The Influencing Factors of Energy Saving in Residential Buildings Based on Energy Consumption and Emission Reduction

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ABSTRACT
The continuous growth of residential buildings has led to increasing attention on energy consumption and emission reduction. Taking an old residential building in Zhengzhou as an example, this article used Dest-h to simulate and calculate its energy-savings. A nine-factor, three-level orthogonal table was designed to analyze factors such as external wall heat transfer coefficient and building orientation, to understand the impact of different factors on energy savings. The results showed that among the 27 orthogonal experiments, the cooling consumption of experiment 23 was the lowest (21,236 kWh); the heating consumption of experiment 20 was the lowest (11,376 kWh); experiment 25 had the lowest total energy consumption (37,416 kWh). The comprehensive energy-saving rate was 36.12%, 43.29%, and 49.02%, respectively, in experiments 23, 20, and 25 as compared to the existing building. The annual energy-saving benefits were 6.57 yuan/m^2, 7.87 yuan/m^2, and 8.91 yuan/m^2, respectively. Among the nine factors studied, the heat transfer coefficients of the external wall and window had the greatest impact on the energy savings of this building. In the case of minimum total energy consumption, the heat transfer coefficient of the external wall was 0.6 W/(m^2·K), and that of the external window was 0.8 W/(m^2·K). The results prove the reliability of Dest-h in building energy conservation research, and it can be applied to practical research on energy consumption and emission reduction.

1. INTRODUCTION

Due to factors such as economic development, population growth, and climate change [1], energy shortage has become an increasingly prominent issue [2]. Thus, emission reduction and energy conservation have become increasingly important [3]. The energy consumption of buildings makes up a significant share of all energy consumption [4], and its emission accounts for approximately 40% of the total emissions [5]. Therefore, studying energy conservation in buildings is particularly necessary [6]. Buildings include public buildings, office buildings, etc., among which the number of residential buildings is increasing rapidly, with a large construction area and a continuous growth trend in the future. It remains one of the main components of the national economy [7]. Researchers have studied and analyzed the choice of building materials, cutting-edge technology, and improved energy management to address the issue of energy consumption in buildings [8]. Gounni et al. [9] found that in dynamic simulations using a transient system, insulation had a greater impact on cooling loads

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compared to heating demands during the COVID-19 pandemic, resulting in an annual growth rate of energy demand of approximately 10%-35%. Based on meteorological data from 2004 to 2018, Bazazzadeh et al. [10] examined the effect of climate change on building energy usage in Poznan, Poland. They found that by 2080, the average cooling load will increase by 135% and the average heating load will decrease by 40%, requiring strict control measures. Pujani et al. [11] analyzed the energy-saving opportunities of three buildings in Andalas University, Indonesia, using real-time monitoring, and found that the energy-saving opportunities during non-working hours were 21.06%, 20.17%, and 9.85% for engineering faculty, lecturing, and central library, respectively. Odineca et al. [12] analyzed the impact of energy-saving glass on the total energy consumption of buildings and proved that the use of specific glass types based on the building conditions could reduce the energy consumption of existing buildings during the design phase and reduce the construction cost of new office buildings. Zhang et al. [13] conducted research on the influence of building envelope structures on building energy efficiency in cold regions using sensitivity analysis methods. They discovered that the annual cumulative load sensitivity coefficients for windows, exterior walls, and roofs of buildings were 7.93%, 5.76%, and 5.75% respectively, indicating significant practical value in reducing energy consumption in cold regions. Sotehi et al. [14] conducted a study using TRNSYS 17 software to investigate the effects of insulation materials under different climates in Algeria, taking a typical apartment as an example. The study revealed that enhancing the thermal performance of buildings and glass surfaces led to reductions in heating and cooling demands by 72%, 78.21%, and 65.21% for the cities of Annaba, Setif, and Biskra respectively. Missoum et al. [15] investigated the transient heat transfer through the building facades of multi-story buildings in Bechar, a city located in southwestern Algeria, and conducted numerical simulations to determine the effects of structural thermal behavior and radiative heat flux on different components. Focusing on energy consumption and emission emissions, this paper took an old residential building in Zhengzhou, Henan, as an example, to study the factors affecting its energy consumption using Dest-h. This work provides a reference for both the renovation of existing buildings and the construction of new buildings in the future.

