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Analysis the Influence of Building Design Parameters on Energy Consumption of Air Conditioning Using Orthogonal Experimental Design and Numerical Simulation

By

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Abstract

This paper selected the residential buildings in Guangxi, China, to assess energy consumption of air conditioning. Numerical analysis was carried out to evaluate design parameters that could influence the energy consumption of air conditioning. A total of 16 valid cases using an orthogonal array, L16(4^5) orthogonal experimental design (OED) were selected. OED analysis showed significant probability and, therefore, the design parameters effects on the energy consumption of air conditioning were quantitatively characterized. The conclusions were as follows: 1) the significance probability of design factors affecting the energy consumption of air conditioning ranked highest to lowest in sequence were found to be thickness of the roof, insulation material of external wall, thickness of external wall, and insulation material of the roof; 2) The simulation results of the optimal combination(A4B4C4D4) show that the cold load and the heat load are reduced by 7.63% and 17.06% respectively, and the optimization effect is significant. The results of such an evaluation can be used as an index for the planning and design process and for feedback of green building projects.

Keywords: Energy consumption of air conditioning; Envelop enclosure; Green building; Orthogonal experimental

Introduction

Buildings account for more than 40% of global energy consumption and release considerable amounts of greenhouse gases [1]. This energy use in different buildings is high because, as household buildings are powered to provide enough energy for heating, cooling, and use electrical appliances [2], industrial buildings are powered to enhance production and other commercial activities. As energy in buildings is used for heating and cooling, ventilation, lighting, etc. to reduce energy consumption in buildings, there must be efforts to design buildings that have good natural aeration and ventilation, good natural lighting, with effective and efficient heating/cooling systems [3]. The focus of a future trend in building design is on the green building due to the following advantages, e.g. its low energy demand, efficient use of resources, use of sustainable and healthy materials, etc[4].

In addition, air conditioning accounted for the high rate of annual primary energy consumption in buildings, so studies were then conducted that focused on optimizing the operating parameters and energy-saving controllers in air conditioning systems [5,6]. Huang et. al. minimized building energy use and energy life-cycle cost by optimizing the total number of chillers and the size of each chiller under cooling load uncertainty [7]. Limphitakphong N, Chaikatetham N, Khaimook T, et al. by a building case at Chulalongkorn University found revealed that the efficiency of the air conditioning system was poor as most equipment failed to meet the Thai industrial standards. Either a highly efficient air conditioner replacement or improving building envelope should be implemented to amend this [8].

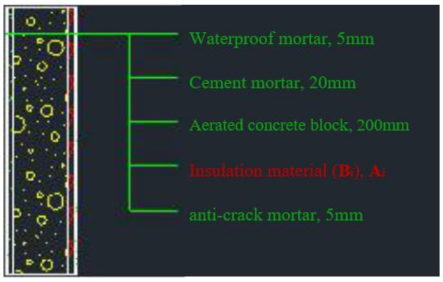
Designing a green building requires the evaluation of numerous conflicting parameters, such as orientation choice, facade design, window area, wall insulation, envelope design, and construction cost [9,10]. The design of air conditioning systems is also a nonlinear programming problem [11]. Therefore, architects' subjective designs may not yield optimal building envelope and air conditioning system configurations [4].

Relatively few studies, however, have been specifically devoted to better conduct multi-objective optimization design for building envelope and air conditioning systems. In this study, design factors that could affect the energy consumption of air conditioning on a residential architectural scale were chosen. Numerical simulations were then employed to determine the effects of design factors on the the energy consumption of air conditioning. We aimed to discover the following through an orthogonal experimental design (OED) method: (1) The order of significance probability for the design parameters were considered that could affect the energy consumption of air conditioning; (2)The optimal combination is determined by the minimum number of experiments.

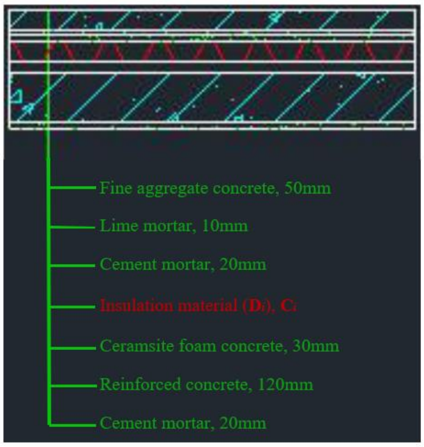
Methods and Procedure 2.1 Project Introduction

The research object of this paper is an apartment building, which is located in Nanning City, Guangxi Province, and belongs to the hot summer and warm winter climate zone. The 3D model of the apartment building created by Revit2020 is shown in Figure 1.

