Study on the Influence of Skylight Form of Single-story Industrial Building on Building Energy Consumption in Severe Cold Area

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Abstract. Since the release of the "Evaluation Standard for Green Industrial Buildings" in 2013 and "Unified Standard for Energy Efficiency Design of Industrial Buildings" in 2017, the field of industrial buildings in China has officially entered a new era of energy-saving and emission reduction. Energy consumption in severe cold area is a prominent problem due to the low temperature environment. However, studies on the combination of climate change and the diversity of skylight forms for industrial buildings are still insufficient. As a common structural element in green industrial buildings, the forms of skylights have a significant influence on building energy consumption. This paper focuses on three common skylight forms: flat skylight, trapezoidal skylight and rectangular skylight. It studies the influence of these forms on energy consumption in single-story industrial buildings situated in severe cold area. Through experimental simulation method, the influence of different skylight forms on energy consumption is comparatively studied by using Design Builder energy consumption simulation software. This method provides a scientific foundation and practical guidance for energy-saving design. The simulation results show that flat skylight has the lowest total annual building energy consumption of 2.59 million KWh, while rectangular skylight has the highest of 2.67 million KWh. The total energy consumption of buildings is made up of five components, with heating energy consumption being the highest at 71%.

Keywords: Green industrial building,Severe cold area,Skylight form, Single-story industrial building,Building energy consumption.

1 Introduction

Green development occupies a central place in current national development strategies. Particularly in the building sector, energy consumption and carbon emissions have a particularly significant impact on cities. Relevant studies show that China's building energy consumption currently accounts for more than 30% of the total energy consumption of the national economy, and the trend is increasing year by

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year. Therefore, in the process of realizing the goal of "carbon peak, carbon neutral", the development of green buildings, the implementation of energy saving and emission reduction is particularly critical [1]. At present, the energy saving of civil buildings has been developed rapidly, and the government has successively issued a number of building energy-saving norms and standards, while the energy saving of industrial buildings is often neglected. In fact, industrial buildings in the energy consumption is far more than civil buildings, the survey shows that in China's energy consumption, industrial energy consumption accounts for nearly 70%, and industrial building energy consumption accounts for more than 10% of industrial energy consumption [2]. This means that the development of green industrial buildings not only has great potential, but also is urgent.

The energy consumption of industrial buildings is uncertain, and it is necessary to establish a model at the design stage to predict the energy consumption and develop a reasonable design program. Many scholars have done corresponding study on energy-saving in industrial buildings. For example, Wang used DeST simulation software to investigate the current energy consumption status of existing typical industrial buildings in Shenyang City over the past 10 years, to derive effective energy-saving methods for industrial buildings and proposed optimization measures for high-energy-consuming industrial buildings [2]. Some developed countries have made it possible to reduce the energy consumption of industrial buildings to about 30% of the total energy consumption through measures such as preparation of charters related to building energy consumption [3].

For industrial buildings, skylight, as one of the important ways to obtain natural light, can not only improve the quality and efficiency of indoor lighting and save energy consumption of lighting, but also as one of the external enclosure structures, a reasonable design can effectively reduce the building energy consumption [4]. Coordinating the lighting performance and energy-saving requirements of skylight has become an important part of green building design. Wang comprehensively analyzes the main characteristic parameters of natural lighting for industrial buildings in Chongqing, obtains the relationship between lighting and energy consumption, and proposes corresponding design strategies [5]. Zheng studied the natural lighting energy consumption characteristics of skylight, and analyzed the changing law of energy consumption under different skylight areas through energy consumption simulation [6]. In her study on energy-saving design of green industrial buildings, Niu found that skylights play an important role in the prediction of energy consumption in such buildings, and the degree of energy consumption impact is particularly significant in the enclosure structure [7].

