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Study on design method of building thermal parameters of ultra-low-energy building in Shanghai

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Abstract. Ultra-low-energy buildings have attracted increasing attention particularly for ensuring a comfortable indoor climate in summer and in winter with ultra-low energy demand. To permit this, there are high requirements on various parameters such as building envelope structure, and emphasizes the importance of building energy-saving optimization design. However, most of the current optimization analysis of the influencing factors of the building load is based on actual buildings with fixed spatial factors. Few studies have comprehensively considered the influence of building envelope parameters and spatial factors on building load. Actually, different architectural spatial design factors such as length-width ratio, building standard layer area, floor height correspond to different analysis results. Therefore, this paper first analyzes the influence of architectural space design factors on building load. Based on this, the orthogonal test method is used to study the contribution rate of nine building envelope thermal parameters to building load changes. The study found that under the premise of different spatial design factors, the thermal parameters of the envelope structure have different effects on the building load. The results of this paper provide a basis for energy-saving design and development of ultra-low-energy buildings in hot summer and cold winter regions.

Keywords. Ultra-low-energy building, Building thermal parameter, Spatial design factor

1. Introduction

In recent years, ultra-low-energy buildings have become one of the major directions for the development of China's construction industry with its low-carbon environmental protection and energy-saving advantages. The realization path of ultra-low-energy buildings is to reduce the building load by passive technology and then use the high-efficiency active technology to achieve the goal of ultra-low energy consumption. For the building itself, the factors affecting the building load include two categories, namely the architectural space design factor and the thermal parameters of the envelope structure. Liu Li^[1] studied the influence of architectural space design factors such as length-width ratio, building orientation and standard floor area on building energy consumption, and result proved the role of architectural space design factors. Jokisalo^[2] found that for every unit that reduces air tightness, heating energy consumption due to air infiltration will fall by 4%-12%. Fang Tao^[3] quantitatively analyzed the effects of heat transfer coefficient of outer protective structure, heat transfer coefficient of window and window-wall ratio on heating and cooling energy consumption of residential buildings, and obtained optimized design indexes of various parameters. Ferrara^[4] optimizes the enclosure design parameters of a single home to reduce heating and cooling energy



consumption by 20%. It can be seen that these two factors are of great significance for building energy conservation work. However, in the related energy conservation research, the research on the two types of influencing factors is mostly independent research, and few attention are paid to considering the two types of factors comprehensively. This paper takes the office buildings in Shanghai as the research object, analyzes the building load under the coupling of architectural space design factors and thermal parameters of the envelope structure, and discusses the technical path of ultra-low energy buildings. The research results of this paper provide a research basis for the development of ultra-low energy buildings in Shanghai.

2. Simulation parameters

2.1. Spatial design factors

Architectural space design factors include building orientation, architectural layout, standard floor area, length-width ratio, and height. This paper investigates 46 multi-storey office buildings with green building ratings in the hot summer and cold winter regions. The survey results show that the direction of the building is mostly in the south direction. There are some differences in the values of the standard layer area, length-width ratio (L-W ratio) and floor height (h_{floor}). Therefore, this paper selects these three factors as the research object to analyze the influence of architectural space design factors. The floor area commonly applied is in the range of 600-2400m², with square- or rectangular- plane geometry. Floor-floor height is in the range of 3.6-4.8 m. Length-width ratio is in the range of 1:1-4:1. The building model diagram is shown in Fig 1. For further simulation analysis, various factors need to be quantified, as shown in Table 1.

