Thermal design optimization and analysis on heating load of rural buildings in northern China

Weishu Wang^{1,2*}, Xuewen Ge^{2,3}, and Hanlin Xiong³

¹ School of Electric Power, North China University of Water Resources and Electric Power, Zhengzhou 450045, PR China

² Institute of Engineering Thermophysics, North China University of Water Resources and Electric Power, Zhengzhou 450045, PR China

³ School of Environmental and Municipal Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, PR China

Abstract. The envelope of rural buildings has been lack of effective and reasonable thermal insulation method and therefore its energy consumption has always been high. In order to address this problem, this paper aims to optimize the thermal design of building envelope. The simulation using DesignBuilder software for modeling and analyzing, using the orthogonal experimental design method to study the effects of external wall, external window and roof on heating load, and optimal thermal insulation scheme was obtained, which was 100mm PUF (external wall), 6mm+12mm+6mm low-E glass (external window) and 100mm PUF (roof). Results revealed that the addition of sunspace can significantly reduce the heating load and thus the selection of window thermal insulation material is very important. Compared with the condition of highest heating load, the energy-efficient rate of optimal scheme reached to 21.4%. The results of this study will serve as the idea for optimal design of rural buildings envelope.

1 Introduction

Energy issue, particularly in buildings is always a worldwide problem. More and more energy has been consumed in buildings due to the development of buildings area [1]. In China, there are about 37% of total national building energy is consumed in rural areas. More than 97% of the rural buildings have no thermal insulation on external envelopes, and the windows are not airtight [2]. Thus, it is significant for rural area to optimize building envelope and develop energy-efficient buildings.

In order to address energy savings problem, many researchers focused on active strategies to reducing energy consumption. For example, Heating Ventilation and Air Conditioning (HVAC) systems is widely used in buildings, however, its energy consumption is enormous affected by a number of factors such as operation strategies and climate change. Therefore, different HVAC control strategies need to be formulated for different occasions and climate region [3-5]. In addition, lighting technology plays an increasingly important role in reducing energy consumption. Makaremi et al. [6] investigated the effects of applying different design strategies on lighting energy use and visual comfort level and found that there is no single design solution to guarantee both low energy demand and high visual quality, therefore integrating different strategies based on the type of task and the occupant's activities is highly recommended.

Many passive technical methods were also studied. Passive solar walls, which can trap and transmit the solar

energy efficiently into the building, are widely used in cold climates. Several studies have been paid attention to develop new solar wall such as using phase change material (PCM) based Trombe walls or using PV integrated Trombe walls [7-9]. Solar house is a reliable method utilizing solar energy for space heating, particularly in some plateau region, its high-altitude makes the sky of plateau mostly transparent and with low dust content, providing the potentials for the application and development of solar houses [10,11].

Passive renovation of rural residential buildings is an effective way to reduce building energy consumption and is popular with people. One of the most popular passive solar systems is the sunspace. This is caused firstly by its potential as an energy collecting system and secondly by its good and pleasant appearance [12]. However, An optimized envelope design can reduce building energy consumption and improve indoor environment quality as well.

In this paper, the passive renovation of rural residential buildings in cold region is carried out. First, a sunspace was attached in the south, then, three envelope, external wall, external window and roof were selected to analyze the impact on load. Each of envelope has three different thermal insulation materials. By adopting orthogonal experimental design method, the optimal envelope design scheme was obtained. The results of this study will serve as the idea for optimal design of rural buildings envelope.

* Corresponding author: wangweishu@ncwu.edu.cn

2 Research methodology

2.1 Weather Data

The study was carried out on rural residential buildings in Xingtai City (latitude 37.07°N, longitude 114.50°E, and altitude 78.0 m), Hebei Province. Fig. 1 shows the climatic zoning for building thermal design, and nearly 45% of the total land area of China falls into cold zones [13]. This city is located in the cold region, with a maximum mean monthly temperature of 28.12°C in July and minimum mean monthly temperature of -1.08°C in January, respectively, which is shown in Fig. 2. Xingtai City is the typical region of cold climate, thus the great concern issue is the heating in winter.

Fig. 1. Climatic zoning for building thermal design.

Fig. 2. The outside dry-bulb temperature of Xingtai.

2.2 Building information

Fig. 3 shows diagram of building layout. It is a single-storey house facing the south, with the height of 3.5m, an east–west length of 14.0m and south–north length of 7m, and its total floor area is 98m². To improve indoor thermal environment of buildings and address energy issue problem, maximizing the use of renewable energy is crucial, thus a sunspace is attached in the south.

2.3 Building envelope parameters

Because of the poor thermal insulation performance of

rural building envelope, the heating load is always high. Thus, the selection of envelope materials plays an important role in optimization on heating load of rural buildings. Table 1 shows the original parameters of rural building envelope.

Fig. 3. Diagram of building layout: (a) 3D model (b) 2D plane layout.

Table 1. Original parameters of building envelope.