The climatic conditions and energy consumption structure of severe cold areas determine the necessity of building energy-saving in this region, while skylight, as an important component of industrial buildings, are prevalent in all types of industrial buildings. It has been found through simulation that the total building energy consumption increases linearly with the increase of skylight form by changing only the skylight area, provided that other parameters remain unchanged. It was found that skylight, as an important feature of industrial buildings, come in a variety of forms, which not only enhance the indoor environment, such as lighting and ventilation, but also shape the unique image of the building. However, different designs of skylights also bring different building energy consumption problems. This paper focuses on the impact of different skylight forms on the energy consumption of industrial buildings by controlling the same skylight area and obtaining the corresponding building energy consumption data.

In order to explore the influence of skylight forms on building energy consumption in severe cold areas, this paper takes a single-story industrial building in Harbin as the study object, selects different skylight forms, and uses Design Builder software to conduct energy consumption simulation analysis of building heating, cooling, lighting, and other energy consumption. It will provide a reference for the promotion and implementation of energy-saving green industrial buildings in severe cold areas.

2 The Skylight Forms of Common Industrial Buildings

In order to allow sufficient natural light and air circulation in the interior of single-story industrial buildings, skylights of different forms are often installed on the roof of the building. According to the use function, skylights are mainly categorized into two types: lighting skylight and ventilation skylight. In this paper, we do not consider the impact of ventilation problems on energy consumption, and only study the impact of lighting skylight form on building energy consumption. The common lighting skylight forms in single-story industrial buildings include flat skylight, rectangular skylight, trapezoidal skylight, sawtooth skylight, etc (see Fig. 1). Among them, flat skylights have high lighting efficiency, simple structure, and low cost, but they are more difficult to maintain; rectangular skylights can prevent dust, but they have low lighting efficiency and are complicated to install; trapezoidal skylights require a separate skylight frame, are complicated to construct, and have high costs; sawtooth skylights have high lighting efficiency, but they have high construction costs and are limited by indoor height.

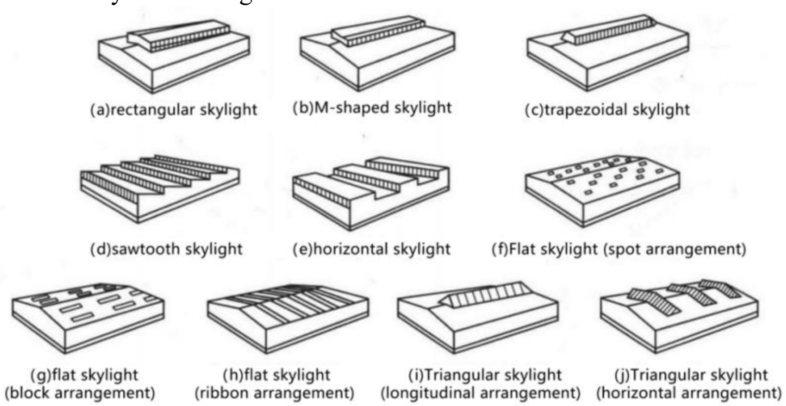


Fig. 1. The forms of lighting skylight [8]

3 Simulation Experiment Design

The technical roadmap for energy consumption simulation experiments is shown below (see Fig. 2).

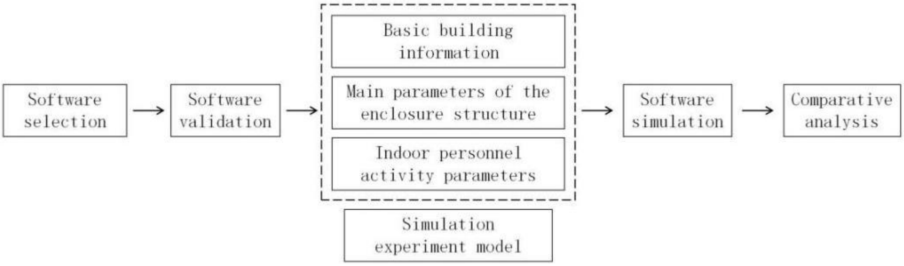


Fig. 2. The technical roadmap

3.1 Energy Consumption Simulation Software

Common energy consumption simulation software are Design Builder, DeST, Ecotect, PKPM, etc. By comparing and analyzing the advantages and disadvantages of different energy consumption software, it can be seen that the simulation performance of Design Builder is relatively comprehensive and stable in many software [9]. Many researchers have been based on this software for energy consumption analysis, so this paper selects this software to simulate and analyze energy consumption. This software is a building environment analysis software that integrates 3D modeling, visualization, building energy consumption, air conditioning system, natural lighting, natural ventilation and other functions. It is a graphical interface simulation software developed on the basis of the Energy Plus kernel to model complex buildings. It also provides a comprehensive energy consumption simulation analysis for heating, cooling, lighting and ventilation of buildings.