2. FACTORS INFLUENCING THE ENERGY EFFICIENCY OF RESIDENTIAL BUILDINGS

Many buildings have the defect of high energy consumption, which may be caused by the deficiency of the construction process, the lack of energy-saving technology, etc. The calculation of building energy consumption and energy saving can not only provide strong support for the construction of new buildings, but also provide some referenceable opinions for the renovation of existing buildings. In the research of building energy consumption and saving, energy consumption simulation software can realize the simulation calculation of building energy consumption size, cooling/heating consumption, etc., which is widely used in the research of energy consumption and emission reduction [16]. At present, the commonly used software include:

(1) DOE-2: a programmed input that allows for good simulation of complex buildings, but requires a high level of skill from the user;
(2) eQUEST [17]: Windows system based, with relatively simple input, but deficient in meteorological information;

(3) EnergyPlus [18]: good scalability and ability to simulate a wide range of building systems, but difficult to use;
(4) DesignBuilder [19]: graphical interface, easy to use, but less scalable;
(5) Dest [20]: capable of good simulation of building energy consumption and environment, Chinese interface.

In summary, Dest was chosen to perform the energy consumption simulation in this paper. In Dest, Dest-h is specifically used to analyze residential buildings; therefore, this paper used Dest-h to analyze the factors affecting the energy savings of residential buildings.

An old residential building in Zhengzhou was taken as an example. The house type was one kitchen, four rooms, and two bathrooms. Two households share one elevator. There are six floors above ground and one floor below ground. The floor height is 3 meters, and the total area was 2260 m^2. Zhengzhou has a continental monsoon climate with cold winters and hot summers, so the study of the energy consumption and saving in Zhengzhou is of great importance. First of all, many parameters are involved in energy saving simulations, and the reference bases are listed in Table 1.

Table 1. Parameter reference basis

Reference basis	Standard number
Architectural Lighting Design Standards	GB50034-2013
Green Building Evaluation Standards	GB/T50378-2019
Uniform Standards for Civil Building Design	GB50352-2019
Thermal Design Code for Civil Buildings	GB50176-2016
Energy Conservation Design Standards for Residential Buildings in Severe Cold and Cold Regions	JGJ26-2018
Energy Conservation Design Standards for Ultra-low Energy Consumption Public Buildings in Henan Province	DBJ41/T246-2021

For the energy saving simulation, outdoor gas phase parameters were simulated using the Medpha module of Dest-h. According to GB50176-2016, the outdoor meteorological parameters of this residence are shown in Table 2.

Table 2. Outdoor meteorological parameters

Climate zone	2B
East longitude (°)	113.65
North latitude (°)	34.72
Altitude (m)	111
Coldest monthly average temperature (℃)	0.8
Hottest monthly average temperature (℃)	27.2
Heading degree day (℃·d)	2106
Cooling degree day (℃·d)	125

According to JGJ26-2018, the limits of the thermal performance parameters of the residential envelope are presented in Table 3.

Table 3. Limits of thermal performance parameters of residential envelope

Enclosure part	Heat transfer coefficient K [W/(m²·K)]	
	≤ 3 levels	≥ 4 levels
Roofing	0.3	0.3
Exterior walls	0.35	0.45
Overhead or outlying floor slabs	0.35	0.45
External window/window and wall area ratio ≤ 30%	1.8	2.2
External windows/30% < window-to-wall area ratio ≤ 50%	1.5	2.0
Enclosure part	**Thermal resistance of insulation material layer R [(m²·K)/W]**	
Ground	1.5	1.5
Basement exterior walls (exterior walls in contact with soil)	1.6	1.6
Inner envelope	**Heat transfer coefficient K [W/(m²·K)]**	
Non-heated basement roof slab	0.5	
Partition walls separating heated and unheated spaces	1.5	
Doors separating heated and unheated spaces	2.0	

According to JGJ26-2018, the limits of the window-to-wall ratio of this residence are displayed in Table 4.

