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Application of building integrated photovoltaic (BIPV) system in green building[1]

Jiawei Cai[2], Zhenfei Zhang[2]

Abstract. Solar energy is an important direction of the development and application of modern clean energy, and great achievements have been made in the development of photovoltaic technology in China. However, in the specific practical applications, the photovoltaic technology and green building have not been unified to form a comprehensive function of the integrated building. In order to study the building integrated photovoltaic (BIPV) in the green building, the energy consumption and solar radiation heat gain of solar panels installed in a green building in China were simulated and analyzed by using Energy Plus software and the CTF method. Through the analysis, it can be found that solar panels can effectively reduce the cooling energy consumption of the air-conditioning system in summer, and it has no significant effect on the solar radiation in winter.

Key words. Photovoltaic, air conditioning energy consumption, energy saving, BIPV.

1. Introduction

With the development of modern economy, the use of natural resources and the destruction of ecology are becoming more and more serious, which is not conducive to the long-term, sustainable and healthy development of human society [1]. In addition, with the further increase of energy demand in recent years, the energy problem has become an urgent problem that human society needs to solve [2]. People are trying to find new energy sources to solve the energy crisis now facing, such as water, nuclear power, solar energy and so on. Among them, the utilization of solar energy is one of the effective ways to solve the human energy crisis [3]. Solar energy is clean, pollution-free, inexhaustible, and very applicable. From the beginning of 1990s, people put forward the building integrated photovoltaic (hereinafter referred

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[2]Nanyang Institute of Technology, Nanyang, Henan, China, 473000

to as BIPV). The building and the components of solar photovoltaic power generation were combined and used efficiently, which could effectively use solar energy that was absorbed by the building's outer surface and improve the indoor thermal environment with many advantages [4]. At present, the combination of green building and green photovoltaic energy saving technology has become a major trend in the development of modern architecture [5]. Although our country has carried on certain research in this aspect, it is still relatively few in the actual application. Therefore, it is necessary to make further application research and apply it to the design and implementation of our architecture, which has a far-reaching and important impact on China's long-term sustainable and healthy development.

2. State of the art

In recent years, many developed countries have put solar power in the primary position of sustainable renewable energy utilization. Since 1970s, China has increased the investment in resources and the formulation of policies in this aspect, thus promoting the utilization and development of solar energy [6]. As of 2008, Spain's new installed capacity of photovoltaic power generation exceeded 2500 MW, and Germany's new PV installed capacity in 2010 was more than 4.8 GW [7]. Since 2010, China has entered the rapid development of photovoltaic power generation. Now it has the world's largest photovoltaic industry, becoming the world's largest photovoltaic component production and export country [8]. For buildings, a variety of ways can be used to carry out the sun shading, including the building of mutual sun shading, outdoor shading, indoor shading and green shading. The combination of photovoltaic power generation and green building can simultaneously play its role of sun shading and effectively reduce indoor energy consumption. One of the typical forms of photovoltaic integrated building is photovoltaic shading system. In summer to ensure lighting is reasonable, it can be as much as possible to reduce solar radiation and the energy consumption of air conditioning. In addition, it can obtain more solar radiation heat and reduce the energy consumption of heating in winter [9]. Therefore, in building design, it is necessary to consider the performance optimization problem of the whole year, and combine the self-generating function to make it possible to achieve the optimal annual power generation situation [10].

3. Methodology

3.1. Simulation analysis of building energy consumption

With EnergyPlus software, the simulation analysis of energy consumption based on building integrated photovoltaic is carried out. The software is used because of its integration method of load/device/system simulation. In the process of use, the user can select the time step, and each module simulation is synchronized. In addition, the time step results are feedback to each other, which is more accurate than the traditional sequential simulation method [11]. The comparative analysis of integrated synchronous and sequential analog load/device/system simulation methods is shown in Fig. 1. The building system simulation includes heat and mass balance simulation, equipment simulation, air conditioning system simulation and so on. Data transfer and overall control of each part are simulated based on analog manager [12].

