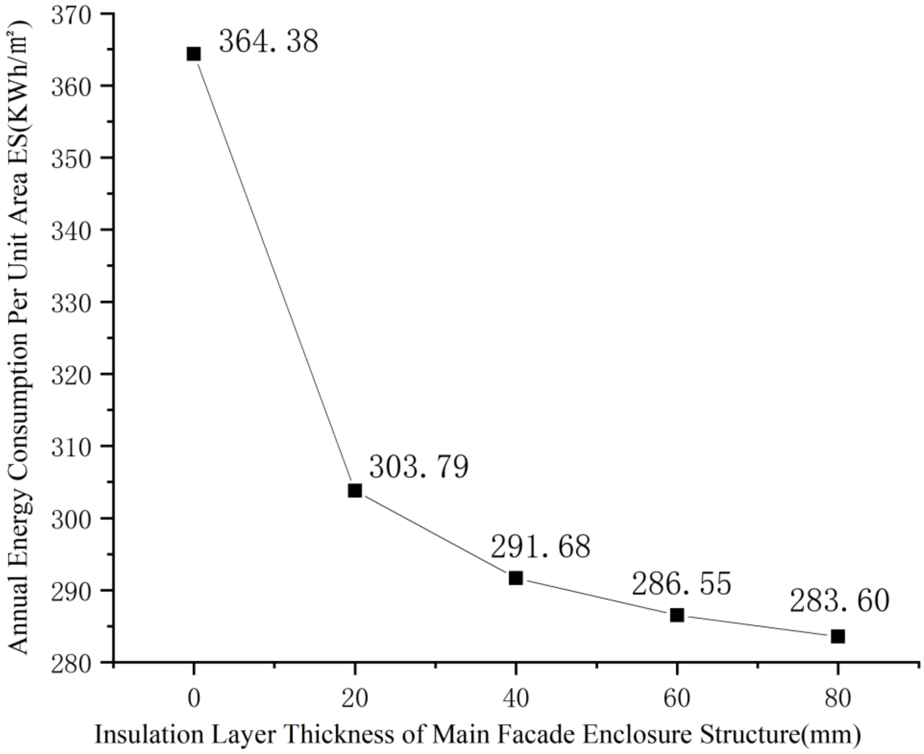
building models of this level analysis are all transformed from building model A. The temperature control system is set to full air-conditioning system, and the temperature comfort range is set to 18~26℃. The thermal insulation material is common extruded polystyrene board with thermal conductivity of 0.033W/m·K. The window-wall ratio is adjusted by changing the window size of the front envelope structure. The specific size is shown in TABLE III, and the level analysis results are shown in Fig 6.

TABLE III Wall-window ratio and corresponding window size

window size	Window-wall ratio	window size	Window-wall ratio
1.2m×1.2m	0.12	1.4m×1.5m	0.16
1.6m×1.6m	0.19	1.7m×1.7m	0.21
1.8m×1.8m	0.23		