Table 4. Residential window-to-wall ratio limits

Orientation	Window-to-wall area ratio
North	0.3
East-west	0.35
South	0.5

The input parameters of the existing residential model are displayed in Table 5.

In residential buildings, the overall energy consumption of the building is closely related to the external wall heat transfer coefficient; the orientation of the building affects the solar radiation received by the building, thus changing the energy consumption of the building; the ratio of windows to walls, the heat transfer coefficient of the exterior windows, and the solar heat gain coefficient (SHGC) are just a few of the values of the building's windows that have an impact on how much solar radiation enters the space [21]; the power density of the indoor lighting and equipment is also an important part of the energy saving of the building. This paper uses orthogonal experiment [22] to analyze each influencing factor. Orthogonal experiment is a multi-factor and multi-level analysis method, and its formula can be written as:

$$L_n = (q^m), \tag{1}$$

where L stands for an orthogonal table, n stands for the number of tests, q stands for the number of factor levels, and m stands for the number of factors.

Table 5. Input parameters of the existing residential model

Parameter	Value
Equipment power density	3.8 W/m^2
Lighting power density	5 W/m^2
Ratio of south-facing windows to walls	0.45
Ratio of north-facing windows to walls	0.25
East-west window-to-wall ratio	0.3
Roof heat transfer coefficient	0.3 [W/(m^2·K)]
External wall heat transfer coefficient	0.45 [W/(m^2·K)]
Internal wall heat transfer coefficient	1.2 [W/(m^2·K)]
External window heat transfer coefficient	2.1 [W/(m^2·K)]
External window shading factor	0.5
Heating period	11.15-3.15
Cooling period	6.1-9.1

The energy consumption of the existing building was computed in Dest-h, and the results are presented in Table 6.

Table 6. Energy consumption of the existing building

Cooling consumption	32,158/kWh
Heat consumption	41,236/kWh
Total energy consumption	73,394/kWh

According to the above influencing factors, three levels were set for analysis, and the selected influencing factors of energy saving, and their level values are presented in Table 7.

Table 7. Factors influencing the energy saving of the building and their level values

Number	Factor	Level 1	Level 2	Level 3
A	External wall heat transfer coefficient [W/(m^2·K)]	2.0	1.1	0.6
B	Building orientation	45° south by west	South	45° south by east
C	Ratio of south-facing windows to walls	0.3	0.5	0.7
D	Ratio of north-facing windows to walls	0.1	0.2	0.3
E	External window heat transfer coefficient [W/(m^2·K)	0.8	1.2	1.6
F	South-facing external window SHGC	0.4	0.6	0.8
G	North-facing external window SHGC	0.1	0.3	0.5
H	Lighting power density W/m^2	3	4	5
I	Equipment power density W/m^2	3	3.4	3.8

From Table 7, it was seen that $L_{27}(3^9)$ orthogonal table was used, as shown in Table 8.

Table 8. The orthogonal experiment table

Experiment number	A	B	C	D	E	F	G	H	I
1	2.0	45° south by west	0.3	0.1	0.8	0.4	0.1	3.0	3.0
2	2.0	45° south by west	0.3	0.2	1.2	0.6	0.5	5.0	3.8
3	2.0	45° south by west	0.3	0.3	1.6	0.8	0.3	4.0	3.4
4	2.0	South	0.7	0.1	1.2	0.8	0.1	4.0	3.8
5	2.0	South	0.7	0.2	1.6	0.4	0.5	3.0	3.4
6	2.0	South	0.7	0.3	0.8	0.6	0.3	5.0	3.0
7	2.0	45° south by east	0.5	0.1	1.6	0.6	0.1	5.0	3.4
8	2.0	45° south by east	0.5	0.2	0.8	0.8	0.5	4.0	3.0
9	2.0	45° south by east	0.5	0.3	1.2	0.4	0.3	3.0	3.8
10	1.1	45° south by west	0.7	0.1	1.6	0.6	0.5	4.0	3.0
11	1.1	45° south by west	0.7	0.2	0.8	0.8	0.3	3.0	3.8
12	1.1	45° south by west	0.7	0.3	1.2	0.4	0.1	5.0	3.4
13	1.1	South	0.5	0.1	0.8	0.4	0.5	5.0	3.8
14	1.1	South	0.5	0.2	1.2	0.6	0.3	4.0	3.4
15	1.1	South	0.5	0.3	1.6	0.8	0.1	3.0	3.0
16	1.1	45° south by east	0.3	0.1	1.2	0.8	0.5	3.0	3.4
17	1.1	45° south by east	0.3	0.2	1.6	0.4	0.3	5.0	3.0
18	1.1	45° south by east	0.3	0.3	0.8	0.6	0.1	4.0	3.8
19	0.6	45° south by west	0.5	0.1	1.2	0.8	0.3	5.0	3.0
20	0.6	45° south by west	0.5	0.2	1.6	0.4	0.1	4.0	3.8
21	0.6	45° south by west	0.5	0.3	0.8	0.6	0.5	5.0	3.4
22	0.6	South	0.3	0.1	1.6	0.6	0.3	3.0	3.8
23	0.6	South	0.3	0.2	0.8	0.8	0.1	5.0	3.4
24	0.6	South	0.3	0.3	1.2	0.4	0.5	4.0	3.0
25	0.6	45° south by east	0.7	0.1	0.8	0.4	0.3	4.0	3.4
26	0.6	45° south by east	0.7	0.2	1.2	0.6	0.1	3.0	3.0
27	0.6	45° south by east	0.7	0.3	1.6	0.8	0.5	5.0	3.8