Name	Materials	Thermal conductivity(W/m ² •K)
External wall	Solid brick	0.81
Internal wall	Solid brick	0.81
Windows	6mm Window	6.4
Roof	Concrete	1.74
Floor	Cement board	1.35

As we can see in the Table 1, the original envelope is simple and not energy-efficient. In order to improve the thermal insulation performance of buildings, the envelope was redesigned. To further reduce unnecessary heat loss and improve the indoor thermal comfort, it is necessary to select and add appropriate thermal insulation material in the envelope. For the purpose of thermal design optimization, the effects of external wall, external windows and roofs on heating load are considered. 100mm EPS, 100mm XPS and 100mm Polyurethane

Table 2. Redesigned parameters of building envelope.

Name	Material	Thickness(m)	Thermal conductivity(W/m ² •K)
External wall	Cement plaster	0.02	0.72
	EPS/XPS/PUF	0.1	0.04/0.034/0.028
	Solid brick	0.12	0.58
Internal wall	Cement plaster	0.02	0.72
	Cement plaster	0.02	0.72
	Solid brick	0.12	0.58
External windows	Cement plaster	0.02	0.72
	6mm glass	N/A	5.7
	6mm+12mm+6mm double-insulation glass	N/A	2.8
Roofs	6mm+12mm+6mm low-E glass	N/A	1.4
	Cement plaster	0.02	0.72
	EPS/XPS/PUF	0.1	0.04/0.034/0.028
Floor	Concrete	0.2	2.5
	Crushed stone concrete	0.05	1.3
	Concrete	0.15	2.5

foam (PUF) was applied to external wall and roofs, respectively. 6mm glass, 6mm+12mm+6mm double-insulation glass and 6mm+12mm+6mm low-E glass was applied to external windows, respectively. The redesigned parameters of building envelope are presented in Table 2.

2.4 Description of the HVAC system

Ideal loads air system is the simplest piece of zone equipment which can acquire the energy demand of the building. In this study, air exchange rate was 0.5/h and for the purpose of avoiding the effects of subjective factors such as personnel, equipment and lighting, we assume that these values are all 0. The house heating period started from November 15th to March 15th of the next year.

Table 3 shows the detailed heating set-point temperature schedule of HVAC system. Considering people stayed in bedroom frequently during 0:00-08:00, 12:00-14:00 and 18:00-24:00, thus we usually set the temperature of bedroom to 22°C, which is comfortable and energy-efficient. Others include living room, kitchen and toilet, considering people are often not in these places, thus we usually set the temperature of 18°C during 0:00-

08:00, 08:00-12:00 and 14:00-18:00.

Table 3. Heating set-point temperature schedule.

Room	0:00-08:00(°C)	08:00-12:00(°C)	12:00-14:00(°C)	14:00-18:00(°C)	18:00-24:00(°C)
Bedroom	22	18	22	18	22
Others	18	18	22	18	22

3 Results and analysis

3.1 Design of simulation condition

Orthogonal experimental design method is a design method for studying multi-factors and multi-levels. Based on orthogonality, it can select some representative points from the comprehensive experiment to carry out experiments. In this study, the effects on heating load of three factors, external wall, external window and roof, were considered respectively. If the comprehensive experiment was carried out, too many simulation

Table 4. Simulation factors and selection of level.

Level	Factors		
	External wall(A)	External windows(B)	Roof(C)
1	100mm EPS	6mm glass	100mm EPS
2	100mm XPS	6mm+12mm+6mm double-insulation glass	100mm XPS
3	100mm PUF	6mm+12mm+6mm low-E glass	100mm PUF

Table 5. L₉(3³) 9 Simulation conditions of orthogonal table.

Simulation conditions	Factors		
	External wall(A)	External window(B)	Roof(C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3

8	3	2	1
9	3	3	2

conditions need to be considered. But if we adopt the orthogonal experimental design method, it can not only greatly reduce the number of simulation, but also obtain conclusions promptly and accurately. Table 4 shows the simulation factors and selection of level.

In this simulation, three factors were considered on heating load, without considering the interaction among each other. As is shown in Table 5, We selected $L_9(3^3)$ orthogonal table and only 9 simulation conditions were needed to set, which can replace 27 full simulation conditions.

3.2 Analysis of simulation result

Using DesignBuilder to simulate 9 conditions listed in Table 5, each simulation result of heating load was obtained, which is shown in Table 6.

Table 6. Each simulation result of heating load.