(a) Insulation layer thickness of main facade enclosure structure

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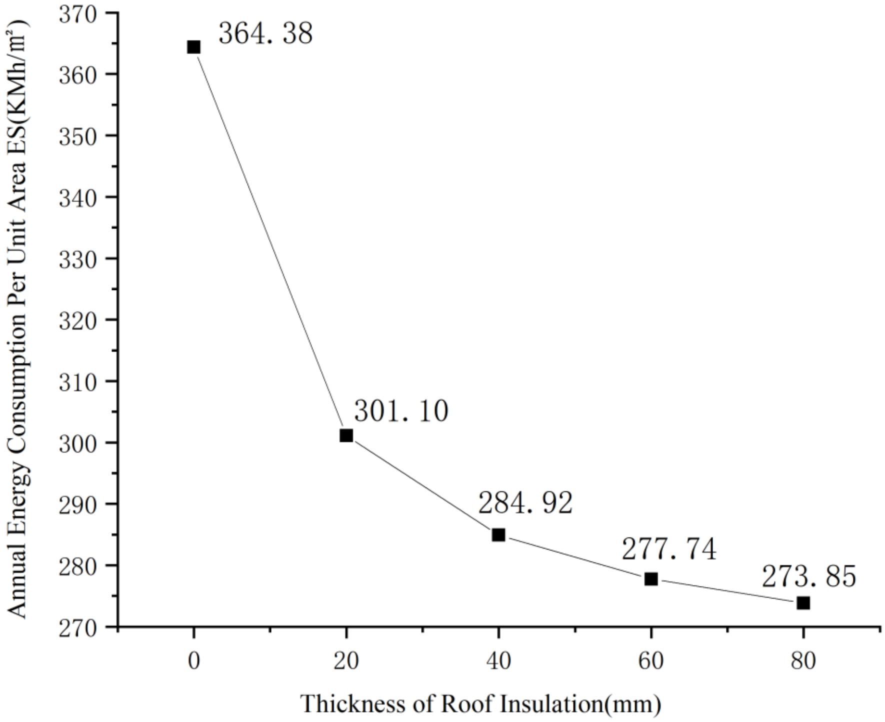
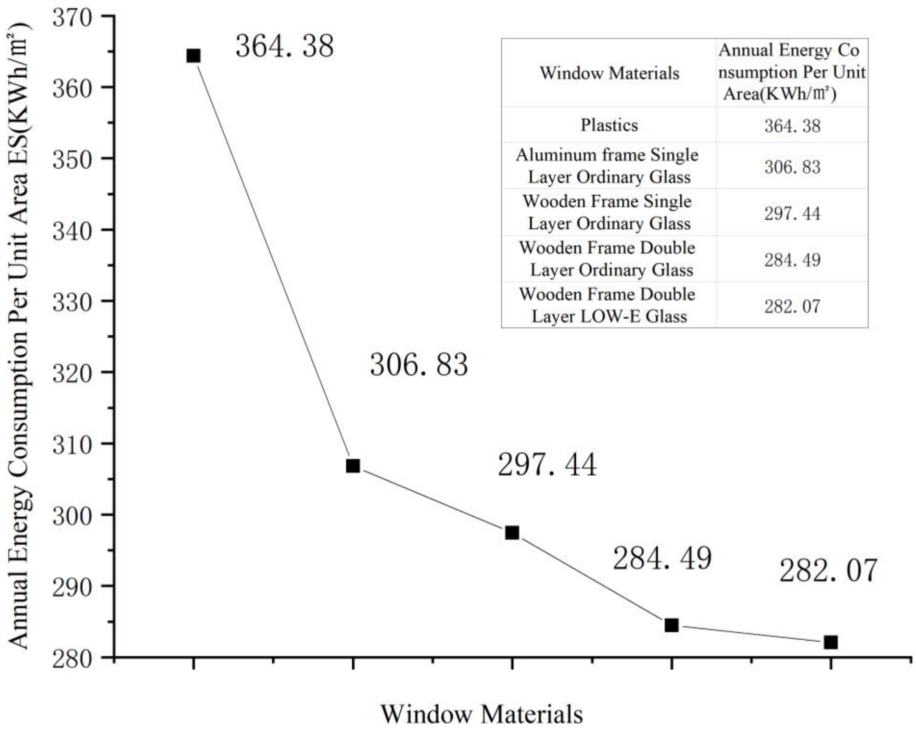