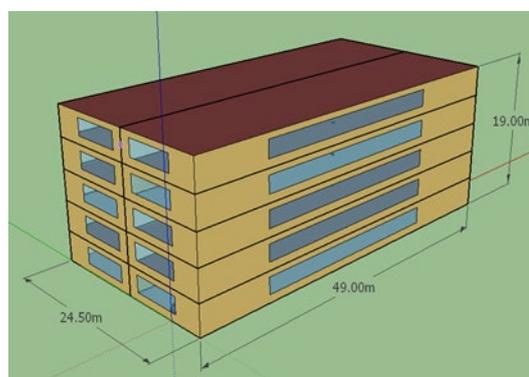


Figure 1. Building model diagram

Table 1. The value of building space design factors

Building space design factor	Typical value
Orientation	South
Plane shape	Square- or rectangular- plane
Length-width ratio	1:1、2:1、3:1、4:1
Floor-floor height	3.9m、4.2m、4.5m、4.8m
Standard layer area	600m ² 、1200m ² 、1800m ² 、2400m ²

2.2. Building envelope thermal parameters

The value of thermal parameters of the envelope structure is based on the rules: the upper limit is taken from the value in China's current standard^[5], and the lower limit is taken from the current value of the ultra-low energy demonstration building in the hot summer and cold winter area. Taking the value of air tightness as an example, the recommended index of air tightness for ultra-low-energy buildings in China is $n_{\pm 50} \leq 0.6 \text{ h}^{-1}$, and the air-tightness of ultra-low-energy buildings built in summer hot and cold winter areas can reach 0.2 h^{-1} , so the air tightness ($n_{\pm 50}$) range is $0.2-0.6 \text{ h}^{-1}$.

Table 2. The value of building envelope thermal parameters

Building envelope thermal parameter	Range of value
East window-to-wall ratio	0.1-0.7
West window-to-wall ratio	0.1-0.7
South window-to-wall ratio	0.1-0.7
North window-to-wall ratio	0.1-0.7
External wall heat transfer coefficient (W/m ² •K)	0.2-0.8
Roof heat transfer coefficient (W/m ² •K)	0.2-0.5
Window heat transfer coefficient (W/m ² •K)	1.0-2.5
Air tightness (n _{±50})	0.2-0.6 h ⁻¹
Window solar heat gain coefficient (SHGC)	0.2-0.5

3. Research methods

The research content of this paper is divided into two parts. The first step is to simulate the spatial design factors of the building and analyse the impact of different spatial design factors on the building load. The second step is to optimize the thermal parameters of the envelope structure based on the first step. Due to the many thermal parameters of the envelope structure, the work load of the exhaustive method is very large, and the achieve difficulty is high. Meantime, the purpose of this paper is to seek better working conditions to guide the design of ultra-low energy buildings. Therefore, the orthogonal test method is adopted in this paper to analyse the thermal parameters of the envelope structure.

3.1. Exhaustive method

The three architectural space design factors analyzed in this paper have selected four levels, and analyzed by exhaustive method, a total of 64 working conditions. When simulating the spatial design factors, the thermal parameters of the enclosure are referenced to the existing ultra-low-energy buildings in the hot summer and cold winter regions. The four oriented window-to-wall ratio is assumed to be 0.3. The heat transfer coefficient of the outer wall is set to 0.2 W/m²•K, The heat transfer coefficient of the window is set to 1.0 W/m²•K, and the heat transfer coefficient of the roof is set to 0.2 W/m²•K. The air tightness is n_{±50}=0.6 h⁻¹, and the indoor heat is not considered in the room, that is, the indoor heating power is 0 W/m².

This paper takes the standard layer area of the factor as the first-level index, and the load level as the secondary index classifies the 64 working conditions, which are divided into 8 categories. Meantime, a basic building is selected for each type of buildings to represent such building load levels. The specific classification results are shown in the table 3.

Table 3. Spatial design factor classification

Standard floor area(m ²)	Heating and cooling load (kW•h/m ²)	Working condition	Selected condition
600	High (26-30)	h _{floor} 4.5m L-W ratio 1:1-4:1	h _{floor} 4.5m
		h _{floor} 4.8m L-W ratio 1:1-4:1	L-W ratio 4:1
	Low (22-26)	h _{floor} 3.9m L-W ratio 1:1-4:1	h _{floor} 3.9m
		h _{floor} 4.2m L-W ratio 1:1-4:1	L-W ratio 3:1
1200	High (21-24)	h _{floor} 4.5m L-W ratio 1:1-4:1	h _{floor} 4.8m
		h _{floor} 4.8m L-W ratio 1:1-4:1	L-W ratio 2:1
	Low (18-21)	h _{floor} 3.9m L-W ratio 1:1-4:1	h _{floor} 4.2m
		h _{floor} 4.2m L-W ratio 1:1-4:1	L-W ratio 1:1

