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Optimization of Energy Conservation for Rural Residential Buildings in the Guangzhong Plain

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Abstract. Most of the rural residential buildings in China are built by occupants themselves lacking of building energy-efficiency design, leading to the problems of poor indoor thermal environment and energy waste. To maximize energy efficiency and minimize life-cycle costs in the premise of thermal comfort, a study was conducted to find the optimal combination of energy conservation factors for rural residential buildings on Guanzhong Plain. The orthogonal test is designed to figure out the optimal solution among an array of building energy-efficiency design factors. Nine design factors were selected to establish 32 combinations in the orthogonal test. Taking the energy consumption per unit area as the evaluation value, the factors in descending order of influencing building energy consumption were concluded and the optimal combination for residential building design was obtained. These results provide an explicit approach to design energy-efficiency dwelling in Guanzhong rural area.

Keywords. Energy-efficiency optimal design, orthogonal test, Guanzhong Plain

1. Introduction

The total area of rural residential buildings in China was 229 million m^2. The commodity energy consumption of rural dwelling buildings was 216 million tce, and it took more than 22% of the total building energy consumption [1]. Because of improvements in living quality requirements of rural dwellers, rising along with economic development, energy consumption of rural dwelling buildings is expected to rise in the near future [1,2]. There is an urgent need to optimize the energy efficiency of rural residential buildings, reduce building energy consumption, and improve the quality of living level.

The energy consumption of buildings is affected by many factors [3]. When considering energy-saving optimization, various factors are combined to form a variety of design schemes. In design practice, calculating the energy consumption for each

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scheme to select the most suitable requires considerable manpower and material resources. For easier access to minimize energy consumption, optimization design methodology has been raised to identify and select building shapes as well as building design parameters [4]. Guanzhong Plain is one of the important densely populated area in the Western China [5]. Numerous studies try to find the optimum design approach of the rural dwelling in Guanzhong plain to achieve building energy efficiency. J. He analyzed the energy conservation in rural dwellings of Xi'an in Guanzhong plain according to the individual measures affecting the energy efficiency of buildings [6]. Z. Yu proposed the roof slope and its material construction, wall insulation, and window design points for Guanzhong rural dwellings [7]. However, very limited investigations have focused on the appropriate of energy conservation for rural residential buildings in Guanzhong plain based on the overall performance.

The objective of this study is to investigate the optimization of rural residential buildings in Guanzhong plain that maximizes its energy efficiency, and provide a primary research foundation to build an adequate rural dwelling design guideline for Guanzhong Plain in the future.

2. Method

2.1. Orthogonal Experiment

An orthogonal test is a method of scientifically arranging and analyzing multi-factor and multi-level tests, which can be used to greatly reduce the number of tests and evenly match the combinations of various factors and levels [8]. Orthogonal test method is often used to optimize buildings on account of its easier operation, such as energy saving optimization [9]. In this study, the orthogonal test method was used to obtain a suitable local energy-saving plan for rural residential buildings of Guanzhong plain which general plane graph is shown in figure 1.

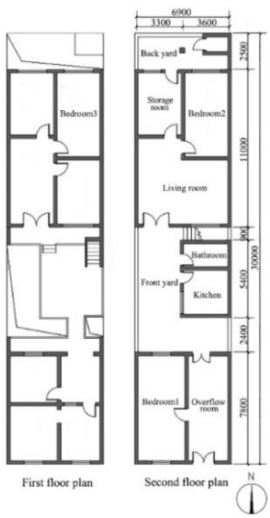

Figure 1. The plane graph of rural residential buildings in Guanzhong Plain.

The factor impact on building energy consumption is numerous. In order to simplify the research work, nine main factors affecting residential energy consumption were selected: plane (A), floor height (B), orientation (C), south window wall ratio (D), north window wall ratio (E), external wall heat transfer coefficient (F), roof heat transfer coefficient (G), exterior window heat transfer coefficient (H), and door heat transfer coefficient (I). According to the current situation of rural housing and related standards [10,11], 4 levels are set for each factor, as shown in table 1.

Table 1. Levels of factors for energy consumption in rural dwelling buildings in Guanzhong Plain.

Design variables	Factors								
	A	B	C	D	E	F	G	H	I
	Plane (m×m)	Floor height (m)	Orientation	South window to wall ratio	North window to wall ratio	U value of external wall [W/(m^2·K)]	U value of roof [W/(m^2·K)]	U value of window [W/(m^2·K)]	U value of door [W/(m^2·K)]
Level 1	6.9m×8m	2.8	30°east of south	0.15	0.20	2.00	1.62	4.7	3.5
Level 2	6.9m×11m	3.0	15° east of south	0.25	0.25	1.40	1.00	3.6	3.0
Level 3	9.7m×8m	3.3	south	0.35	0.30	0.65	0.50	2.5	2.5
Level 4	9.7m×11m	3.5	15° west of south	0.45	0.35	0.45	0.35	2.0	2.0

The conventional L32 (49) orthogonal array was selected, regardless of the interaction between the factors, and each factor was set in the orthogonal table to fill in the corresponding position. A total of 32 design schemes were obtained, as shown in table 2.