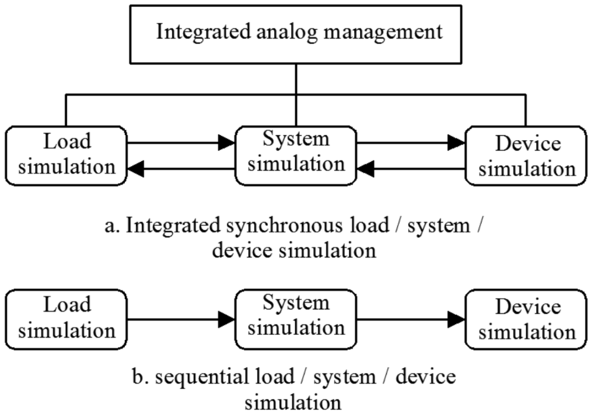

Fig. 1. Comparison of integrated, synchronous, and sequential load/system/device simulations

When using EnergyPlus software, the CTF method is used to simulate the transient heat transfer of the roof, floor, wall and so on, in which the essence is the response coefficient method [13]. The method is based on the interior surface temperature of the enclosure structure, and the results of calculation are more accurate. It is assumed that the long wave radiation heat exchange rate of the surface is q''_{lwx}, the heat flux of the wall is q''_{ki}, the convection heat exchange rate of regional air is q''_{conv}, the absorption of solar radiation through the injected region is q''_{sol}, long wave radiation heat flow from the interior surface receiving net shortwave and equipment in the area are q''_{sw} and q''_{lws}, respectively. The heat transfer process of the inner and outer surfaces of the enclosure is shown in Fig. 2. Thus, the internal surface heat balance equation can be obtained in the form

$$q''_{\mathrm{lwx}} + q''_{\mathrm{sw}} + q''_{\mathrm{lws}} + q''_{\mathrm{ki}} + q''_{\mathrm{sol}} + q''_{\mathrm{conv}} = 0\,. \tag{1}$$

Heat flow is assumed to be q''_{ko} based on heat conduction into the wall. The convective exchange volume between the outer surface and the air is q''_{conv}. The net heat exchange volume of the outer surface and the long wave radiation of air and environment are q''_{lwr}. The radiant heat flux of the outside surface absorption, direct scattering and scattering is $q''_{\alpha\mathrm{sol}}$. Now, the heat balance equation of the exterior surface of the enclosure structure can be obtained im the form

$$q''_{\alpha\mathrm{sol}} + q''_{\mathrm{lwr}} + q''_{\mathrm{conv}} - q''_{\mathrm{ko}} = 0\,. \tag{2}$$

The starting point of the energy simulation process is load simulation, which provides the required parameters for the simulation of the air conditioning system.