1800	High (18.5-22)	$h_{\text{floor}}4.5\text{m}$ L-W ratio 1:1-4:1 $h_{\text{floor}}4.8\text{m}$ L-W ratio 1:1-4:1	$h_{\text{floor}}4.5\text{m}$ L-W ratio 3:1
	Low (15-18.5)	$h_{\text{floor}}3.9\text{m}$ L-W ratio 1:1-4:1 $h_{\text{floor}}4.2\text{m}$ L-W ratio 1:1-4:1	$h_{\text{floor}}3.9\text{m}$ L-W ratio 4:1
2400	High (17.5-20)	$h_{\text{floor}}4.5\text{m}$ L-W ratio 1:1-4:1 $h_{\text{floor}}4.8\text{m}$ L-W ratio 1:1-4:1	$h_{\text{floor}}4.5\text{m}$ L-W ratio 1:1
	Low (15-17.5)	$h_{\text{floor}}3.9\text{m}$ L-W ratio 1:1-4:1 $h_{\text{floor}}4.2\text{m}$ L-W ratio 1:1-4:1	$h_{\text{floor}}4.2\text{m}$ L-W ratio 2:1

3.2. Orthogonal test

Orthogonal test method is a kind of experimental design method for studying multi-factor and multi-level. In this paper, we need to consider the impact of nine factors related to the thermal parameters of the enclosure on the building load. If a full simulation is performed, 49 simulations are required, and the workload is huge. However, the orthogonal test design can greatly reduce the number of simulations, and at the same time, reasonable and correct conclusions can be obtained. This simulation only considers the impact of nine factors on the load of each basic building, regardless of the interaction between the factors. The factors and levels of the test are selected as shown in Table 4. Using the $L_{32}(4^9)$ orthogonal table, we can draw conclusions by setting 32 simulation conditions for each type of basic building.

Table 4. Selection of factors and levels

Level	Factor								
	Air tightness (A) ($n_{\pm 50}$)	K_{wall} (B) ($\text{W}/\text{m}^2\cdot\text{K}$)	K_{window} (C) ($\text{W}/\text{m}^2\cdot\text{K}$)	K_{roof} (D) ($\text{W}/\text{m}^2\cdot\text{K}$)	SHGC (E)	South WWR	North WWR	West WWR	East WWR
1	0.2	0.2	1.0	0.2	0.2	0.1	0.1	0.1	0.1
2	0.3	0.3	1.5	0.4	0.3	0.3	0.3	0.3	0.3
3	0.4	0.4	2.0	0.6	0.4	0.5	0.5	0.5	0.5
4	0.6	0.5	2.5	0.8	0.5	0.7	0.7	0.7	0.7

4. Results and discussion

4.1. Impact of spatial design factors

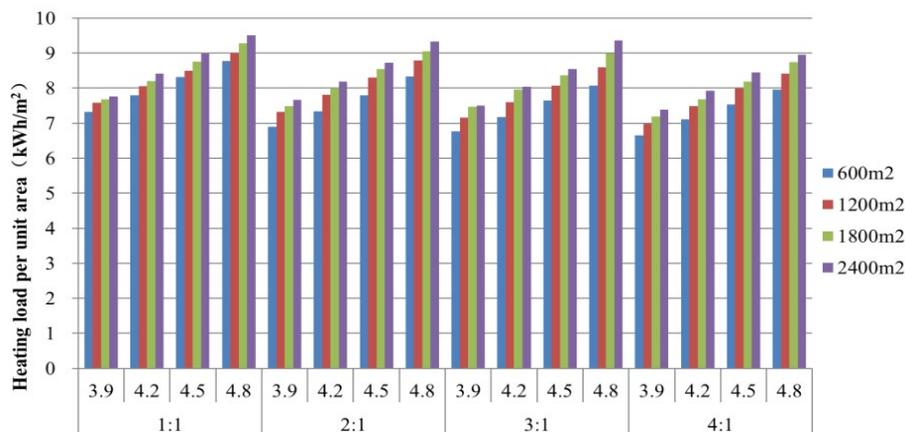


Figure 2. Heating load per unit area

It can be seen from Fig. 2 that the heating load is gradually increased with the increase of the standard layer area. When the standard layer area is increased to 2400m², and the heating load increase rate is in the range of 8%-12% compare to the standard layer area of 600 m². Moreover, as the height