(b) Thickness of roof insulation



(c) Window materials

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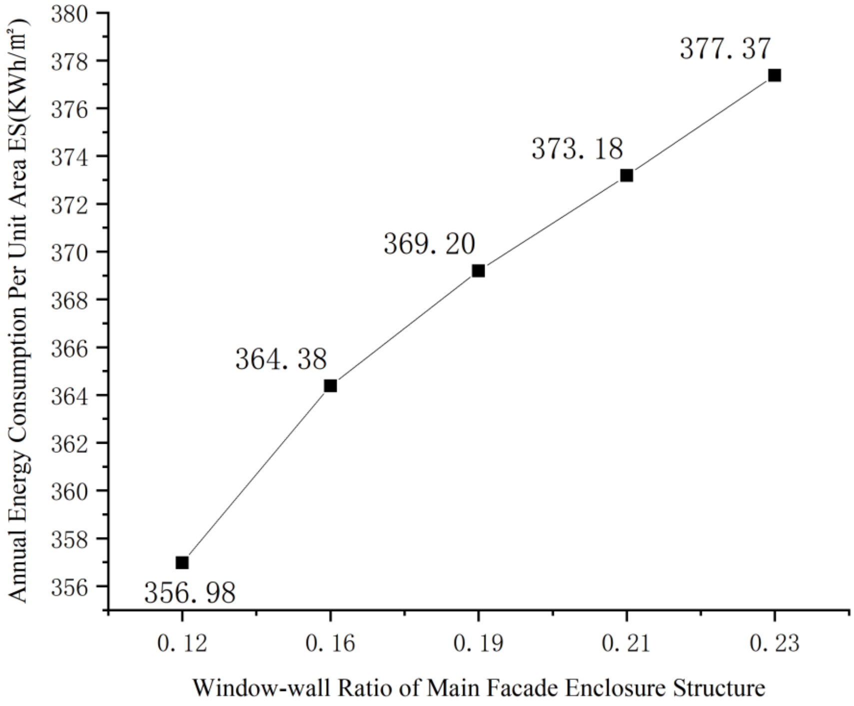

(d) Window-wall ratio of main facade enclosure structure

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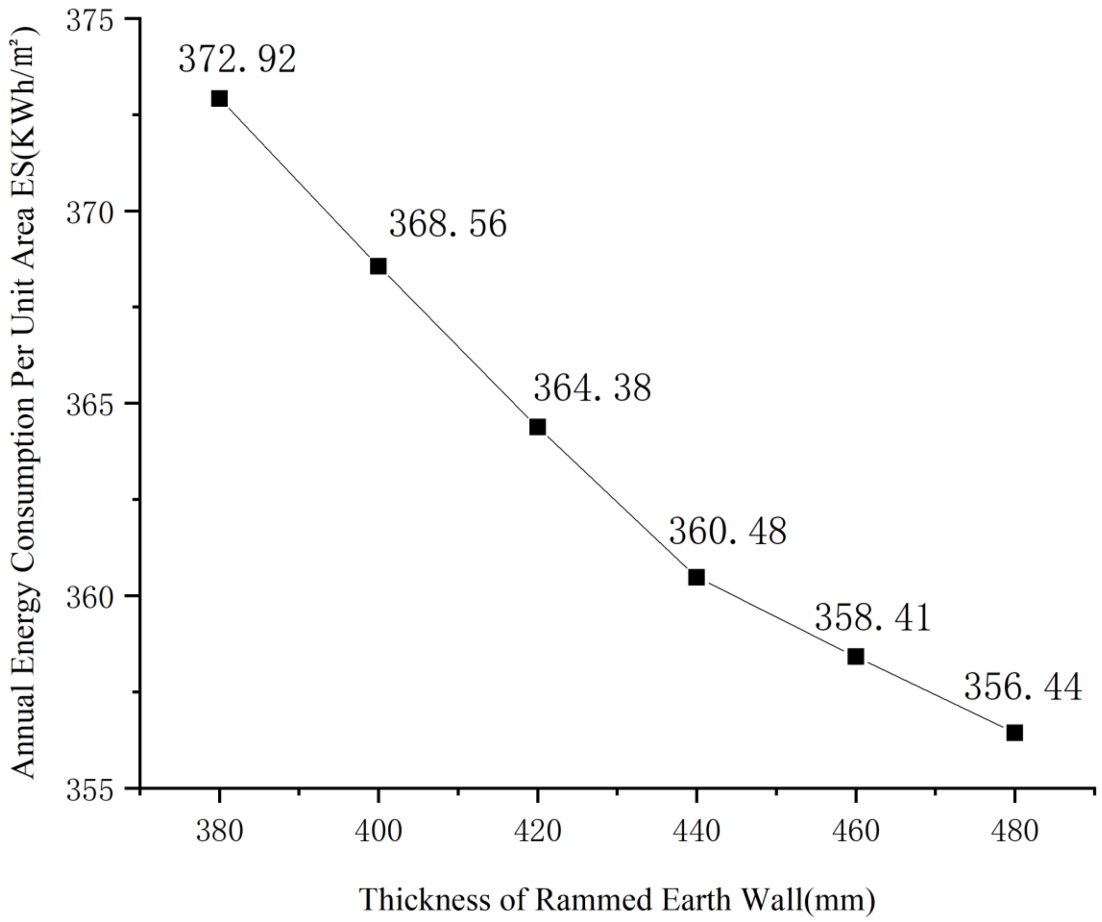