The energy savings in different experiments were analyzed using the following indicators.

(1) Comprehensive building energy-saving rate: it means the energy saving rate of the test result relative to the existing building. The formula is:

$$\delta_p = \frac{|E_D - E_R|}{E_R} \times 100\%, \tag{2}$$

where E_D stands for the energy consumption of the building obtained from the test and E_R stands for the energy consumption of the existing building.

(2) Annual energy-saving benefit C_e: it refers to the benefit generated by energy saving, which is the product of the saved electric quantity Δq (kWh/m^2) and local energy charge b (yuan/kWh). Its formula is:

$$C_e = \Delta q \times b. \tag{3}$$

Disregarding the peak and valley electricity, the electricity charge of Zhengzhou is 0.56 yuan/kWh.

3. RESULTS AND ANALYSIS

First, the building energy consumption was calculated in Dest-h based on the values of the factors in Table 8, and the results are presented in Table 9.

Table 9. Calculation results of the energy saving of the building

Test number	Cooling consumption/kWh	Heat consumption/kWh	Total energy consumption/kWh
1	23256	25469	48725
2	25254	23685	48939
3	32015	33215	65230
4	35642	15268	50910
5	37258	16528	53786
6	38158	17528	55686
7	39245	18421	57666
8	42502	22968	65470
9	44582	23654	68236
10	29857	21411	51268
11	28657	15264	43921
12	27456	14625	42081
13	25648	21418	47066
14	25648	14952	40600
15	23658	15282	38940
16	25635	13258	38893
17	40258	14452	54710
18	26582	15214	41796
19	38362	13258	51620
20	30245	11376	41621
21	33625	15962	49587
22	36425	17528	53953
23	21236	25647	46883
24	40328	12020	52348
25	24652	12764	37416
26	28526	12776	41302
27	27663	12508	40171

From Table 9, among the 27 experiments, the cooling consumption in experiment 23 was minimum, 21,236/kWh, the heat consumption in experiment 20 was minimum, 11,376/kWh, and the total energy consumption in experiment 25 was minimum, 37,416/kWh. The values of the influencing parameters in these three experiments are presented in Table 10.

Table 10. Test parameters when the cooling consumption, heat consumption, and total energy consumption are at a minimum

Experiment number	23	20	25
External wall heat transfer coefficient [W/(m^2·K)	0.6	0.6	0.6
Building orientation	South	45° south by west	45° south by east
Ratio of south-facing windows to walls	0.3	0.5	0.7
Ratio of north-facing windows to walls	0.2	0.2	0.1
External window heat transfer coefficient [W/(m^2·K)	0.8	1.6	0.8
South-facing external window SHGC	0.8	0.4	0.4
North-facing external window SHGC	0.1	0.1	0.3
Lighting power density W/m^2	5.0	4.0	4.0
Equipment power density W/m^2	3.4	3.8	3.4

