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# *Analysis on Energy Saving Potential of Residential Building Enclosure Based on Orthogonal Experimental Analysis*

**He Jun[1], Gao Ke[2]**

[1]*China Construction Engineering Design Co., Ltd, Hefei Anhui, 230041, China*
[2]*Anhui Zhongrun Road and Bridge Engineering Co., Ltd, Anqing Anhui, 246400, China*

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***Abstract:*** According to the orthogonal experimental design method, DeST is used to simulate the energy consumption of the residential buildings in hot summer and cold winter zone. Through range analysis, the order of five factors affecting the energy consumption of residential buildings in hot summer and cold winter zone is determined, namely, the south window-wall ratio, followed by the north window-wall ratio, the external wall U-value, the outer window U-value, and finally the roof U-value. At the same time, the optimal scheme and the most unfavorable scheme of the outer envelope structure design of residential buildings with the above factors and levels are obtained. Compared with the most unfavorable scheme, the energy saving rate of the optimal scheme is increased by 40.96%.

## 1. Introduction

According to statistics, the proportion of total building energy consumption in China has risen from 19.12% in 2014 to 46.5% in 2018 [1] [2]. The rapid rise in the proportion of building energy consumption is hindering the healthy development of China's economy. Realizing building energy conservation has become the primary task of the Chinese government to improve the social energy use efficiency.

Building energy saving is included in various stages of the whole life cycle of the building. One of the key stages is the energy saving design of the building scheme stage, which contains more than 30% of the building energy saving potential [3]. Generally speaking, the building from design to use can be divided into scheme design, preliminary design, detailed design and other 7 stages [4]. As the first step, scheme design has an important impact on the improvement of building energy conservation. It is an important stage for architects to make decisions on building, body and space scheme after comprehensively considering various restrictive factors. At this stage, the determined building shape, space, epidermis and other parameters are the key to affect the building energy consumption and indoor ventilation and natural lighting. Therefore, analyzing the influence of various factors of building envelope on building load in the phase of building scheme is the key to determine the best building energy saving scheme and realize building energy saving.

Hot summer and cold winter zone is an important climate zone in China, where about half of the national population lives in [5]. There is hot in summer, wet and cold in winter, with drastic climate conditions change, resulting in high building energy consumption in the area. Therefore, the building energy saving of residential buildings in this area has a very important impact on the improvement of national energy efficiency. By establishing building model, the load change of residential buildings in hot summer and cold winter zone is simulated by using building energy consumption simulation software. According to the orthogonal experimental analysis method, experimental table L16(45) is obtained, and 16 groups of orthogonal experimental results are simulated. The order of influence of each factor of envelope structure on building energy consumption and the best design scheme of each factor of the envelope structure are obtained by range analysis. The experimental results can provide a reference for the energy saving design of buildings in hot summer and cold winter zone.

## 2. Experimental design and energy consumption simulation

Factors affecting building energy consumption include building non-ontology factors and the ontology factors. The building non-ontology factors include outdoor meteorological parameters, indoor personnel, indoor equipment heat efficiency, etc. The building ontology factors are mainly building envelope, such as exterior wall structure, roof structure, outer window structure, south window-wall ratio, and north window-wall ratio [6] [7]. Assuming that there are four options for each building envelope factor, then the comprehensive experiment needs to be done 45 times, that is, 1,024 times, which is a very large and unnecessary workload. After the orthogonal experiment design, the above experiment only needs 16 times to get enough experimental data for analysis.

### 2.1 Orthogonal experimental design

Orthogonal experimental design is a multi-factor, multi-level experimental design method, which is designed to select some representative points from the comprehensive experiment, which can effectively reduce the workload. According to the selected factors and levels, the orthogonal experiment table was generated by querying the relevant literature or using the computational software, and the building energy consumption simulation was conducted according to the experimental arrangement [8].

### 2.2 Energy consumption simulation

This experiment uses DeST (Designer's Simulation Toolkit) building energy consumption simulation software developed by Tsinghua University. A large number of scholars' research results show that the software is an accurate and reliable building energy consumption simulation software.

#### 2.2.1 Building model

Hefei city is located in the middle of hot summer and cold winter zone in China. Its climate parameters have obvious climate characteristics of hot summer and cold winter zone. Figure 1 shows the Hefei meteorological data built in DeST. This paper selects a residential building in Hefei as the research object, and establishes a model in DeST. The plane layout of the building is shown in Figure 2. The building has 7 floors and a height of 2.90m. The roof form is flat, and the total construction area is 1883.98$m^2$.The cooling and heating area is 1582.49$m^2$. The main rooms in the house are living room, bedroom, study, kitchen and toilet.