3.2 Energy Consumption Software Validation

In order to verify the accuracy of the data from the simulation software, a weather day with the characteristics of winter climate in severe cold areas was selected in the Chinese Baroque neighbourhood of Harbin, and on 19 January 2024, real measurements were made using a small meteorological station, a black sphere thermometer, and other measuring instruments. Then, the parameters of the building and environment are imported into the Design Builder software for numerical simulation. Comparison results show that the air temperatures derived from the two are highly consistent in trend changes and the data are similar, which fully verifies the accuracy and reliability of the software (see Fig. 3).

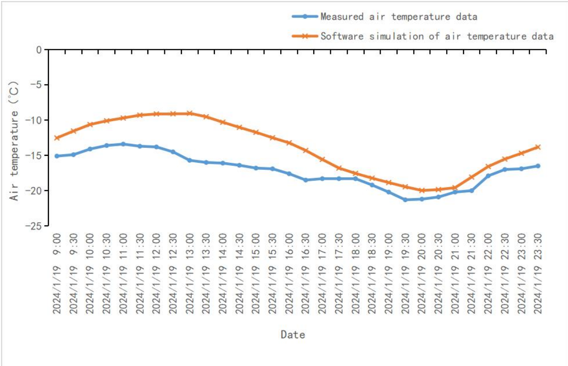


Fig. 3. Energy Consumption Software Validation

3.3 Simulation Experiment Model

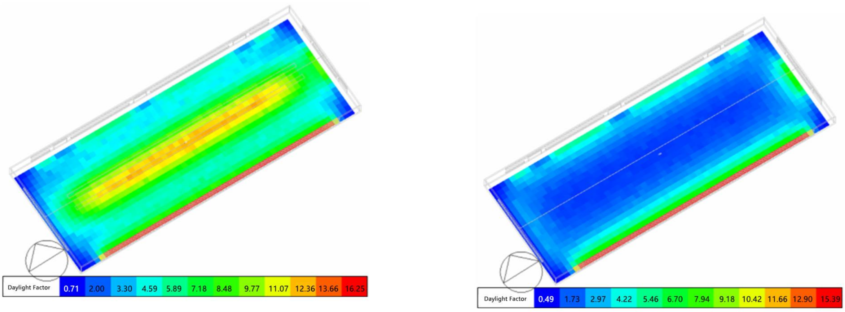
Building Typical Models. The existing lighting skylight surface can be classified into three categories based on its angle of inclination with respect to the roof: parallel, perpendicular, and at a certain angle of inclination. By considering factors such as installation cost, construction complexity and the angle between the skylight and the roof, and combined with research, the common forms of skylights for single-story industrial buildings for machining in severe cold areas are flat skylights, trapezoidal skylights, and rectangular skylights, and most of the other forms have evolved from these. Therefore, three skylight forms were selected to create typical models.

According to the "General Code for Built Environment" (GB 55034-2022), common industrial buildings include 17 categories such as the electromechanical industry, electronics industry, pharmaceutical industry, and rubber industry. A single-story industrial building is selected for study, based on the common industrial buildings in the Harbin area. The building is a welding workshop, which is a general processing workshop in the machining category. The standard value for illumination in buildings is 300 lx, with the possibility of additional local lighting. The industrial building is 112 meters long, 45 meters wide and 10.8 meters high, with a total floor area of 5,085 square meters. To facilitate the control of parameters, the window opening area and position on the north and south sides are fixed without the use of sunshades. The industrial building is equipped with lighting, heating and cooling.