Table 2. Design schemes for the orthogonal array.

Scheme number	Factors								
	A	B	C	D	E	F	G	H	I
	Plane	Floor height	Orientation	South window to wall ratio	North window to wall ratio	U value of external wall	U value of roof	U value of window	U value of door
1	6.9×8	2.8	30°east of south	0.15	0.20	2.00	1.62	4.7	3.5
2	6.9×8	3.0	15°east of south	0.25	0.25	1.40	1.00	3.6	3.0
3	6.9×8	3.3	south	0.35	0.30	0.65	0.50	2.5	2.5
4	6.9×8	3.5	15°west of south	0.45	0.35	0.45	0.35	2.0	2.0
5	6.9×11	2.8	30°east of south	0.25	0.25	0.65	0.50	2.0	2.0

6	6.9×11	3.0	15°east of south	0.15	0.20	0.45	0.35	2.5	2.5
7	6.9×11	3.3	south	0.45	0.35	2.00	1.62	3.6	3.0
8	6.9×11	3.5	15°west of south	0.35	0.30	1.40	1.00	4.7	3.5
9	9.7×8	2.8	15°east of south	0.35	0.35	2.00	1.00	2.5	2.0
10	9.7×8	3.0	30°east of south east	0.45	0.30	1.40	1.62	2.0	2.5
11	9.7×8	3.3	15°west of south	0.15	0.25	0.65	0.35	4.7	3.0
12	9.7×8	3.5	south	0.25	0.20	0.45	0.50	3.6	3.5
13	9.7×11	2.8	15°east of south	0.45	0.30	0.65	0.35	3.6	3.5
14	9.7×11	3.0	30° east of south	0.35	0.35	0.45	0.50	4.7	3.0
15	9.7×11	3.3	15°west of south	0.25	0.20	2.00	1.00	2.0	2.5
16	9.7×11	3.5	south	0.15	0.25	1.40	1.62	2.5	2.0
17	6.9×8	2.8	15°west of south	0.15	0.35	1.40	0.50	3.6	2.5
18	6.9×8	3.0	south	0.25	0.30	2.00	0.35	4.7	2.0
19	6.9×8	3.3	15°east of south	0.35	0.25	0.45	1.62	2.0	3.5
20	6.9×8	3.5	30°east of south	0.45	0.20	0.65	1.00	2.5	3.0
21	6.9×11	2.8	15°west of south	0.25	0.30	0.45	1.62	2.5	3.0
22	6.9×11	3.0	south	0.15	0.35	0.65	1.00	2.0	3.5
23	6.9×11	3.3	15°east of south	0.45	0.20	1.40	0.50	4.7	2.0
24	6.9×11	3.5	30°east of south	0.35	0.25	2.00	0.35	3.6	2.5
25	9.7×8	2.8	south	0.35	0.20	1.40	0.35	2.0	3.0
26	9.7×8	3.0	15°west of south	0.45	0.25	2.00	0.50	2.5	3.5
27	9.7×8	3.3	30°east of south	0.15	0.30	0.45	1.00	3.6	2.0
28	9.7×8	3.5	15°east of south	0.25	0.35	0.65	1.62	4.7	2.5
29	9.7×11	2.8	south	0.45	0.25	0.45	1.00	4.7	2.5
30	9.7×11	3.0	15°west of south	0.35	0.20	0.65	1.62	3.6	2.0
31	9.7×11	3.3	30°east of south	0.25	0.35	1.40	0.35	2.5	3.5
32	9.7×11	3.5	15°east of south	0.15	0.30	2.00	0.50	2.0	3.0

The analysis of orthogonal test results mainly considers the mean value of the range of each factor and each factor at different levels. The calculation formula is as follows:

K_i^j is defined as the sum of the relevant test results of the ith level of factor j; then, the mean value of the ith level of the factor is

$$\text{Mean value: } k_i^j = \frac{K_i^j}{\text{Number of tests at } i\text{th level}} \quad (1)$$

R^j is defined as the difference between the minimum value and the maximum value in the mean value of each level of factor j; then, the range of factor j is

$$\text{Difference: } R^j = k_{i_{max}}^j - k_{i_{min}}^j \quad (2)$$

The aforementioned formula was used to calculate and process the results of the orthogonal test and obtain the average value for each factor and the range of each factor. The primary and secondary order of the impact of each factor on building energy consumption could then be determined. The optimal scheme and the most unfavorable scheme of rural housing in Guanzhong Plain could be obtained.