Figure 1. *The three-dimensional model of apartment building*



(a)Structure of exterior wall



(b)Structure of roof

Figure 2. *Schematic diagram of main constructions*

Figure 2 shows the Schematic diagram of main constructions, in which the selection of insulation material and the thickness value about exterior wall and roof refer to Table 1 [12-16].

Research Methods and Procedure

Considering that Revit can interact with more BIM softwares, so it is selected for modeling. 3D models of Revit2020 that can be used directly with BECH2020 software, saving secondary modeling time. The specific operation process is shown in Figure 3.

BECH2020 software can be used to simulate the heat consumption and dynamic cold consumption of air condition, so that the air condition system has a higher work efficiency. Heat consumption in this article refers to the heat required to heat a room through air condition in winter, and cold consumption refers to the amount of cold required for indoor cooling through air condition in summer.

In order to explore the building envelope's influence on the energy consumption of air conditioning system, this paper choose the thickness of external wall, insulation material of external wall, the thickness of the roof, insulation material of roof as influencing factors, each factor has four different levels, adopting $L16(4^5)$ orthogonal test analysis of the influence level of different factors on the energy consumption of air conditioning and the optimal level of each factor. The scheme design of orthogonal test is shown in Table 1.

Conclusion

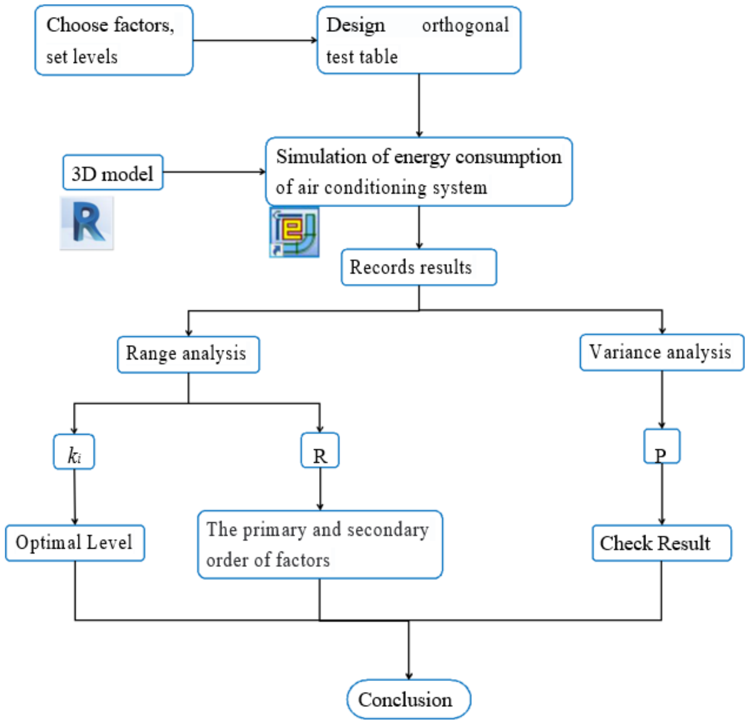


Figure 3. *Research methods and procedure of this study Table 1. Factors and Levels of Orthogonal Test*

Table 1. *Factors and Levels of Orthogonal Test*

Levels	Factors			
	Thickness of external wall(mm) A	Insulation material of external wall B	Thickness of the roof(mm) C	Insulation material of the roof D
1	30	Inorganic light aggregate insulation slurry type I	30	Extruded Polystyrene (XPS), α=1.2
2	40	Phenolic foam	40	Graphite polystyrene board (SEPS)
3	50	Extruded Polystyrene (XPS), α=1.15	50	Expanded Polystyrene (EPS)
4	60	Polyurethane, α=1.2	60	Polyurethane, α=1.35

Note: The correction coefficient α of Extruded Polystyrene and Polyurethane are different when they are used for exterior wall and roof insulation, which will affect the calculation of heat transfer coefficient, so this paper is considered them separately.