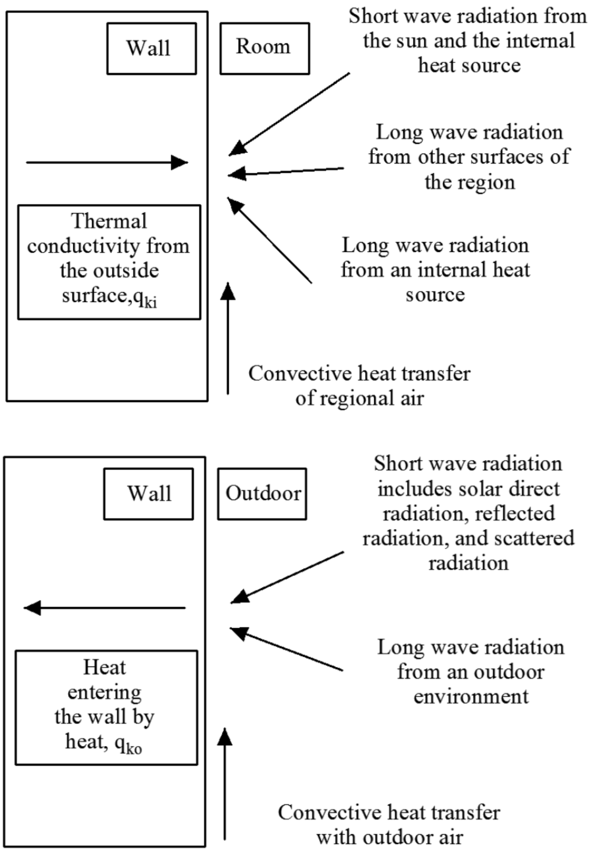

Fig. 2. Sketch of heat transfer of inner and outer surface of enclosure

The key to simulate the load by heat balance method is to calculate the regional air heat balance equation [14]. It is assumed that the heating capacity of the air conditioning system is $\dot{Q}_{\mathrm{s}}$, the outdoor air temperature is T_∞, the mass flow rate between the simulated area and ambient air is $\dot{m}_{\mathrm{st}}$, the air temperature of simulated solution area and adjacent area is T_{zi}, the air mixing mass in the region and adjacent area is $\dot{m}_i$, the regional surface temperature is T_{si}, the surface area of the solution area is A_i, the convective heat transfer coefficient of the zone surface is h_i, the number of heat sources, surfaces and adjacent areas in the solution area is N_{sl}, N_{s} and N_{z}, respectively, the convection heat transfer of the internal heat source in the solution is $\dot{Q}_i$, the area temperature is T_{z}, the area air specific heat is C_{p} and the regional heat capacity is C_{z}. Thus, we can obtain the thermal balance as follows:

$$C_{\mathrm{z}}\frac{\mathrm{d}T_{\mathrm{z}}}{\mathrm{d}t} = \sum_{i=1}^{N_{\mathrm{sl}}} \dot{Q}_i + \sum_{i=1}^{N_{\mathrm{s}}} h_i A_i \left(T_{\mathrm{s}i} - T_{\mathrm{z}}\right) +$$

$$+ \sum_{i=1}^{N_{\mathrm{z}}} \dot{m}_i C_{\mathrm{p}} \left(T_{\mathrm{z}i} - T_{\mathrm{z}}\right) + \dot{m}_{\mathrm{st}} C_{\mathrm{p}} \left(T_{\infty} - T_{\mathrm{z}}\right) + Q_{\mathrm{s}}\,. \tag{3}$$

If the heat capacity of the regional air is not considered, and the air heat storage in the solution area is 0, the output quantity of the steady air conditioning system can be obtained:

$$-\dot{Q}_{\mathrm{s}} = \sum_{i=1}^{N_{\mathrm{sl}}} \dot{Q}_i + \sum_{i=1}^{N_{\mathrm{s}}} h_i A_i \left(T_{\mathrm{si}} - T_{\mathrm{z}}\right) + \sum_{i=1}^{N_{\mathrm{z}}} \dot{m}_i C_{\mathrm{p}} \left(T_{\mathrm{z}i} - T_{\mathrm{z}}\right) + \dot{m}_{\mathrm{st}} C_{\mathrm{p}} \left(T_{\infty} - T_{\mathrm{z}}\right)\,. \tag{4}$$

The cold and heat load in the simulated area is eliminated by the hot and cold air supplied by the air conditioning system. The energy output from the air conditioning system can be calculated by using the air supply rate and the air supply temperature difference [15]. The air supply rate and the air supply temperature of the air-conditioning system are $\dot{m}_{\mathrm{s}}$ and T_{s}, respectively. In this way we obtain

$$\dot{Q}_{\mathrm{s}} = \dot{m}_{\mathrm{s}} C_{\mathrm{p}} \left(T_{\mathrm{s}} - T_{\mathrm{z}}\right)\,. \tag{5}$$

After completing the calculation of the dynamic heat balance of each time step, the software will issue instructions to the system simulation manager to update the indoor environment and the air conditioning system simulation. The system is simulated by EnergyPlus software with modular method. The air conditioning system type and configuration are made into modules, including the direct evaporative system, ground source heat pump, cooling system, and VAV system. Among them, the cold and heat source equipment is simulated by curve fitting method.

3.2. Construction of calculation model of building energy consumption

In this paper, an office building in a southern city of our country is used as a model of calculation. The floor plan of the standard layer is shown in Fig. 3. The building is facing the south with a total of 8 stories and the height of 3.5 m. The length and width are 60 m and 20 m respectively, and the total construction area is 9600 m^2. The height of windowsill and window height are 0.8 m and 1.8 m, respectively, and the ratio of window to wall is 50 %. The building is equipped with photovoltaic sun shading board with the size of 0.8 m×1.2 m×1.6 m, installed in the East, South and West of the office building in three directions. The length of each row of photovoltaic shading panels is outer wall length.