Due to the large depth of the industrial building, there is a large area that is far from the side windows and has insufficient natural lighting. Only 28% of the area reaches the standard indoor illumination value of 300 lx (see Fig. 4a). The lighting requirements of the room cannot be met by opening the side window alone. Therefore, when designing lighting for industrial buildings with large spans or large depths, skylights should be used at the top to improve the natural lighting effect in the industrial building and reduce energy consumption.

At present, the best building orientation in China is generally due south, so the model is also oriented in the south direction. The building combines the three skylight forms described above to establish three simplified models of industrial buildings (see

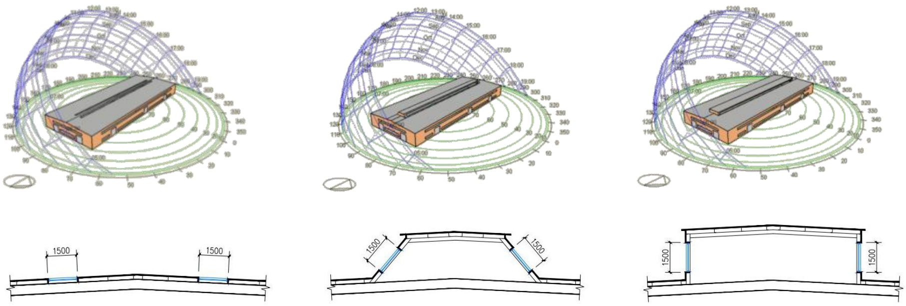
Fig. 5). Through simulation, all three skylight forms can achieve the interior lighting values required by the standard when the skylight area is fixed. (see Fig. 4b).



a. Natural lighting with no skylight (Unit: 100lx)

b. Natural lighting with flat skylight (Unit: 100lx)

Fig. 4. Interior natural lighting before and after installation of flat skylight



a. Flat skylight

b. Trapezoidal skylight

c. Rectangular skylight

Fig. 5. Simplified model of the industrial building and skylight pattern

Table 1. Basic information of architecture

Number of floor	Total floor area (㎡)	Height (m)	Length (m)	Width (m)	Building form factor
1	5085	10.8	112	45	0.15

Numerical Simulation Parameters and Condition Settings. Building energy simulation is a method of evaluating the energy consumption and performance of buildings under different climatic conditions. It is calculated based on meteorological parameters. Severe cold areas refer to areas in China where the average temperature in the coldest month is less than -10℃ or the average daily temperature is less than 5℃ for more than 145 days. The subject of this paper is an industrial building in Harbin. According to the "Unified Standard for Design of Civil Buildings" (GB

50352-2019) and "Energy Efficiency Design Standard for Residential Buildings in Severe Cold and Cold Zones" (JGJ 26-2018), China is divided into 7 main climate zones and 20 sub-climate zones, of which Harbin is in the severe cold area B. Winters are long and cold, summers are short and hot, and the temperature changes rapidly during the transition seasons. Buildings in this area not only need to have sufficient sunlight, but also need to meet winter insulation and other performance requirements. Therefore, the energy consumption of heating buildings in this area in winter is huge, and studying the energy consumption of industrial buildings in severe cold areas is of great practical significance.

In this paper, energy consumption of buildings is simulated and analyzed using meteorological parameters of Harbin city, which include temperature, humidity, wind speed and solar radiation and so on. According to the "Unified Standard for Energy Efficiency Design of Industrial Buildings" (GB 51245-2017), "General Code for Building Energy Efficiency and Renewable Energy Utilization" (GB 55015-2021), "Evaluation Standard for Green Industrial Buildings" (GB/T 50878-2013), and "Design Standard for Energy Efficiency of Public Buildings in Heilongjiang Province". Set the enclosure structure parameters (Table 2) and indoor personnel activity parameters (Table 3) for the three simplified industrial building models.