of the building layer increases, the value of the load increase rate is gradually increasing. When the building height is increased, the heating load is also gradually increasing. When the floor height is increased from 3.9m to 4.8m, the heating load increase rate is between 19% and 22%. As the length-width ratio of the building increases, the heating load shows a gradual decline. When the length-width ratio increases from 1:1 to 4:1, the heating load is reduced by 5%-9%. According to the degree of influence on the building heating load, it can be sorted: layer height>standard layer area> length-width ratio.

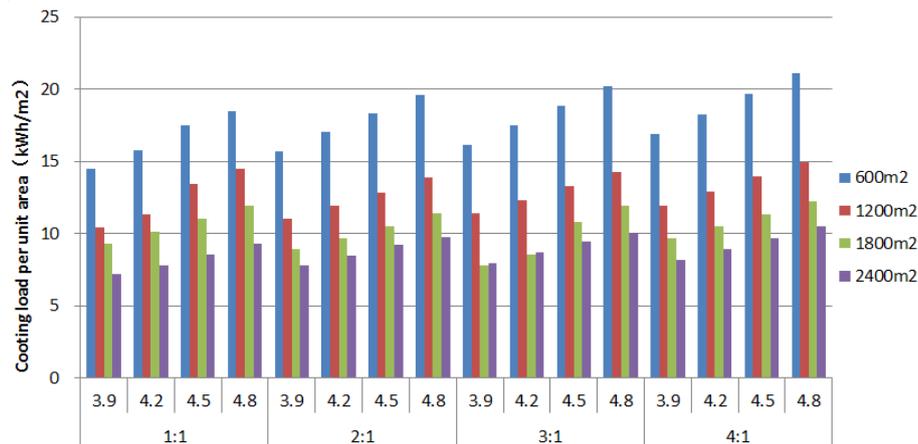


Figure 3. Cooling load per unit area

It can be seen from Fig. 3 that the cooling load is greatly reduced with the increase of the standard layer area, and the value of the cooling load reduction rate is decreasing as the standard layer area increases. When the floor area is increased from 1800 m² to 2400 m², the air conditioning load reduction rate is between 13% and 16%. When the standard layer area is increased to 2400 m², the numerical comparison with the standard layer area of 600 m² can be obtained, and the cooling load reduction rate reaches 49%-52%. With the building layer height increased, the cooling load is also gradually reduced. When the floor height is increased from 3.9m to 4.8m, the cooling load reduction rate is between 25% and 29%. When the length-width ratio increases, the cooling load tends to increase gradually. When the length-width ratio increases from 1:1 to 4:1, the cooling load increase rate is between 12%-17%. According to the degree of influence on the building cooling load, it can be sorted: standard layer area > layer height > length-width ratio.