2.2. Simulation of Building Energy Consumption

The building energy consumption simulation software Energyplus was applied to analyze the energy consumption of dwellings in this study. The building models and thermal properties of envelops were established according to the orthogonal experiment. The setpoints of cooling and heating were set to 30 ℃ and 14 ℃ respectively and the air change per hour, lighting load, and occupancy were set referring to Ref. [11]. Since there is few indoor equipment in rural dwellings, the equipment load can be negligible.

3. Results and Discussion

3.1. Analysis the Influence Factors of Energy Consumption

The energy consumption of 32 design schemes for this rural dwelling building in Guanzhong Plain is simulated and calculated, shown in figure 2. From the results of the orthogonal test, the range of each column can reflect the impact of changes in various factors on the test results, shown in table 3. The larger the range, the greater the impact of the change of the factor on the test results. The factor with the largest range is the most important factor. In this experiment, the range value was RF > RG > RB > RA > RH > RD > RE > RC > RI. It can be indicated that the impact of these nine factors on building energy consumption from primary to secondary is as follows: external wall heat transfer coefficient, roof heat transfer coefficient, floor height, plane, heat transfer coefficient of exterior windows, south window wall ratio, north window wall ratio, orientation, and heat transfer coefficient of door.

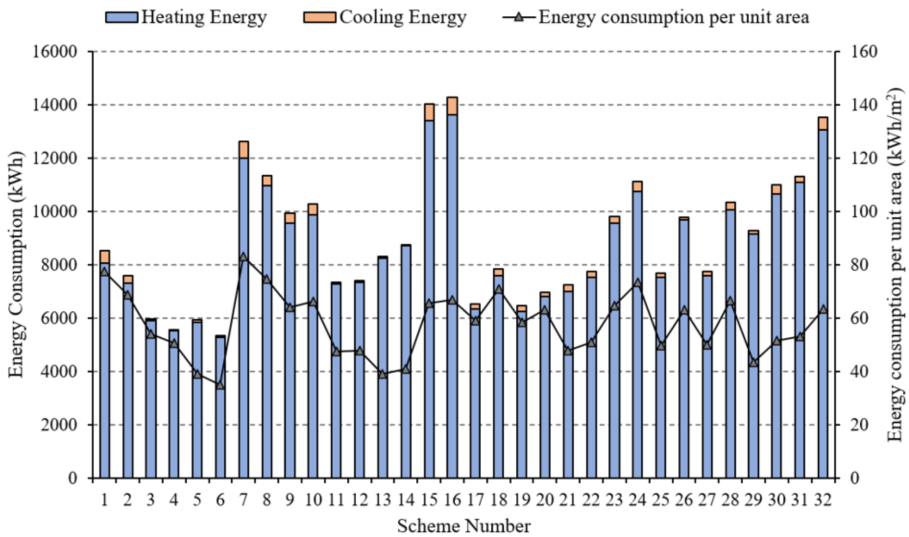

Figure 2. Energy consumption of different schemes.

Table 3. Results of the orthogonal array.

Average building energy consumption (kWh/m2)	Factors								
	A	B	C	D	E	F	G	H	I
	Plane	Floor height	Orientation	South window to wall ratio	North window to wall ratio	U value of external wall	U value of roof	U value of window	U value of door
k_1^j	62.81	52.39	57.88	56.26	56.85	70.15	64.77	60.79	58.04
k_2^j	58.60	55.97	57.49	57.43	57.55	62.88	60.09	59.03	58.02
k_3^j	56.78	59.55	58.38	58.35	58.27	51.45	54.03	55.89	57.96
k_4^j	53.02	63.30	57.46	59.18	58.54	46.73	52.32	55.49	57.19
R^j	9.79	10.91	0.92	2.92	1.69	23.42	12.45	5.30	0.85
Factor order	F > G > B > A > H> D > E > C > I								
Most favorable scheme	A4- B1- C4- D1- E1- F4- G4- H4- I4								

Least favorable scheme	A1- B4- C3- D4- E4- F1- G1- H1- I1

3.2. Comparison of different Combinations

The evaluation index of the orthogonal test is energy consumption per unit area; hence, the index is means the more conducive it is to energy saving. Therefore, the optimal scheme combination is A4-B1-C4-D1-E1-F4-G4-H4-I4, and the most unfavorable scheme combination is A1-B4-C3-D4-E4-F1-G1-H1-I1. The simulation of the optimal combination and the most unfavorable combination shows that the energy consumption per unit area of the optimal combination is 29.33 kWh/m^2, and the most unfavorable combination is 98.27 kWh/m^2, which is more than three times that of the optimal combination. This shows that it is necessary to optimize the energy conservation of rural houses in Guanzhong Plain.

