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Energy-saving design of office buildings considering light environment and thermal environment

N. Ding^{1,†}, H. Guo²¹ School of Urban Construction and Transportation, Hefei University, Hefei 230601, China² Anhui Jin Yi Kun Chen Architectural Design Consulting Limited, Hefei 230031, China

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Abstract

The energy consumption of office buildings is analysed, and the influential factors to be considered in architectural design that affect the light and heat environment of office buildings are summarised. The original building model was established by Ecotect, and variable methods were adopted to simulate the influence of different influencing factors on the light and thermal environment, and to quantitatively evaluate the importance of different factors on energy consumption of buildings. This analysis provides an important basis for optimised energy saving design, and finally puts forward the optimal design strategy for energy saving, so as to build harmonious light and heat architectural environment.

Keywords: Light environment; thermal environment; thermal discomfort; energy conservation; architectural design

1 Introduction

With the continuous growth and acceleration of urbanisation, new buildings proliferate, especially public buildings, which make energy conservation and environmental protection become a new subject of contemporary architectural theory research. In the design of office buildings, how to improve comfort while saving energy and protecting the environment has become a hot topic in architectural theory and technology research (Yu and Su, 2015; Huang and Niu, 2016).

The main factors affecting the thermal performance of exterior windows are window area, glass material, shading form and so on. The designer can optimise the design parameters and use the software to seek the optimal design scheme (Kwon et al., 2018; Li et al., 2018; Acosta et al., 2016; McDonald and Chakradhar, 2017; Aksamija and Peters, 2017).

[†]Corresponding author.Email address: 752856183@qq.com

Some scholars have studied window design to optimise daylighting performance. The influence of window design parameters is evaluated on heating demand and light and heat environment by using contour map, and the appropriate window design scheme is determined (Vanhoutteghem et al., 2015).

The combination of natural and artificial light was studied while maintaining visual comfort. Glare index and sunshine factor were selected to evaluate visual comfort. In hot climate, the office model was established by using the simulation programme Design Builder, and three types of glass window office models were designed, which not only reduces energy consumption, but also improves visual comfort (Fasi and Budaiwi, 2015).

In the design of the light environment of Shanghai Museum of Natural History, Li (2016) considered architectural form, functional layout, usage requirements and other factors into overall consideration to create a good internal light environment atmosphere. Specific integrated application of light environment design is mainly composed of natural light and daylighting system, exterior shading system and artificial lighting system.

Liu (2015) explored the relationship between natural lighting and interior design through four aspects such as window hole design, atrium lighting, reflective devices and shading measures, so as to make the best use of natural light.

Windows have a great influence on the indoor thermal environment and visual effect. Large Windows allow more light into the interior, improving the visual comfort of the interior, but may lead to the increase or loss of too much heat, thus affecting the thermal environment and energy consumption of the interior.

Architectural design elements that affect the thermal environment of buildings include window-wall ratio, window type, and horizontal sunshade size. Through orthogonal experiment and CFD simulation, the design element collocation scheme that makes the building thermal environment relatively optimised was obtained (Zhang et al., 2015).

DOE-2 software was used to analyse external window shading multi-story buildings. The research shows that when 28°C is assumed as the indoor comfortable temperature, external shading has the most significant effect on indoor cooling (Dou and Tang, 2011).

Shi (2019) studied the variable building skin and adjusted the solar radiation heat, ventilation and heat storage of the building through the dynamic control of the changeable components on the skin, so as to adapt to the constantly changing external environment of building.

The optimal control strategy of air conditioning system was studied, and the results showed that the optimised control strategy could save 56% of energy (Ascione et al., 2016).

Many literatures have described the energy-saving optimisation method of building design. Note that when meeting the requirements of light environment or thermal environment, the energy consumption should be reduced as far as possible. However, the optimisation of thermal comfort, lighting performance and energy saving is implemented separately (Lee et al., 2013; Zhang et al., 2017; Goia, 2016).

The light environment evaluation software Daysim was used. The design was carried out by balancing the performance of light environment and energy consumption (Sun et al., 2013).

Susorova (2013) studied the effects of geometric factors of commercial office buildings. The office building model created by Design Builder was used to simulate six climatic zones of the United States, and the lowest energy consumption parameter combination was found to determine the energy saving potential.

Thalfeldt (2013) optimised appearance parameters to achieve the best energy saving effect.

Liu (2018) firstly summarised the typical value or range of spatial design factors based on case study and established a typical model. Then, six spatial design factors were selected for analysis namely plane aspect ratio, building orientation, standard floor area, height, window-wall ratio and horizontal window visor length. Through experimental design and simulation analysis, the space energy-saving effect of point-type high-rise office buildings in Tianjin is maximised.