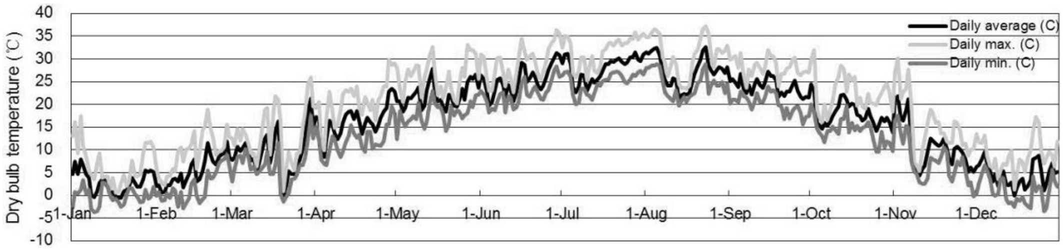


Figure 1 Meteorological data of Hefei area

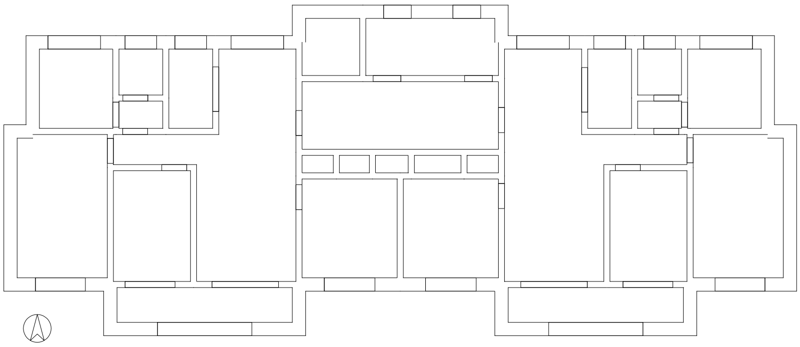

Figure 2 Building Plan

### 2.2.2 Simulation parameter setting

The meteorological parameters in Hefei were selected from DeST as the external conditions of this study. The main purpose of this study is to investigate the influence of various factors of building envelope on building energy consumption, in addition to the factors under investigation, other factors such as the number of people in the room, staff time, furniture coefficient, lighting heat transfer efficiency and other factors are adopted the default setting. See Table 1 for details. External wall insulation material adopts rock wool board, and roof insulation material adopts extruded polystyrene foam board (XPS).

Table 1: Orthogonal experimental factors and levels

| Levels | Exterior wall A | | Roof B | | Exterior window C | | South window-wall ratio D | North window-wall ratio E |
|---|---|---|---|---|---|---|---|---|
| | Insulation layer thickness X / (mm) | U-value / [W/(m$^2$•K)] | Insulation layer thickness Y / (mm) | U-value / [W/(m$^2$•K)] | Structure | U-value / [W/(m$^2$•K)] | | |
| 1 | 50 | 0.513 | 70 | 0.401 | ordinary double-layer insulating glass 6mm + 12A + 6mm | 2.5 | 0.45 | 0.40 |
| 2 | 60 | 0.454 | 80 | 0.359 | double glazing glass 5mm+20A+5mm | 2.3 | 0.35 | 0.30 |
| 3 | 70 | 0.408 | 90 | 0.325 | multiple glazing 5mm+6A+5mm+6A+5mm | 2.1 | 0.25 | 0.20 |
| 4 | 80 | 0.370 | 100 | 0.296 | double layer with argon insulating glass 6mm + 12 argon + 6mm | 1.9 | 0.15 | 0.10 |

Note: 1. External wall structure: 20mm cement mortar + Xmm rock wool board + 370mm, concrete porous brick + 20mm cement mortar. 2. Roof structure: 30mm cement mortar + 30mm, light concrete + Ymm extrusion polystyrene foam board (XPS) + 20mm cement mortar + 120mm reinforced concrete

### 2.2.3 Results of the simulation

According to the above factors and levels of the envelope structure, SPSS software was used to generate orthogonal experiment table $L_{16}(4^5)$. And DeST software is used for load simulation. The orthogonal experiment table and load simulation results are shown in Table 2.