Results and Discussion

3.1 Range Analysis

According to the results of orthogonal test under different factors and levels, the average value ki and range R of cold load and heat load of each index of four factors (A, B, C and D) were calculated, as shown in Table 2.

Table 2. *Results of L16(4^5) Orthogonal Test*

				Factors			Cold	Heat
Test number	**A**	**B**	**C**	**D**	**E**	**load**	**load**	
						(Blank)	(W/m2)	(W/m2)
	1	1	1	1	1	1	64.21	30.2
	2	1	2	2	2	2	63.19	28.5
	3	1	3	3	3	3	61.76	27.7
	4	1	4	4	4	4	60.66	26.9
	5	2	1	2	3	4	63.33	29.4
	6	2	2	1	4	3	62.59	27.9
	7	2	3	4	1	2	60.68	26.7
	8	2	4	3	2	1	61.36	27.0
	9	3	1	3	4	2	61.93	28.4
	10	3	2	4	3	1	60.67	26.6
	11	3	3	1	2	4	62.75	27.8
	12	3	4	2	1	3	60.87	26.5
	13	4	1	4	2	3	61.33	28.2
	14	4	2	3	1	4	60.53	26.3
	15	4	3	2	4	1	60.53	26.4
	16	4	4	1	3	2	61.69	26.8
	K1	249.82	250.8	251.24	246.29	246.77		
	K2	247.96	246.98	247.92	248.63	247.49		
	K3	246.22	245.72	245.58	247.45	246.55		
	K4	244.08	244.58	243.34	245.71	247.27		
	k1	62.455	62.7	62.81	61.5725	61.6925		
Cold	k2	61.99	61.745	61.98	62.1575	61.8725		
	k3	61.555	61.43	61.395	61.8625	61.6375		
load	k4	61.02	61.145	60.835	61.4275	61.8175		
(W/m2)	R	1.435	1.555	1.975	0.73	0.235		
	Priorities		C>B>A >D					
	Optimal Level	A4	B4	C4	D4			
	Optimum Assembly		A4B4C4D4					
Heat	K1	113.3	116.2	112.7	109.7	110.2		
load	K2	111	109.3	110.8	111.5	110.4		
(W/m2)	K3	109.3	108.6	109.4	110.5	110.3		
	K4	107.7	107.2	108.4	109.6	110.4		
	k1	28.325	29.05	28.175	27.425	27.55		
	k2	27.75	27.325	27.7	27.875	27.6		
	k3	27.325	27.15	27.35	27.625	27.575		
	k4	26.925	26.8	27.1	27.4	27.6		
	R	1.4	2.25	1.075	0.475	0.05		
	Priorities							
	Optimal Level	A4	B4	C4	D4			
	Optimum Assembly	A4	B4	C4	D4			

The ordering of range difference of cooling load is RC＞RB＞RA＞RD, so the order of influence degree is thickness of the roof＞ insulation material of external wall＞ thickness of external wall ＞insulation material of the roof. However, the ordering of range difference of heat load is RB＞RA＞RC＞RD, so the order of influence degree is insulation material of external wall ＞thickness of external wall ＞ thickness of the roof >insulation material of the roof. Which indicates that when different indicators are considered, there are some differences in the influence degree of each factor. However, by comprehensive analysis of the two indicators (cold load and heat load), it can be found that the influence degree of factor D (insulation material of the roof) is minimal, it is relatively large and the influence degree of factor B (insulation material of external wall).