According to Table 10, it was appropriate to set the external wall heat transfer coefficient to 0.6 [W/(m^2·K)] because the cooling consumption, heating consumption, and total energy consumption of the residential building were low. In terms of building orientation, when facing south, the cooling consumption was low when the building was oriented to the south, and the heating consumption was low when the building was oriented to 45° southwest; the cooling consumption was low when the ratio of south-facing windows to walls was 0.3, and the heating consumption was low when it was 0.5; when the ratio of north-facing windows to walls was 0.2, and the north-facing external window SHGC was 0.1, the cooling and heating consumption of the residential building was low. In the actual construction of new residential buildings, the total energy consumption of the buildings, i.e., the parameter in experiment 25, should be considered in order to achieve energy savings.

The energy consumption of the above three experiments was compared with the existing building, and the results are displayed in Figure 1. From Figure 1, it was observed that the cooling/heating consumption as well as the total energy consumption of experiment 23, experiment 20, and experiment 25 were greatly reduced compared with the existing building. The total energy consumption of the existing building reached 73,394 kWh, while the total energy consumption of all three test methods was below 50,000 kWh. Compared with the existing building, the cooling consumption of experiment 23 was reduced by 33.96%, and the heating consumption was reduced by 37.8%; the cooling consumption of experiment 20 was reduced by 5.95%, and the heating consumption was reduced by 72.41%; the cooling consumption of experiment 25 was reduced by 23.34%, and the heating consumption was reduced by 69.05%. The energy-saving rates of the above three tests relative to the existing building and the annual energy saving benefits were calculated, and the results are illustrated in Figure 2.