Table 2: The orthogonal experiments and load simulation results

| Number | External wall U-value A / [W/(m²•K)] | Roof U-value B / [W/(m²•K)] | Outer window U-value C / [W/(m²•K)] | South window-wall ratio D | North window-wall ratio E | Annual cold and heat load index per unit floor area / [kWh/(m²•a)] |
|---|---|---|---|---|---|---|
| 1 | 0.513 | 0.401 | 2.50 | 0.45 | 0.40 | 28.00 |
| 2 | 0.513 | 0.359 | 2.10 | 0.15 | 0.30 | 21.66 |
| 3 | 0.513 | 0.325 | 1.90 | 0.35 | 0.20 | 21.18 |
| 4 | 0.513 | 0.296 | 2.30 | 0.25 | 0.10 | 20.88 |
| 5 | 0.454 | 0.401 | 1.90 | 0.25 | 0.30 | 20.95 |
| 6 | 0.454 | 0.359 | 2.30 | 0.35 | 0.40 | 24.49 |
| 7 | 0.454 | 0.325 | 2.50 | 0.15 | 0.10 | 19.37 |
| 8 | 0.454 | 0.296 | 2.10 | 0.45 | 0.20 | 22.29 |
| 9 | 0.408 | 0.401 | 2.30 | 0.15 | 0.20 | 18.91 |
| 10 | 0.408 | 0.359 | 1.90 | 0.45 | 0.10 | 20.95 |
| 11 | 0.408 | 0.325 | 2.10 | 0.25 | 0.40 | 21.49 |
| 12 | 0.408 | 0.296 | 2.50 | 0.35 | 0.30 | 22.72 |
| 13 | 0.370 | 0.401 | 2.10 | 0.35 | 0.10 | 18.98 |
| 14 | 0.370 | 0.359 | 2.50 | 0.25 | 0.20 | 19.76 |
| 15 | 0.370 | 0.325 | 2.30 | 0.45 | 0.30 | 23.27 |
| 16 | 0.370 | 0.296 | 1.90 | 0.15 | 0.40 | 19.20 |

## 3. Analysis of experimental results

### 3.1 Range analysis

The main analysis methods of orthogonal experimental results are range analysis and variance analysis. The range analysis method is an intuitive analysis method, which can quickly judge the influence of each factor on the experimental results through the range of each factor, and then determine the degree of influence of each factor on the experimental results. The larger the range value is, the more significant the change of corresponding factors will be on the experimental results.

According to the above advantages, the range analysis method is used to analyze the orthogonal experimental simulation results of the above 16 groups of schemes. According to the different factors, the simulation results of different levels of each factor are added up respectively to obtain the sum of different levels of each factor, namely $K1$, $K2$, $K3$ and $K4$ in Table 3. According to $K1$, $K2$, $K3$, and $K4$, the range of each factor can be obtained. In particular, when the level number of each factor is different, in order to avoid the deviation of the analysis result caused by the different level number of each factor, it is necessary to calculate the average value of the level sum of each factor, and then obtain the average range value $\overline{K}$, and then analyze the average range value. The sum and range $R$ (A) of different levels of factor A obtained in Equations (1) ~ (6) were calculated, and the results of other factors were calculated in the same way.

$$K1=\sum_{i=1}^{n} A1(i) \qquad (i=1,2,\cdots,16) \tag{1}$$

$$K2=\sum_{i=1}^{n} A2(i) \qquad (i=1,2,\cdots,16) \tag{2}$$

$$K3=\sum_{i=1}^{n} A3(i) \qquad (i=1,2,\cdots,16) \tag{3}$$

$$K4=\sum_{i=1}^{n} A4(i) \qquad (i=1,2,\cdots,16) \tag{4}$$

$$\bar{K}(i)=\frac{K(i)}{4} \qquad (i=1,2,3,4) \tag{5}$$

$$R(\mathrm{A})=Max\left(\bar{K}(i)\right)-Min\left(\bar{K}(i)\right) \qquad (i=1,2,3,4) \tag{6}$$