Table 2. Main parameters of the enclosure structure

Enclosur	Parameter values					
	Structural level	Density (kg/m^3)	Thermal conducti vity (W/m·K)	Specific heat capacity (J/kg·K)	Thickn ess (mm)	Heat transfer coefficient ($W/(m^2·k)$)
External wall	XPS board	32	0.03	1400	100	0.25
	mortar layer	1800	0.93	1050	20	
	porous brick	1400	0.58	1062.3	240	
	mixed mortar	1700	0.87	1050	20	
External window	double-layered low-E glass					1.5
Roof	metal surface	7824	45.28	500	6	0.16
	XPS board	32	0.03	1400	180	
	metal surface	7824	45.28	500	5	
Ground	rammed earth				300	0.58
	concrete pad	1841.1	1.04	586.15	200	
	XPS board	32	0.03	1400	40	
	concrete surface	2321.40	2.21	837.36	50	
External door	metal surface	7824	45.28	500	6	0.16
	XPS board	32	0.03	1400	180	
	metal surface	7824	45.28	500	5	

Table 3. Indoor personnel activity parameters

Technical indicators	Parameter values
Indoor temperature of heating	16
Indoor temperature of air conditioner	28
Air conditioning and heating system operating hours	1:00-24:00 (full year)
Working hours of room staff	1:00-24:00 (full year)
Illuminance standard value	300 lx

4 Analysis of Energy Consumption Simulation Results

The building energy consumption with three forms of skylights are shown in Figure 6.

4.1 Total Annual Energy Consumption of Buildings

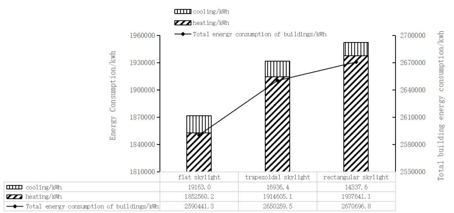
Figure 6 (a) shows the total annual energy consumption of buildings. Flat skylight have the lowest energy consumption, while rectangular skylight have the highest. The gap between the lowest and highest energy consumption is 80,255 KWh. Comparing the energy consumption data for cooling and heating, the flat skylight consumes the least energy for heating, at 1,852,560 KWh, while the rectangular skylight consumes the most, at 1,937,641 KWh. The gap between the two is 85,081 KWh. In terms of energy consumption for cooling, the rectangular skylight has the lowest energy consumption of 14,337 KWh, while the flat skylight has the highest energy consumption of 19,163 KWh. The gap between the two is 4,826 KWh.

4.2 Building Energy Consumption of Components

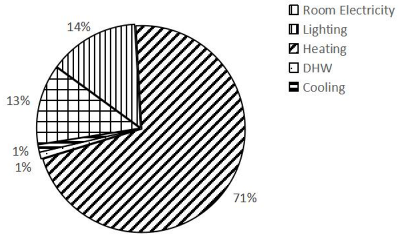
Figure 6 (b) shows the percentage of energy consumption of each component of the building. The total energy consumption of the building is composed of five components. The percentage of energy consumption for each component of the three skylights is basically the same. It can be concluded that the heating energy consumption in severe cold areas accounts for the largest percentage, reaching 71% of the total building energy consumption, which is 1.85 million KWh. Next in line are lighting energy consumption and electricity consumption, which account for 14% and 13% of the total energy consumption of the building, respectively. DHW and cooling energy consumption account for the lowest percentage, each accounting for about 1% of the total energy consumption of the building.

4.3 Monthly Building Energy Consumption

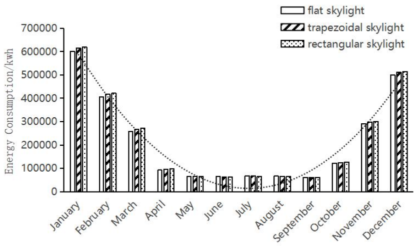
Figures 6 (c) and (d) show the monthly energy consumption of the three skylight forms. It can be seen that the annual energy consumption of the three forms all show a parabolic trend, with the energy consumption during the heating season being significantly higher than other times. For example, the flat skylight has the highest energy consumption in January, reaching 600 thousand KWh, while the lowest energy consumption is in September, only 60 thousand KWh, which is about 10% of the energy consumption in January. During the heating season, the lower the outdoor temperature, the greater the gap between the three types of skylights. The flat skylight is the lowest, and the rectangular skylight is the highest, with a maximum gap of 18,679 KWh; In the opposite direction during the cooling season, with a gap of 1,676 KWh.