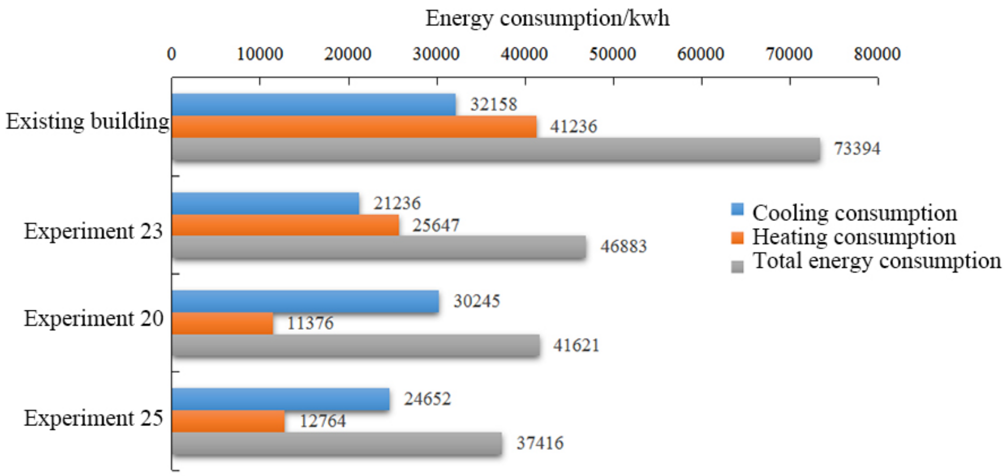

Figure 1. Comparison of energy consumption with the existing building

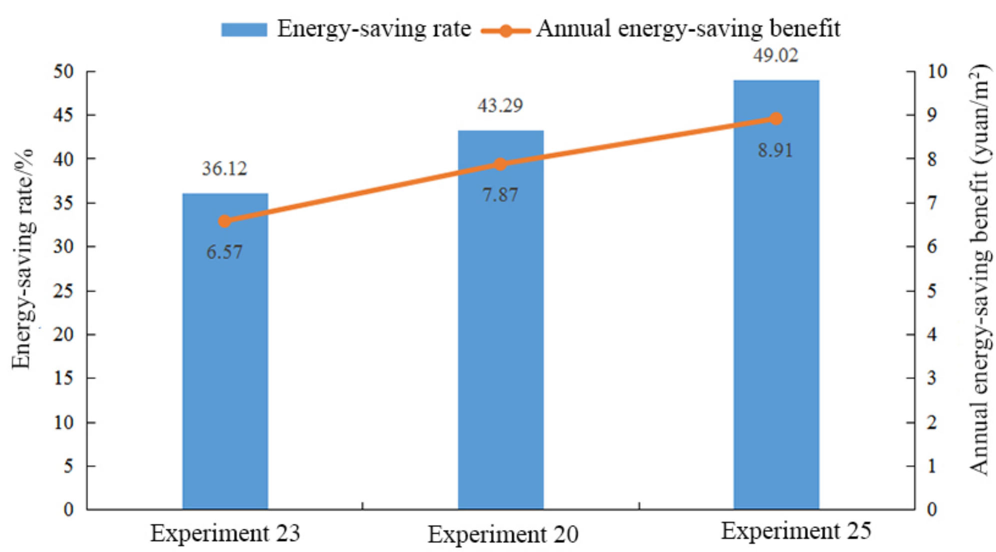

Figure 2. Comprehensive energy-saving rate and annual energy-saving benefit analysis

From Figure 2, first, the comprehensive energy-saving rate of experiment 23 was 36.12%, experiment 20 was 43.29%, and experiment 25 was 49.02%, which indicated that all three schemes made the residential building achieve energy saving. Then, the annual energy-saving benefits of experiment 23, experiment 20, and experiment 25 were 6.57 yuan/m^2, 7.87 yuan/m^2, and 8.91 yuan/m^2, respectively, showing good economic benefits.

Finally, the significance of the influence of different factors was analyzed (Figure 3).

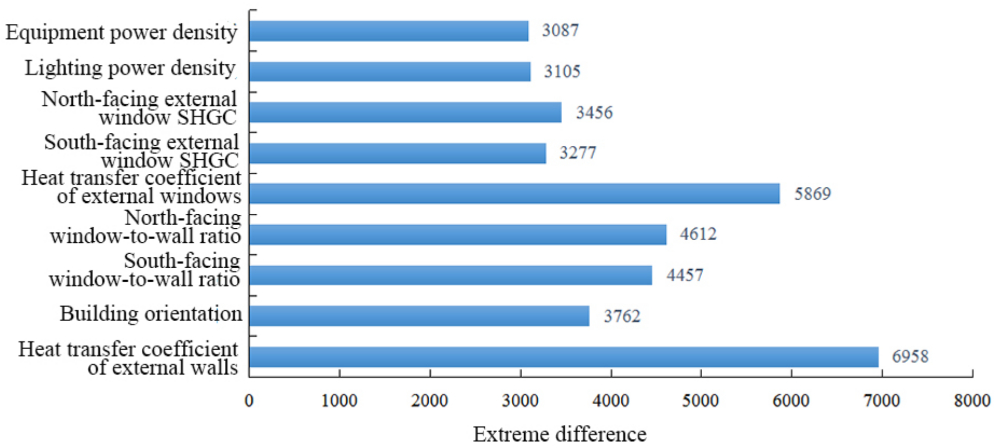

Figure 3. Significance analysis of the influence of different factors on total energy consumption

According to Figure 3, among all the analyzed factors, the external wall heat transfer coefficient had the greatest influence on the total energy consumption of the residential building, followed by the external window heat transfer coefficient. Therefore, in practical engineering, these two factors should be considered first, and energy-saving materials and energy-saving structures can be selected to reduce the heat transfer coefficient. Because the area of the windows directly influences the quantity of solar radiation entering the interior, the ratio of windows to walls also had a substantial impact on overall energy usage. In practical engineering, this factor should be considered based on actual conditions. Finally, although the power density of equipment and lighting had a relatively small impact on the total energy consumption of the residential building, it also contributes to the energy conservation of the building.

4. CONCLUSION

This article mainly studied the factors influencing energy conservation in residential buildings. Taking a residential building in Zhengzhou as an example, an analysis was conducted using Dest-h software. The results showed that orthogonal experiments could effectively identify the scheme with low building energy consumption, which offers a reference for subsequent actual construction projects. Furthermore, among the nine factors investigated in this article, the external wall heat transfer coefficient and the external window heat transfer coefficient have the greatest impact on the energy saving of this residential building, so they should be emphasized in practical engineering.

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