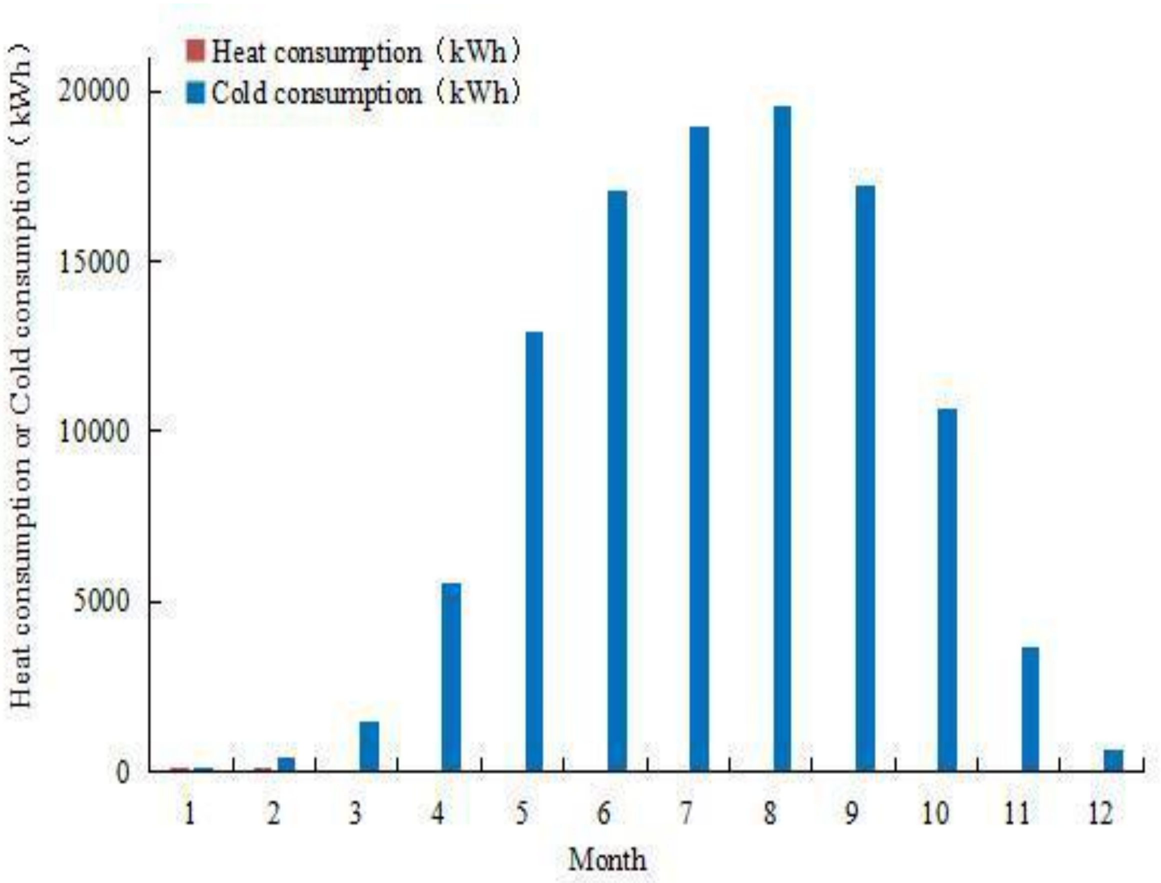


Figure 4. *Heat consumption and cold consumption of air conditioning under optimal combination throughout the year*

Although factors have different influences on cold load and heat load, it can be found from the ki in Table 2 that the optimal combination of the two indexes is A4B4C4D4. Therefore, in this paper, the optimal combination of parameters have a simulation of air conditioning energy consumption, cold load is 59.33W/m^2, heat load is 25.5W/m^2, which is 4.9W/m^2 (about 7.63%) lower than the initial value of cold load (64.23W/m^2), and 7.3W/m^2 (about 17.06%) lower than the initial value of heat load (32.8W/m^2). The annual heat consumption and cooling consumption changes are shown in Figure 4.

It is obvious in Figure 4 that the annual cooling consumption of air conditioning is the main part, so it is more appropriate to determine the influence degree of these factors y comprehensive analysis: C > B > A > D.