Some scholars use intelligent algorithms to find the optimal parameters (Echenagucia et al., 2015; Zhai et al., 2018; Daniel and Krarti, 2010).

In the above mentioned literatures, the relationship between window design and light environment and the relationship between window design and thermal environment were studied respectively, which provided a ref-

erence method for this research. The lack of systematic comprehensive analysis of architectural design, light environment and thermal environment are the problems that will be focussed in our study. The analysis object of this study is office buildings during hot summer and cold winter areas. Variable methods were adopted to simulate the influence of different factors on the light and thermal environment, and to quantitatively evaluate the importance of different factors on building's energy consumption.

2 Description of project

Hefei's temperature is below zero in winter and up to 40° in summer. The Maker Centre project of Baohe Avenue will be located in Binhu New District of Hefei city, Anhui province, China. To the east is Baohe Avenue, which connects Hefei city centre with Binhu New District. It is an important development axis from north to south, with better traffic location advantages. The west side has the completed residential area, the south side has the proposed kindergarten and park green space, and the north side has the planned commercial area, as shown in Figure 1. It has good natural regional advantages, and the regional infrastructure is basically complete. The project covers an area of 9,057 square metres and a building area of 12,350 square metres.

Fig. 1 Schematic diagram of the surrounding environment of the project.

The maker space is not only an office space, but also an open space for entrepreneurs to communicate and for gatherings. In the maker space, the design of the working environment adopts the open concept, which gets rid of the clumsy, single space form and environment features lacking characteristics in the traditional office space and creates an open and mobile working environment. Work and leisure are combined to create a collaborative and creative work space. The design concept attempts to integrate with the surrounding environment while exploring the interaction between architecture and culture.

Overall, the project building is divided into two functional areas, the main body of which is the office room that is set as the maker office space to meet the office needs of users. Group rooms are designed for catering rooms and corresponding property management rooms to meet the daily needs and daily management of the maker office staff. The office area consists of eight floors and six floors, each of which is interconnected, as

Fig. 2 Schematic diagram of building space.

shown in Figure 2.

The design of the building facade adopts the modern and simple style of grid. The grid facade can form a small balcony in the way of grid retreating inside during the day, providing users with a comfortable outdoor rest space. At the same time, it can provide the best lighting conditions and outdoor view, and also reduce the absorption of heat to the maximum extent, playing the energy-saving role of passive shading, as shown in Figure 3.

Fig. 3 Grid elevation diagram of the building.

3 Simulation of light environment, thermal environment and energy consumption

On the premise of building with high comfort, healthy and environmental protection, to make sure that the annual indoor temperature is 20–26°C and the indoor relative humidity is 40–60%, PHPP is used to analyse the overall energy consumption. By means of professional software simulation calculation and comprehensive consideration of photothermal environmental factors, the specific parameters are optimised for analysis, and the design solution with the lowest energy consumption is selected.

Ecotect software was used to analyse natural lighting, artificial lighting, indoor average lighting coefficient and illuminance uniformity, and to optimise window and insulation parameters.

By summarising and analysing the data obtained from PHPP energy simulation analysis, Ecotect daylighting analysis and thermal environment analysis, the overall load were further determined and the specific parameters were optimised to select the design solution with the lowest energy consumption.

The relationship between architectural design parameters and architectural light environment as well as thermal environment and energy consumption was discussed from the perspectives of glass performance, frames parameters, shading coefficient and insulation thickness, respectively. Ecotect and PHPP software were used to simulate the architectural design scheme under the parameter combination.

(1) PHPP software was used to calculate the heating load and cooling load.

(2) The corresponding parameters which were selected according to PHPP analysis results, Ecotect software was used to calculate and analyse the thermal comfort parameters (discomfort time) and lighting parameters (including average illumination and illumination evenness) of each scheme.

In order to simplify the simulation during the process of modelling and analysis, the outer wall and the inner wall are uniformly set at 120 mm, and the outer insulation layer, ground insulation layer and roof insulation layer of the wall are of same thickness. The specific analysis is as follows:

Energy consumption analysis

Calculation formula of window U value:

$$u = \frac{A_f \times U_f + A_g \times U_g + \psi_g \times L_g}{A_f + A_g} \quad (1)$$

A represents the area, U represents the heat transfer coefficient, and φ represents the heat transfer coefficient of the boundary. L_g is the perimeter of the glass.