(e) Thickness of rammed earth wall

Fig 6 Optimization factor level analysis chart

By analyzing the numerical relationship between the optimization factor level value and the optimization target value shown in Fig 6, it is found that the thermal insulation layer thickness of the front envelope structure, the thermal insulation layer thickness of the roof, and the window material exhibit the same variation forms, with their level values negatively correlated with the optimization target value. Moreover, after the level value reaches a certain level, there is gradually slower reduction in optimization target value, so level value with higher economy should be selected when the optimization target value is similar. The level value of window-wall ratio is positively correlated with the optimization target value, and the variation range is similar, so the level value with better optimization target value should be selected. The level value of rammed earth wall thickness is negatively correlated with the optimization target value, and the variation range is similar, so selection of level value is based on the principle that optimization target value is better. Based on the above analysis, appropriate optimization level is selected for each optimization factor, and the factor level table is established as shown in TABLE IV. Among the levels of various optimization factors, A1, B1, C1, D2, and E1 indicate the current levels of traditional dwellings.

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TABLE IV Factor level table

Optimization factor	Level 1	Level 2	Level 3	Level 4
A thermal insulation layer thickness of front envelope structure (mm)	0	20	40	60
B thermal insulation layer thickness of roof (mm)	0	20	40	60
C window material	plastic	Aluminum-framed single layer ordinary glass	Wooden-framed single layer ordinary glass	Wooden-framed double layer ordinary glass
D window-wall ratio	0.12	0.16	0.19	0.21
E Rammed earth wall thickness (mm)	420	440	460	480

4.2 Experiment Optimization and Numerical Analysis

There are 5 optimization factors in this Taguchi test, and each optimization factor has 4 levels, so the orthogonal table of L_{16} (4^5) was selected. After establishing the building models corresponding to the 16 tests using the Ecotect simulation software, the annual building energy consumption E of each model was simulated, and ES was calculated by formula (1) to obtain the orthogonal table of Taguchi test, as shown in TABLE V.

TABLE V Orthogonal table of taguchi test

Factor test	Experiment matrix					Annual energy consumption per unit area E_S ($kw \cdot h/m^2$)
	A	B	C	D	E	
1	1	1	1	1	1	356.98
2	1	2	2	2	2	240.02
3	1	3	3	3	3	221.33
4	1	4	4	4	4	192.98
5	2	1	2	3	4	247.05
6	2	2	1	4	3	249.37
7	2	3	4	1	2	139.90
8	2	4	3	2	1	157.41
9	3	1	3	4	2	233.56
10	3	2	4	3	1	152.12

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11	3	3	1	2	4	204.54
12	3	4	2	1	3	136.32
13	4	1	4	2	3	200.55
14	4	2	3	1	4	145.05
15	4	3	2	4	1	172.53
16	4	4	1	3	2	205.56

In this study, the test results were analyzed using average value analysis method. By calculating the annual average energy consumption per unit area corresponding to different levels of each optimization factor, the responsiveness of each optimization factor to the optimization goal was analyzed, with the calculation results shown in TABLE VI. By analyzing the response values and ranking of each optimization factor, it is found that the degree of influence on the indoor thermal environment of traditional dwellings in cold regions is ranked in descending order as that of thermal insulation layer thickness of roof, window material, thermal insulation layer thickness of front envelope structure, window-wall ratio of front envelope structure, rammed earth wall thickness.