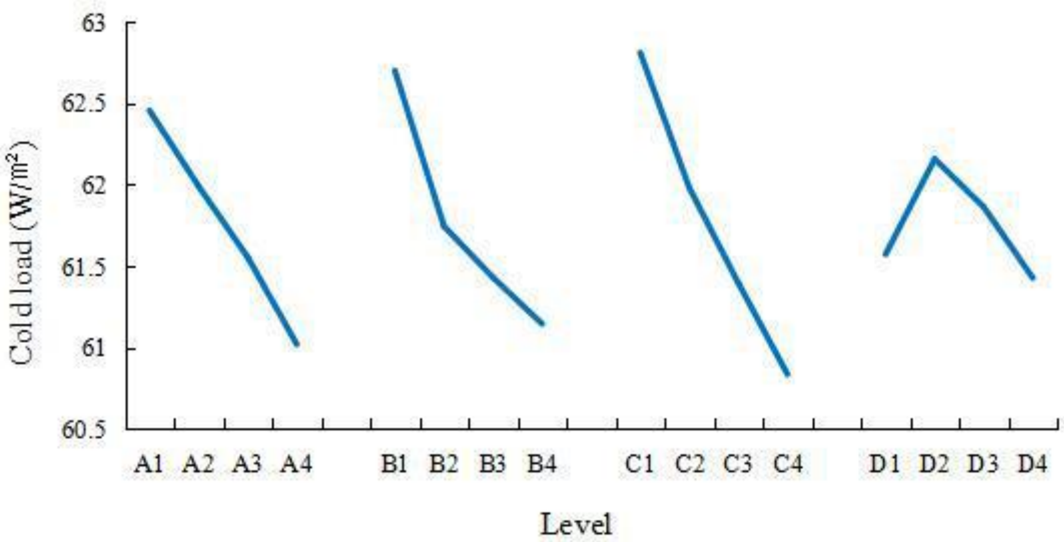


Figure 5. *Relationship curves between cold load and factor level*

Figure 5 shows relationship curves between cold load and factor level, it can intuitively see the law and trend of the influence of various factors on cold load. As can be seen from figure 8, cold load decreases gradually with the increase of material thickness. For thermal insulation materials of external walls, inorganic light aggregate insulation slurry type I has the largest cold load, while polyurethane has the smallest cold load. The thermal insulation material of the roof has the maximum cold load of graphite polystyrene board and the minimum cold load of polyurethane.

Significance Test

Table 3 shows the results from the significant probability analysis. Thus, the multivariate analysis of variance was calculated after analyzing the design parameters using significance probability. As can be seen from Table 3, the order of F value of cooling load parameter is C > B > A > D, and the order of F value of heat load parameter is B > A > C > D, which verifies the conclusion of range analysis. Because, the heat consumption is very small compared with the cold consumption, it is negligible, just the analysis of p-value of cold load shows that thickness of the roof(C), insulation material of external wall(B), thickness of external wall(A), which have extremely significant influence, while insulation material of the roof(D) has a relatively small influence.

Table 3. *Variance Analysis*

	Factor	Sum of Squares	df	Mean Square	F	P
Cold load (W/m^2)	A	4.5018	3	1.5006	31.76993648	0.008966422
	B	5.4834	3	1.8278	38.6972477	0.006735948
	C	8.5586	3	2.852866667	60.39943542	0.003511308
	D	1.2565	3	0.418833333	8.867325335	0.053074267
	E(Error)	0.1417	3	0.047233333		
Heat load (W/m^2)	A	4.311875	3	1.437291667	627.1818181	0.000107774
	B	12.076875	3	4.025625	1756.636363	2.30346E-05
	C	2.606875	3	0.868958333	379.1818181	0.000228833
	D	0.581875	3	0.193958333	84.63636362	0.002134687
	E(Error)	0.006875	3	0.002291667		

Note: When the significance probability P is less than 0.05, the degree of influence is significant, and when the significance probability P is less than 0.01, the degree is extremely significant.

Conclusion and Discussions

In this study, using the method of numerical simulation, taking the material and thickness of building envelope as factors, three levels were selected to simulate and analyze the energy consumption of 16 groups of parameters. Quantitatively determine the influence of various design parameters related to air conditioning energy consumption. The results are as follows:

(1) The orthogonal table of experimental design is developed to study the influence of main design parameters on the energy consumption of air conditioning. In a small number of experiments, the optimal combination(A4B4C4D4) is provided.

(2) The simulation results of the optimal combination(A4B4C4D4) show that the cold load and the heat load are reduced by 7.63% and 17.06% respectively, and the optimization effect is significant.

(3) The significance probability was used to analyze the influence degree of air conditioning energy consumption. It was found that the order of priority was thickness of the roof (C), followed by insulation material of external wall (B), thickness of external wall (A), and insulation material of the roof (D) had the least influence.

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