In the simulation of building energy consumption, it is assumed that there are no other objects around the building for shelter, and the artificial parameters of the

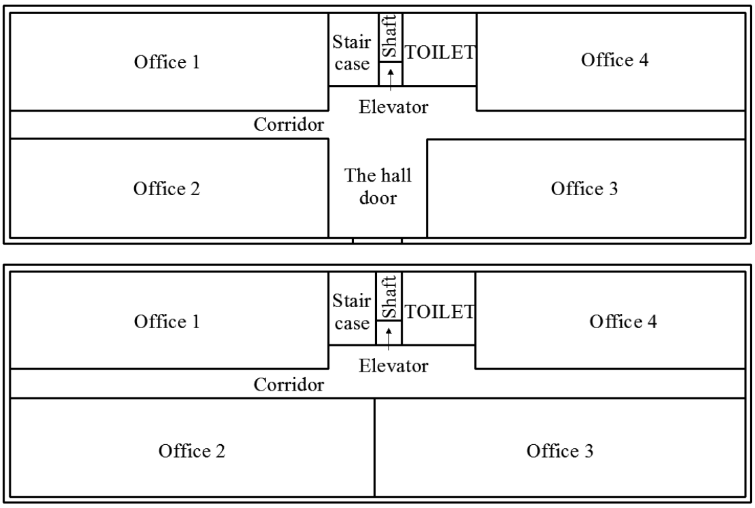

Fig. 3. Layout of building plan

building envelope will not change as the temperature changes. The main thermal parameters are shown in Table 1.

Table 1. Thermal parameters of enclosure structure of building model

Name of enclosure structure	Total heat transfer coefficient W/ (m^2 K)	Concrete construction situation
Interior wall	0.671	Plaster plaster layer + aerated concrete brick + plaster plaster layer
Exterior wall	0.453	Tile and cement mortar + polystyrene board + aerated concrete brick + plaster plaster layer
Roof	0.362	Asphalt and glass fiber cotton + polystyrene board + reinforced concrete pouring + plastering layer
Outside the window	2.716	Glass + hollow sandwich + glass aluminum alloy window frame
Floor	0.630	Plastering layer + reinforced concrete + floor tile

The air conditioning system for an office building is a full air system. In the summer, the chiller uses a chiller and a gas-fired boiler for heating in winter. Among them, the heating efficiency of the gas filter used in the winter heating is 0.9. In the building, corridors and staircases are non-air conditioning area, air-conditioning system operating period is determined to refrigeration 134 days with the heating period of 101 days. The temperature in summer and the amount of radiation in the simulated area are large, and the temperature in winter is low and the radiation quantity fluctuates greatly. Using local weather data as a specific meteorological data, the hourly solar radiation intensity of the whole year is obtained, as shown in Fig. 4.