Table 3: Analysis table of orthogonal simulation results

| Levels of factors | External wall U-value (A) | Roof U-value (B) | Outer window U-value (C) | South window-wall ratio (D) | North window-wall ratio (E) |
|---|---|---|---|---|---|
| $K1$ | 91.72 | 86.84 | 89.85 | 94.51 | 93.18 |
| $K2$ | 87.10 | 86.86 | 87.55 | 87.37 | 88.60 |
| $K3$ | 84.07 | 85.31 | 84.42 | 83.08 | 82.14 |
| $K4$ | 81.21 | 85.09 | 82.28 | 79.14 | 80.18 |
| $\bar{K}1$ | 22.93 | 21.71 | 22.46 | 23.63 | 23.30 |
| $\bar{K}2$ | 21.78 | 21.72 | 21.89 | 21.84 | 22.15 |
| $\bar{K}3$ | 21.02 | 21.33 | 21.11 | 20.77 | 20.54 |
| $\bar{K}4$ | 20.30 | 21.27 | 20.57 | 19.79 | 20.05 |
| Range ($R$) | 2.63 | 0.44 | 1.89 | 3.84 | 3.25 |

It can be seen from Table 3 that the range values of each factor are different, indicating that each factor has different effects on building energy consumption. The greater the range value, the greater the influence of the corresponding factor on the experimental results, that is, the more significant the impact of the factor on the building energy consumption. For this experiment, the extreme differential values of each factor were ranked as: $R$(D)> $R$(E)> $R$(A)> $R$(C)> $R$(B).

According to the above analysis, the significant order of each factor on the energy consumption of the residential buildings is:

Major → Minor

D ; E ; A ; C ; B

According to the significant order of the factors obtained by range analysis, in hot summer and cold winter zone, the biggest impact on the annual energy consumption of residential buildings is the south window-wall ratio, followed by the north window-wall ratio, the external wall U-value, the external window U-value, and finally the roof U-value. However, such a result does not mean that the roof U-value is not important, because the top house does not have the upper house as its insulation layer like the middle layer. If the roof U-value is too low, the indoor thermal comfort environment of the top floor residents will be very poor, so we should also pay attention to the design of the roof U-value.

### 3.2 Determination of the optimal scheme

The optimal level of factors obtained by range analysis is related to the index of each factor. If the experiment purpose is that the biggest the result, the better, the factor level of large indicators should be selected. On the contrary, if the experiment purpose is that the smaller of the result, the better, the factor level of small indicators should be selected. The purpose of this study is to reduce the building energy consumption, that is, the less the building energy consumption, the better.

Therefore, the optimal scheme in the 16 sets of experiments: $D_4E_4A_4C_4B_4$. The optimal scheme: The exterior wall adopts 80mm rock wool board as insulation layer with U-value of 0.370W/ ($m^2$•K). The roof adopts 100mm extruded polystyrene foam board (XPS) as insulation layer with U-value of 0.296W/ ($m^2$•K). The outer window adopts double layer argon plus insulating glass constructed as 6mm+12Argon +6mm with U-value of 1.9W/($m^2$•K), the south window-wall ratio is 0.15, and the north window-wall ratio is 0.10.

In the same way, the most unfavorable scheme is obtained: $D_1E_1A_1C_1B_1$. The most unfavorable scheme: The exterior wall adopts 50mm rock wool board as insulation layer with U-value of 0.513W/ ($m^2$•K). The roof adopts 70mm extruded polystyrene foam board (XPS) as insulation layer with U-value of 0.401W/ ($m^2$•K). The outer window adopts Ordinary double-layer insulating glass constructed as 6mm+12Air +6mm with U-value of 2.5W/($m^2$•K), the south window-wall ratio is 0.45, and the north window-wall ratio is 0.40.

DeST software was used to simulate the above two schemes. The annual cold and heat load index per unit building area of the optimal scheme is 16.53kWh/($m^2$•a),and the same index of the most unfavorable scheme is 28.00kWh/($m^2$•a)。Compared with the most unfavorable scheme, the energy saving rate of the optimal scheme is increased by 40.96%.

## 4. Conclusion

In this paper, orthogonal experimental design and range analysis are carried out for five factors affecting energy consumption of residential buildings in hot summer and cold winter areas. It determines the primary and secondary order of five surrounding structure factors affecting the energy consumption of residential buildings, namely the south window-wall ratio, followed by the north window-wall ratio, the external wall U-value, the external window U-value, and finally the roof U-value. At the same time, the optimal scheme and the most unfavorable scheme of the outer envelope structure design of residential buildings with the above factors and levels are obtained. Compared with the most unfavorable scheme, the energy saving rate of the optimal scheme is increased by 40.96%.

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