Simulation conditions	Factors			Load (kWh)
	A	B	C	Heating load
1	1	1	1	8805.3
2	1	2	2	7866.71
3	1	3	3	7160.66
4	2	1	2	8530.18
5	2	2	3	7586.01
6	2	3	1	7363.57
7	3	1	3	8243.66
8	3	2	1	7781.82
9	3	3	2	7080.93

For the purpose of analyzing the effects on heating load of three factors at different levels, it is necessary to calculate the average value of each factor at different levels. We take the analysis of the effects of factor A at different levels on the simulation results as an example:

$$A_1 = 8805.3 + 7866.71 + 7160.66 = 23832.67 \text{ kWh}$$

$$K_{A1} = A_1 / 3 = 23832.67 / 3 = 7944.22 \text{ kWh}$$

$$A_2 = 8530.18 + 7586.01 + 7363.57 = 23479.76 \text{ kWh}$$

$$K_{A2} = A_2 / 3 = 8149.39 / 3 = 7826.59 \text{ kWh}$$

$$A_3 = 8243.66 + 7781.82 + 7080.93 = 23106.41 \text{ kWh}$$

$$K_{A3} = A_3 / 3 = 7702.14 \text{ kWh}$$

According to the three values of K_{A1} , K_{A2} , K_{A3} , we can found that the effects of A_1 , A_2 , A_3 on heating load. Due to the simulation result index is heating load and $K_{A1} > K_{A2} > K_{A3}$, thus it can be known that A_1 is the level affects heating load the most. Hence, an appropriate material of A_3 (PUF) is identified and it can provide lower heating load. Using this method, we can also determine the optimal material for B and C. The heating load with varying thermal insulation materials are shown in Fig. 4-6.

Fig 4. Heating load with different external wall thermal insulation materials.

Fig 5. Heating load with different external window thermal insulation materials.

Fig 6. Heating load with different roof thermal insulation materials.

As is shown in Fig. 4-6, it can be observed that the heating load decreases with the decrease of thermal conductivity of selected thermal insulation material. However, it is obviously that the extent of reduction of heating load in external window are faster than external wall and roof. This is because for one thing, the addition of sunspace can provide more solar energy into building, which can greatly reduce the heating load, for another, the thermal conductivity of window material is much greater than external wall and roof and thus the selection of window thermal insulation will greatly affect the heating load.

3.3 Analysis of optimal simulation result

Based on the calculation method in section 3.2, it can be found that B₃ and C₃ are the appropriate materials, and thus we can draw a conclusion that A₃B₃C₃ is the optimal scheme and the minimum heating load is 6918.1kWh. The optimal scheme is not among previous simulation conditions, and that is the advantage of orthogonal experimental design method, which we can obtain the optimal result with the minimum amount of calculation.

As is shown in Fig. 7, heating load of simulation condition 1 is 8805.3kwh, which is the highest value in the 9 conditions. With the continuous optimization of the building envelope, its heating load gradually decreases and finally reaches to 6918.1kwh, and its maximum energy-efficient rate can be achieved to 21.4%.

Fig 7. Comparison diagram of heating load under different simulation conditions.

4 Conclusions

From the results obtained in the previous section, the following conclusions may be drawn:

1. The energy-efficient potential of rural building is enormous and the selection of building envelope is important in early design states. Using the orthogonal experimental design method can significantly reduce the number of simulation conditions and select appropriate materials quickly and accurately.

2. With the selection of better thermal insulation materials, finally the lowest heating load could be obtained. However, not only because of the addition of sunspace, but window materials have a greater impact on heating load. Therefore, the selection of windows material is more important than the external wall and roof.

3. The optimal scheme obtained by calculation and analysis was A₃B₃C₃, which thermal insulation materials of external wall, external window and roofs were 100mm PUF, 6mm+12mm+6mm low-E glass and 100mm PUF, respectively. In this condition, the heating load was lowest, and compared with the condition of highest heating load, its energy-efficient rate reached to 21.4%.

References

1. J. T. Kim, C. W. F. Yu, *Indoor Built. Environ.* **27**, 734-751 (2018).
2. J. Liu, X. Zhu, L. Yang, R. Hu, *Front. Energy Power*

- Eng. China **4**, 122-130 (2010).
3. M. Fasiuddin, I. Budaiwi, A. Abdou, *Int. J. Energy Res.* **34**, 1-19 (2010).
4. S. Papadopoulos, C. E. Kontokosta, A. Vlachokostas, E. Azar, *Build. Environ.* **155**, 350-359 (2019).
5. X. Sun, Z. Gou, S. S. Y. Lau, *J. Cleaner Prod.* **183**, 35-45 (2018).
6. N. Makaremi, S. Schiavoni, A. L. Pisello, F. Cotana, *Indoor Built. Environ.* **28**, 552-563 (2019).
7. V. V. Tyagi, D. Buddhi, *Renewable Sustainable Energy Rev.* **11**, 1146-1166 (2007).
8. J. Ji, H. Yi, W. He, G. Pei, J. Lu, B. Jiang, *Build. Environ.* **42**, 1544-1552 (2007).
9. O. K. Ahmed, K. I. Hamada, A. M. Salih, *Energy* **171**, 14-26 (2019).
10. Z. Liu, D. Wu, J. Li, *J. Therm. Sci.* 1-14 (2018).
11. Z. Liu, D. Wu, B. J. He, Y. Liu, X. Zhang, H. Yu, G. Jin, *Energy. Build.* **178**, 294-303 (2018).
12. G. Mihalakakou, *Renew. Energy.* **26**, 415-429 (2002).
13. L. Zhang, L. Zhang, Y. Wang, *Sol. Energy* **132**, 38-50 (2016).