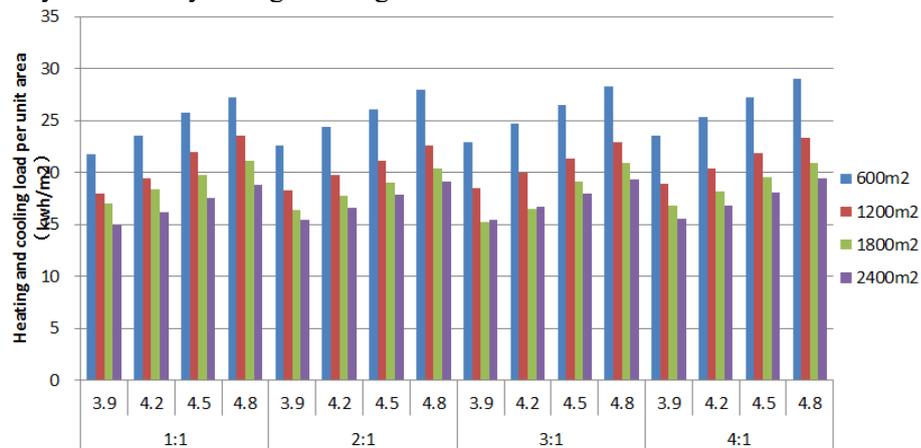


Figure 4. Heating and cooling load per unit area

It can be seen from that the influence of the standard layer area on the heating and air conditioning load is basically the same as that of the cooling load. As the standard layer area increases, the heating and air conditioning load is greatly reduced. When the standard layer area increased to

2400 m², the comparison with the standard layer area of 600 m² can be obtained, and the heating and cooling load reduction rate reaches 31%-33%. When the building height increases, the annual heating and cooling load is also gradually reduced. As the floor height increases from 3.9m to 4.8m, the heating and cooling load reduction rate is between 23% and 25%. When the length-width ratio is increased from 1:1 to 4:1, the cooling load increase rate is between 4% and 8%. According to the degree of influence on the building heating and cooling load, it can be sorted: standard layer area > layer height > length-width ratio.

According to the simulation results, the length-width ratio has less influence on the load than the other two factors, and the standard layer area is the most critical factor determining the load level. This paper selects two models at the first level of load level (standard layer area 600m², layer height 4.5m, length-width ratio 4:1) and load at the eighth level(standard layer area 2400m², layer height 4.2m, length-width ratio 2:1) as the basic building for the second step of research work.

4.2. Influence of thermal parameters of the envelope structure

Some studies [6] [7] have shown that indoor heat sources are the most significant factor affecting building load. Therefore, the two basic buildings take four quantitative values of indoor heating value from 0-30W/m², which are 0 W/m², 10 W/m², 20 W/m², and 30 W/m². Then, the influence of thermal parameters of the enclosure structure on each indoor heating value is analysed according to the orthogonal test method. The results of thermal parameter analysis of the envelope structure of the two basic buildings are shown in Table 5 and Table 6.

Table 5. Contribution rate of various factors of the first level of basic building

	Contribution rate /%	n _{±50}	K _{wall}	K _{window}	K _{roof}	SHGC	South WWR	North WWR	West WWR	East WWR
Heating load	G0	57.57	6.01	14.79	0.58	12.51	8.16	0.29	0.00	0.09
	G10	61.45	6.24	16.01	0.46	10.36	4.87	0.44	0.07	0.11
	G20	64.00	6.14	16.59	0.32	9.07	2.98	0.60	0.17	0.13
	G30	65.21	6.03	16.78	0.24	8.55	1.97	0.82	0.25	0.15
Cooling load	G0	5.42	0.08	1.07	0.05	41.35	29.82	14.73	4.51	2.97
	G10	5.40	0.06	1.21	0.07	43.28	28.71	14.09	4.40	2.80
	G20	7.57	0.04	1.39	0.04	43.19	27.48	13.51	4.12	2.66
	G30	11.14	0.04	1.37	0.03	41.74	26.18	12.83	4.07	2.59
Heating and cooling load	G0	61.46	4.49	8.66	0.30	4.97	4.11	11.38	2.87	1.76
	G10	57.47	3.47	6.39	0.19	8.22	7.02	11.85	3.44	1.95
	G20	55.35	2.55	4.81	0.10	10.64	9.33	11.71	3.53	1.98
	G30	53.08	1.79	3.52	0.05	12.90	11.36	11.61	3.65	2.04

Note: G0 represents the contribution rate of each parameter when the indoor heating value is 0 W/m².