The G value represents the ratio of the solar radiation energy of the room through the glass to the solar energy entering the room through the glassless opening.

The U value represents the capacity of the glass assembly to allow heat to pass through per unit area. The lower the U value, the lower the heat transfers through the glass.

The glazing G value was set as 0.5, the glazing U value as 0.6 and the frames U value as 0.8. The shading coefficient is set as 0. The original thickness of the wall structure is set as 120 mm. Meanwhile, the insulation thickness of external walls, roofs and grounds should be reduced by 10 mm every time to meet the requirements of energy consumption until the minimum insulation thickness. According to the data in Table 1, it can be analysed that, with the other parameters remaining unchanged, energy consumption increases gradually with the decrease of insulation thickness until fails to meet the requirements. Since the cost of building materials increases greatly with the increase of insulation thickness, it is of practical significance to find the minimum insulation thickness by modelling. Minimum insulation thickness is usually selected during construction.

The glazing G value was set at 0.5, the glazing U value was set at 0.6, and the frames U value was set at 0.8. The shading coefficient is set as 0–20%. The original thickness of the wall is set as 120 mm. Meanwhile, external wall, roof and ground are adjusted to select the minimum insulation thickness and record the influence of energy consumption, as shown in Table 2. By analysing the recorded data, it can be concluded that with the increase of shading coefficient, the minimum insulation thickness increases and the load decreases gradually. When the shading coefficient is continuously increased, the load reduction amplitude gradually decreases. When the

Table 1 Analysis of the influence of insulation thickness on energy consumption.

Insulation thickness (mm)	Heating demand (kWh/(m ² a))	Heating load (W/m ²)	Cooling demand (kWh/(m ² a))	Cooling load (W/m ²)	Non-renewable primary energy demand (kWh/(m ² a))	Primary energy re-newable demand (kWh/(m ² a))
150	2	8	27	9	59	33
140	3	8	27	9	61	34
130	3	8	27	9	62	34
120	4	9	27	9	63	35
110	4	9	28	10	65	36
100	5	10	28	10	67	37
90	6	11	28	10	70	38
80	7	11	29	11	74	41
70	9	12	29	11	78	44
69	9	12	29	11	79	44
68	9	13	29	11	79	45
67	10	13	29	11	80	45
66	10	13	29	11	80	45
65	10	13	30	11	81	46
64	10	13	30	11	82	46
63	10	13	30	11	82	47
62	11	13	30	11	83	47
61	11	13	30	11	84	47
60	11	14	30	12	84	48

minimum insulation thickness increases, the cost of construction will increase. From the data, when the shading coefficient reaches 12%, the minimum insulation thickness 80 mm provides the best parameters, as shown in Figure 4. Therefore, in order to balance the building energy consumption and economic demand, the shading coefficient was set at 12%.

Table 2 Relationship between shading coefficient and minimum insulation thickness.

Shading coefficient (%)	Minimum insulation thickness (mm)	Heating demand (kWh/(m ² a))	Heating load (W/m ²)	Cooling demand (kWh/(m ² a))	Cooling load (W/m ²)
0	66	10	13	29	11
2	68	9	13	29	11
4	70	9	12	29	11
6	72	9	12	29	11
8	75	8	12	29	11
10	77	8	12	29	11
12	80	7	11	29	11
14	84	7	11	29	11
16	88	6	11	29	11
18	93	6	10	29	11
20	99	5	10	29	11

Fig. 4 Relationship between shading coefficient and minimum insulation thickness.

The glazing G value was adjusted to 0.5 while the glazing U value to 0.6, and the shading coefficient was set at 12%. The frames U value was adjusted to 0.1-1.0. The insulation thickness of external wall, roof and ground was adjusted to select the minimum insulation thickness and record the influence of energy consumption, as shown in Table 3. By analysing the recorded data, it can be concluded that the minimum insulation thickness increases when the frames U value increases, as shown in Figure 5. When insulation thickness increases, the cost of construction will increase. After the frames U value reaches to 0.8, the insulation thickness increases more. Therefore, in order to balance the building energy consumption and economic demand, U value of frames can be 0.6, 0.7 and 0.8. The frames U value can also be analysed through the table data, which has little impact on the energy consumption.

Table 3 Relation between U value of frames and minimum insulation thickness.