a. Total annual energy consumption of buildings



b. Percentage of building energy consumption of component (Example of flat skylight)



c. Monthly building energy consumption

month \ energy consumption/kwh \ skylight form	flat skylight	trapezoidal skylight	rectangular skylight	numerical gap between rectangular skylights and flat skylights
January	600661.7	615279.4	619340.9	18679.2
February	406864.0	417357.8	421223.8	14359.8
March	256800.4	266905.5	272059.1	15258.7
April	91975.2	95393.8	97167.2	5192.0
May	64512.5	64612.1	64666.7	154.3
June	64375.5	63715.8	62928.0	-1447.5
July	67280.9	66518.0	65604.1	-1676.7
August	66352.7	65718.7	65032.6	-1320.1
September	60752.4	61009.7	61161.5	409.1
October	121294.2	124789.8	126369.3	5075.2
November	290385.7	297612.7	300465.8	10080.1
December	499186.2	511346.2	514677.6	15491.4

d. Monthly building energy consumption data sheet

Fig. 6. Building energy consumption with three forms of skylights

4.4 Analysis

To analyze the causes of the data results, although the three skylight forms have the same skylight area, the lighting projection area of the final building is different because the lighting surface and the roof have different tilt angles. The larger the projected area, the more the area receives sunlight and the more the building is able to receive light. As a result, heating energy consumption is reduced.

Due to the extremely low temperatures in severe cold areas and the long winter season, the demand for heating increases. Residents have higher requirements for indoor temperature comfort due to their long-term exposure to cold environments. Therefore, during the heating season, heating energy consumption will increase to ensure comfort. At the same time, because the intensity of solar radiation in winter is lower than in summer, energy consumption for lighting increases in winter. So the total energy consumption in winter is greater than in summer, and the energy consumption of buildings throughout the year is distributed in a parabolic pattern.

Based on the above analysis, the flat skylight is not only more efficient than the other two skylight forms in terms of lighting, but is also easier to install and has the lowest energy consumption. So it has high practical value for energy-saving in industrial buildings in severe cold areas.

5 Conclusion

Because the climate in severe cold areas is harsh, buildings need to be highly adaptable to the environment, so green design concepts are required. This paper discusses the impact of skylight forms on building energy consumption. Using the Design Builder software simulation method, energy consumption analysis is shown for a typical single-story industrial building in a severe cold area.

The conclusions are as follows:

(1) The software simulation shows that severe cold areas have insufficient indoor lighting in the building due to the relatively short sunlight hours. The installation of skylights provides adequate lighting and saves energy. (2) When the area of the building's skylight is fixed, the different angles of inclination of the lighting surfaces lead to different lighting projection areas, and different building energy consumption is obtained. It can be posited that the larger the projection area, the lower the energy consumption.The total energy consumption of the building is 2.59 million KWh for the flat skylight, 2.65 million KWh for the trapezoidal skylight, and 2.67 million KWh for the rectangular skylight. The flat skylight is the lowest, and the rectangular skylight is the highest. (3) Due to long harsh winters and short cool summers in Harbin, heating in winter becomes a major component of the building's energy consumption, and cooling needs in summer are relatively low. As a result, the trend in energy consumption throughout the year shows a parabolic variation. Comparing the three types of skylights, the lower the outdoor temperature during the heating season, the greater the gap in energy consumption between the three. The rectangular skylight exhibits the highest energy consumption, while the flat skylight demonstrates the lowest. Conversely, during the cooling season, the energy consumption of the three skylights is opposite.

In light of the aforementioned evidence, it can be concluded that flat skylights represent the most energy-efficient form of skylight in severe cold areas. Skylight form in severe cold areas has a significant influence on energy consumption throughout the year, especially during the heating season. Therefore, when designing buildings in severe cold areas, full consideration should be given to the thermal performance of skylights and local climatic conditions in order to select the most appropriate type of skylight, with the aim of reducing building energy consumption.

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