Table 6. Contribution rate of various factors of the eighth level of basic building

	Contribution rate /%	n _{±50}	K _{wall}	K _{window}	K _{roof}	SHGC	South WWR	North WWR	West WWR	East WWR
Heating load	G0	87.96	1.54	3.97	0.60	3.53	2.25	0.07	0.03	0.04
	G10	89.63	1.58	4.36	0.54	2.63	1.13	0.09	0.00	0.02
	G20	90.70	1.45	4.41	0.44	2.19	0.61	0.12	0.04	0.03
	G30	91.42	1.35	4.34	0.40	1.86	0.34	0.18	0.06	0.05
Cooling load	G0	11.37	0.50	0.91	0.27	36.47	18.93	10.07	13.01	8.48
	G10	9.18	0.12	0.53	0.13	41.01	17.89	9.38	13.49	8.28
	G20	17.30	0.05	0.70	0.08	38.68	15.70	8.20	11.85	7.43
	G30	30.38	0.03	0.61	0.07	32.73	13.06	6.95	10.02	6.16

Heating and cooling load	G0	87.61	1.82	3.60	0.76	0.81	0.27	2.17	1.79	1.18
	G10	84.81	1.41	2.78	0.57	2.33	1.03	2.56	2.86	1.66
	G20	83.60	1.00	1.95	0.39	3.56	1.75	2.61	3.21	1.92
	G30	82.32	0.69	1.37	0.29	4.73	2.42	2.76	3.39	2.03

Note: G0 represents the contribution rate of each parameter when the indoor heating value is 0 W/m².

It can be obtained from Table 5 that for the heating load, the main influencing factors are air tightness > window heat transfer coefficient > SHGC > outer wall heat transfer coefficient > south window-wall ratio. Air tightness is the most influential parameter to the contribution rate, and as the indoor heat generation increases, the contribution rate of air tightness increases gradually. The contribution rate of the roof heating coefficient, the north window-wall ratio, the east window-wall ratio, and the west window-wall ratio are all at a very low level, which is negligible. The south window-wall ratio and the outer window solar heat gain coefficient (SHGC) decrease with the increase of indoor heating value. The contribution rate of the external wall heat transfer coefficient to the heating load is not greatly affected by the change of the indoor heating value. For the cooling load, the main influencing factors are SHGC>south window-wall ratio>north window-wall ratio>air tightness. The contribution rate of SHGC has no obvious change with the increase of indoor heating value. The south window-wall ratio and the north window-wall ratio decreases with the increase of indoor heating value, and the influence of the heat transfer coefficient of the outer wall and roof is negligible. For the annual heating and cooling load, the main influencing factors are air tightness > north window-wall ratio > SHGC > south window-wall ratio.

Comparing Table 5 and Table 6 can be obtained, when the area of the standard layer increases, the degree of influence of air tightness increases by a large margin. For heating load, the contribution rate of air tightness reaches about 90 %, it becomes a decisive indicator. And the influence of other factors on the heating load is greatly reduced. For the cooling load, when the area of the standard layer increases, the influence of the west window-wall ratio exceeds the north window-wall ratio. With the increase of the indoor heating value, the order of the main influencing factors changes greatly. When the indoor heating value is 0 W/m², the main influencing factors are SHGC>south window-wall ratio>west window-wall ratio>air tightness. When the indoor heating value is raised to 30 W/m², the main influencing factors are SHGC>air tightness> south window-wall ratio > west window-wall ratio.

5. Conclusion

The design factors of building space have a non-negligible influence on the building load. In this paper, we find that there are certain gaps in the impact of building load among the three spatial design factors. In the actual building design, increasing the standard floor area and reducing the floor height are two important energy-saving strategies. The impact of length-width ratio is small and can be considered as a secondary consideration.

In the analysis of the thermal parameters of the envelope structure, it is found that the main influencing factors of building load are different, and the contribution rate of each factor also has a certain difference. Moreover, in the comparative analysis of different spatial design factors, it is found that the difference of spatial design factors also affects the contribution rate of thermal parameters of building envelopes to building load changes.

This paper comprehensively analyzes the influence of building space design factors and thermal parameters of building envelopes on building load. Under different building space design factors and different indoor heat generation conditions, the key factors of energy saving optimization are different. The research results can find the best energy-saving solutions in the architectural design, and provide the basis for the development of ultra-low-energy buildings in the hot summer and cold winter regions.

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