Frames U value	Minimum insulation thickness (mm)	Heating demand (kWh/(m ² a))	Heating load (W/m ²)	Cooling demand (kWh/(m ² a))	Cooling load (W/m ²)
0.2	75	7	11	29	11
0.4	77	7	11	29	11
0.6	78	7	11	29	11
0.8	80	7	11	29	11
1	82	7	11	29	11

The external shading coefficient was adjusted to 12%, and the frames U value was varied between 0.6, 0.7 and 0.8. When different material glass is chosen, we adjust the minimum insulation thickness and record it. Low emissivity glass is a coated glass with a high reflectance to the far infrared of the wavelength range of 4.5 μm to 25 μm . There are many kinds of low emissivity glass. The thickness of the whole film is about 45 ~ 75 nm. The overall structure of double silver Low-E coated glass is relatively complex, mainly consisting of two

Fig. 5 Relation between frames U value and minimum insulation thickness.

or more silver layers evenly distributed among other protective metal oxides. The silver layers are separated in the middle layer, and the thickness of the silver-based film layer is about 5–12 nm. Online Low-E coated glass is coated with a film of about 100 nm on the surface of float glass.

This paper selects a triple glazing glass with two cavities (6 Low-E+9 Ar+6+9 Ar+6 Low-E). The glass can be divided into four types according to the form of the material, such as online Low-E coated glass + online Low-E coated glass, single silver Low-E coated glass + single silver Low-E coated glass, double silver Low-E coated glass + double silver Low-E coated glass and triple silver Low-E coated glass + single silver Low-E coated glass.

By simulation analysis, we adjust the minimum insulation thickness and record its value, as shown in Table 4. It can be seen that after the glass type is selected, under the premise of ensuring certain consumption, if there is an increase in of window frame U value, the roof and the floor increase correspondingly, and the construction cost of the building also increases accordingly.

Parameters of luminous environment

The calculation formula of average illuminance is as follows:

$$E_a = \frac{\sum_{i=1}^n E_i}{n} \quad (2)$$

E_a is the average illuminance.

E_i is the illumination of each region.

The calculation formula of uniformity of illumination is as follows:

Table 4 Different glass materials and minimum insulation thickness.

glass type	Low-e type	glazing U value [W/(m ² k)]	glazing G value	Visible transmittance	Frames U value [W/(m ² k)]	Minimum insulation thickness (mm)	Heating demand [kWh/(m ² a)]	Cooling demand [kWh/(m ² a)]
Triple glazing with two cavities 6Low-E+ 9Ar(argon)+ 6+9Ar(argon)+ 6Low-E	online + online,	1.07	0.54	0.57	0.6	114	7	29
					0.7	115	7	29
					0.8	117	7	29
	single silver + single silver	0.97	0.42	0.48	0.6	86	11	29
					0.7	87	11	29
					0.8	88	11	29
		0.92	0.51	0.73	0.6	95	8	29
					0.7	96	8	29
					0.8	98	8	29
		0.89	0.32	0.42	0.6	76	13	29
					0.7	76	13	29
					0.8	77	13	29
	triple silver + single silver	0.88	0.3	0.61	0.6	74	14	29
					0.7	75	14	29
					0.8	76	14	29

$$E_0 = \frac{E_{min}}{E_a} \quad (3)$$

E_0 is the uniformity of illumination.

E_{min} is the minimum illumination.

According to the glass parameters selected in PHPP simulation analysis, that is, the external shading is 12%, and the corresponding parameters of the five glass types. When using Ecotect software to analyse the architectural light environment, the influence of frames U value is not considered because the frames do not transmit light,. On the premise of meeting the requirements of lighting coefficient, lighting simulation and data analysis are carried out, as shown in Figures 6 and 7.

Through the analysis of the simulated data, the larger the visible transmission ratio is, the greater the average illumination of the corresponding building will be. All five types of glass with different visible transmittance have good lighting effects. There is little difference in uniformity of illuminance. The third type has the highest average illumination.

Parameters of thermal comfort

Thermal neutrality is an average temperature most people feel comfortable with. This temperature varies with the annual average temperature and seasonal fluctuations, and its formula used for calculation is as follows:

$$T_n = 17.6 + 0.31T_{ave} \quad (4)$$

According to this formula, the comfort temperature can be calculated, from which the monthly discomfort can be measured. Monthly discomfort is estimating the sum of all uncomfortable temperatures and comfort temperature limits. This is a better indicator of discomfort than simply measuring the sum of times when the comfort temperature is not reached.

Based on the material parameters of as glass, walls, roofs and grounds selected in PHPP simulation analysis, five models were established in Ecotect (Table 5). The natural ventilation environment was taken to analyse

Fig. 6 Uniformity of illumination of the building.