3.3. Energy Consumption for each Setting

Each envelope structure has a primary and secondary impact on energy consumption. Therefore, the main influencing factors should be given priority in energy-saving design; hence, the external walls, roofs, and external windows are gradually optimized in order to make the heat transfer coefficient reach the corresponding value of the optimal plan. Consequently, the optimization plan 1 (optimized wall), optimization plan 2 (optimized wall and roof) and optimization plan 3 (optimized wall, roof and exterior windows) were identified. As the door has a minimal impact on energy consumption, it was not considered. Energy consumption simulation was carried out through Energy Plus to obtain the heating and cooling energy consumption of each scheme. The optimization schemes and energy consumption results are shown in table 4.

Table 4. The optimization scheme and its energy consumption.

Scheme	U value of external window [W/(m^2·K)]	U value of external wall [W/(m^2·K)]	U value of roof [W/(m^2·K)]	Heating energy consumption (kWh)	Cooling energy consumption (kWh)	Annual energy consumption (kWh)	Energy consumption per unit area (kWh/m^2)
Original scheme	4.7	2.00	1.62	12751.78	731.11	13482.89	63.18
Optimization scheme 1	4.7	0.45	1.62	9180.97	310.84	9491.81	44.48
Optimization scheme 2	4.7	0.45	0.35	6756.70	36.48	6793.18	31.83
Optimization scheme 3	2.0	0.45	0.35	6312.34	35.79	6348.13	29.75

4. Conclusion

Most of the rural dwelling buildings in China are lacking building energy-efficiency design, leading to the problems of poor indoor thermal environment and energy waste. Using orthogonal test analysis, it was found that the factors influencing the energy consumption of rural residential buildings in the Guanzhong Plain area from primary to secondary are the roof heat transfer coefficient, external wall heat transfer coefficient, floor height, plane, external window heat transfer coefficient, south and north window wall ratio, orientation, and door heat transfer coefficient. The optimal energy-saving scheme was found to be a 9.7 m×11 m plane, a 2.8 m story height, facing southwest by 15°, a south window wall ratio of 0.15, a north window wall ratio of 0.2, an external wall heat transfer coefficient of 0.45 W/(m^2·K), a roof heat transfer coefficient of 0.35 W/(m^2·K), an exterior window heat transfer coefficient of 2.0 W/(m^2·K), and an external door heat transfer coefficient of 2.0 W/(m^2·K).

Basic study on the current state of thermal environment and energy consumption in rural dwelling buildings helps better understanding of how to improve living environment. The results have positive effect on energy-efficiency building design in Guanzhong Plain rural area.

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References

[1] Building Energy Research Center of Tsinghua University. 2020 Annual Report on China Building Energy Efficiency. Beijing: China Architecture and Building Press, 2020.
[2] Li B, You L, Zheng M, Wang Y, Wang Z. Energy consumption pattern and indoor thermal environment of residential building in rural China. Energy and Built Environment. 2020; 1(3): 327-336.
[3] Zhao H, Magoulès F. A review on the prediction of building energy consumption. Renewable and Sustainable Energy Reviews. 2012; 16(6): 3586-3592.
[4] Ihm P, Krarti M. Design optimization of energy efficient residential buildings in Tunisia. Building and Environment. 2012; 58: 81-90.
[5] Tian Y, Yue T, Zhu L, Clinton Nicholas. Modeling population density using land cover data. Ecological Modelling. 2005; 189: 72-88.
[6] He J. Research on the energy efficiency design optimization of residential building in the rural area of Xi’an. Xi’an: Xi’an University of Architecture and Technology, China. 2014.
[7] Yu Z. Study on the patterns of Guanzhong Folk Dwellings. Beijing: The 7th International Symposium on Architectural Interchanges in Asia; 2008 Jul 15-17; Beijing. p.356-358.
[8] Gong X, Akashi Y, Sumiyoshi D. Optimization of passive design measures for residential buildings in different Chinese areas. Building and Environment. 2012; 58: 46-57.
[9] Hwang RL, Lin TP, Liang HH, Yang KH, Yeh TC. Additive model for thermal comfort generated by matrix experiment using orthogonal array. Building and Environment. 2008; 44:1730-1739.
[10] China Industry Standard (JGJ 26-2018). Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones. Beijing: China Building Industry Press, 2018.
[11] China National Standard (GBT 50824-2013). Design Standard for Energy Efficiency of Rural Residential Buildings. Beijing: China Building Industry Press, 2013.