TABLE VI Optimization factor response table

	A	B	C	D	E
Level 1	252.83	259.54	254.11	194.56	209.76
Level 2	198.43	196.64	198.98	200.63	204.76
Level 3	181.64	184.58	189.34	206.52	201.89
Level 4	180.92	173.07	171.39	212.11	197.41
Response value	71.91	86.47	82.72	17.55	12.35
Ranking	3	1	2	4	5

4.3 Determination and Verification of the Optimization Scheme

Through analysis, it is found that the optimization target value corresponding to level 4 of factor A is optimal, but the effect is unobvious compared to level 3. Based on economic considerations, level 3 is selected as factor A in the optimization scheme; level 4 with the best optimization target value is selected as factor B and factor C; level 1 with the best optimization target value is selected as factor D; level 4 with the best optimization target value is selected as factor E. In the end, the optimization design scheme is A3B4C4D1E4, that is, the thermal insulation layer thickness of the front envelope structure is 40mm, the thermal insulation layer thickness of the roof is 60mm, the window material is wooden-framed double layer ordinary glass, the window-wall ratio of the front envelope structure is 0.12, and the rammed earth wall thickness is 460mm. The annual energy consumption E of the building in the simulation optimization scheme is simulated, and the annual energy consumption ES per unit area is calculated according to formula (1). The comparison of each index before and after optimization is shown in TABLE VII.

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TABLE VII Comparison of indexes before and after optimization

Scheme	A Thermal insulation thickness of front envelope structure	B Thermal insulation thickness of roof	C window material	D Window-wall ratio	E Rammed earth wall thickness	Annual energy consumption per unit area/(KWh/m^2)
Before optimization	0	0	PMMA	0.16	420mm	364.38
After optimization	40mm	60mm	Wooden-framed double layer ordinary glass	0.12	460mm	117.60

According to the simulation results, the annual energy consumption index of traditional dwellings is 364.38 KWh/m^2 before optimization. After the building front envelope is installed with 40mm thermal insulation layer, the roof is installed with 60mm thermal insulation layer, and the window material is changed to wooden-framed double layer glass, window-wall ratio is adjusted to 0.12 and the rammed earth wall thickness is increased to 460mm, the annual energy consumption E_S per unit area is reduced to 117.60kw·h/m^2, with a decrease of 67.7%, showing remarkable optimization effect on the indoor thermal environment of the building.

V. CONCLUSION

Taking Qingcheng Ancient Town in Lanzhou as an example, with the annual energy consumption ES per unit area as the optimization target, the thermal insulation layer thickness of the front envelope, the thermal insulation layer thickness of the roof, the window-wall ratio of the front envelope structure, the window material and the rammed earth wall thickness as optimization factor, appropriate optimization level was selected, then the optimization design scheme for indoor thermal environment of traditional dwellings in cold regions was determined through Taguchi test, and the optimization scheme was simulated and verified with the help of Ecotect simulation software. Finally, the following conclusions are drawn:

(1) According to the measured data and software simulation, the main factors influencing the indoor thermal environment of local traditional dwellings include the front envelope structure, roof material, window material, window-wall ratio and rammed earth wall thickness.

(2) According to the average value analysis and the optimization factor response table, the influence on the optimization target is ranked in descending order as that of thermal insulation layer thickness of roof, window material, thermal insulation layer thickness of front envelope structure, window-wall ratio of front envelope structure and rammed earth wall thickness.

(3) By using Taguchi method to optimize the indoor thermal environment of traditional dwellings in cold regions, it is possible to effectively reduce the annual energy consumption value of buildings and improve the indoor thermal environment comfort of buildings.

(4) Through the Ecotect software simulation analysis, feasibility of the optimization design scheme is verified.

To sum up, Taguchi method can effectively increase the indoor thermal environment comfort of traditional dwellings in cold regions, which can be used to formulate optimization design scheme for the indoor thermal environment of buildings.

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