Fig. 7 Average illumination of the building.

the monthly thermal discomfort, and the data were obtained and analysed. As shown in Figure 8, compared with other modes, thermal discomfort of the first mode is significantly reduced. So select the glass material corresponding to the pattern in No.1. The No.1 kind of glass has the highest visible transmittance, G value and U value, but it corresponds to the highest insulation thickness, so it has the best thermal comfort.

In conclusion, first, the parameters of various types of glass and corresponding frames, walls, roofs and floors are obtained through PHPP simulation under the condition that heating and cooling requirements are met and

Table 5 Simulation parameters.

Type	Glazing G value	Glazing U value [W/(m ² k)]	Visible transmittance	Frames U value [W/(m ² k)]	Minimum insulation thickness (mm)
No.1	0.54	1.07	0.57	0.6	114
No.2	0.42	0.97	0.48	0.6	86
No.3	0.51	0.92	0.73	0.6	95
No.4	0.32	0.89	0.42	0.6	76
No.5	0.3	0.88	0.61	0.6	74

Fig. 8 Thermal discomfort of different glass materials.

heating and cooling loads meet the requirements. Second, with these obtained parameters, Ecotect daylighting simulation is carried out. Through simulation analysis, we obtain the five types of glass with different visible transmittance that all have good lighting effects and there is little difference in illuminance uniformity. Third, with these obtained parameters, Ecotect thermal environment simulation is carried on. The simulated data of monthly discomfort of five types are obtained. The three categories of analysis results were summarised, and the final optimal parameters were obtained, as shown in Tables 6 and 7.

Table 6 U value of exterior walls, roofs and grounds.

Parameter	Exterior wall	Roof	Ground
U value	0.262	0.244	0.242

Comparison of luminous environment and thermal comfort of each floor

Without considering shielding, the average illumination values of the five types of windows selected in the previous study were analysed floor by floor, as shown in Figure 9. The trend of the solid line in the graph is not the higher the illumination, the greater the illumination. It shows that the first floor has the least average illumination. When you analyse higher floors, the illumination from 2nd to 3rd floor increases obviously. However, the illumination from 3rd and 5 floor decreases instead of rising. The illumination of 5th to 8th floor increases with the increase of floors. Compared with the five types of windows, the illumination of the 3rd floor window

Table 7 Parameter of glass and window.

Glass type	Low-e type	Glazing value	Glazing U value $W/(m^2 \cdot K)$	Visible transmittance	Frames U value $W/(m^2 \cdot K)$
triple glazing with two cavities 6Low-E+9Ar(argon)+6+9Ar(argon)+6Low-E	online + online,	0.54	1.07	0.57	0.6

Fig. 9 Comparison of illumination of each floor.

is the greatest. And in the same conditions, the light is brightest in the room.

Fig. 10 Comparison of thermal discomfort of each floor.

Without considering shielding, the average monthly thermal discomfort values of the five types of windows selected in the previous study were analysed by floor, as shown in Figure 10. The solid line in the diagram shows that the thermal environment of the 3rd floor is the most uncomfortable. Of the five types of windows, the thermal environment of the room with the 1st floor is the worst. The trend of values of average monthly thermal discomfort of the others is similar.

4 Conclusion

The parameters of architectural design are optimised in order to improve the indoor comfort at the set temperature and humidity,

First, through PHPP simulation, the minimum insulation thickness is obtained to make the non-renewable primary energy demand meet the requirements of energy conservation, which is good for saving energy and reducing building materials. Second, based on the relationship between shading coefficient and minimum insulation thickness and considering the relationship between actual energy consumption and economic demand, the shading coefficient of 12% is selected. Second, as the frames U value increases, the minimum insulation thickness also increases, but it has little impact on energy consumption. In order to reduce the use of building materials, the frames U value is suggested to be between 0.6 and 0.8. Finally, Ecotect is used to simulate luminous environment and thermal environment. Analysed data shows that the average illumination of the building will be increasing with the increase in visible transmission ratio. In this paper, lighting through the five different modes of windows was discussed. They all have good lighting effects, and the difference between the uniformity ratio of illuminance of all types is small. However, compared with the five types of windows, the thermal discomfort of the first model is significantly the lowest, so this kind of glass material is selected.

The architectural design, light environment and thermal environment are considered comprehensively. Grid algorithm (enumeration method) is used to select the optimal design value. The selected the type of glass is triple glazing with two cavities: 6Low-E+9Ar+6+9Ar+6Low-E. The advantage of this method is the ability to quickly find the design parameters under the conditions of light comfort and thermal comfort, but the disadvantage is that the design parameters selected are discrete variables.

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