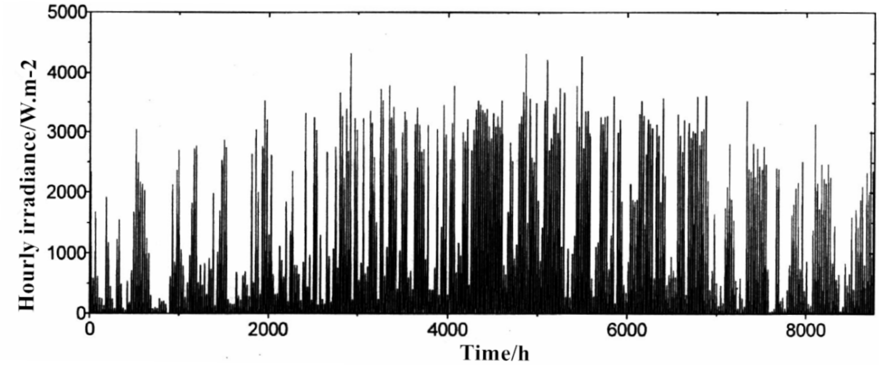

Fig. 4. Hourly solar radiation intensity in simulated region

The computation time step of energy consumption simulation is chosen as 05 h. When the absolute load error or the absolute temperature error of the room is lower than 0.04 W or 0.4 °C, the calculation convergence is considered. In summer, the energy consumption of the air conditioning system in the office is mainly the power consumption of pumps, fans and water-cooled units. In winter, the heating energy consumption of the air conditioning system in the office building is mainly composed of fans, pumps and boilers, and natural gas consumption. As the main energy consumption before and after are different, mainly for electricity and natural gas energy, the two in the taste also has a big difference. Therefore, in order to facilitate the simulation analysis and comparison, the equivalent electrical method is used to calculate the energy of other different types of power. Where the gas is converted into electricity, the coefficient is calculated as 65.9 %. The final simulation calculates that the energy consumption of the reference cooling and heating of the office building is 442.6 MWh and 214.2 MWh, respectively, in the absence of photovoltaic systems. The total energy consumption of air conditioning reached 656.8 MWh, and then the annual energy consumption of air conditioning in unit area was 68.4 MWh/m^2.

4. Result analysis and discussion

By simulating the different angles and widths, the refrigeration and heating energy consumption of the office buildings and the total energy consumption of the air conditioning system are simulated and analyzed. Preliminary analysis shows that the energy consumption of the refrigeration decreases with the increase of the width of the photovoltaic plate, and it decreases with the decrease of the inclination angle. No matter what the width of the photovoltaic panel is, when the dip angle is 60 °, the energy consumption reaches the minimum. With the increase of photovoltaic panels, the energy consumption of air conditioning system is gradually reduced. No matter what the width of the photovoltaic panel is, the energy consumption is the minimum when the inclination angle is 60 °. Thus, whether it is cooling in summer or heating in winter, the installation angle of solar photovoltaic panels is determined at 60 degrees, and the minimum energy consumption of the air-conditioning system can always be obtained.

Compared with the benchmark building, for different forms of photovoltaic panels installed on green buildings, the total energy saving Q and the energy saving q per unit area of the air-conditioning system are shown in Figs. 5 and 6, respectively. As can be seen from the diagrams, as the width of the photovoltaic plate decreases, q increases gradually, but Q decreases. However, for Q and q, they both can achieve maximum energy consumption at the angle of about 60 °, which is determined by the geographical location of the simulated area. Therefore, when it is installed, we can perform the design with reference to this parameter.

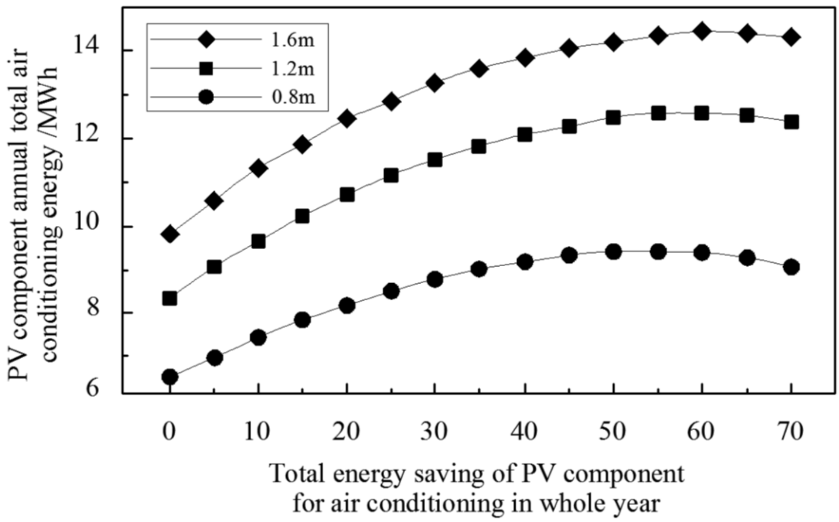

Fig. 5. Solar energy photovoltaic component, annual air conditioning, total energy saving

The effect of photovoltaic sunshade to the building outside the window of the solar heat gain is further studied. Photovoltaic panels can effectively block sunlight from passing through window glass into the room, thus avoiding excessive radiant heat caused by sunlight. Especially in summer, indoor solar heating can be avoided by photovoltaic panels, which can reduce indoor cooling load and reduce energy consumption of air-conditioning system. However, in the winter, too much will cause too small indoor solar heat gain and increase the indoor heating load. In this case, during the choice of photovoltaic panels, we need a compromise consideration. In this paper, the typical summer meteorological days in the simulated area are analyzed. The specific parameters are as follows: solar radiation is direct radiation; the average temperature is 32 °; the maximum temperature is 37.3 °, and the lowest

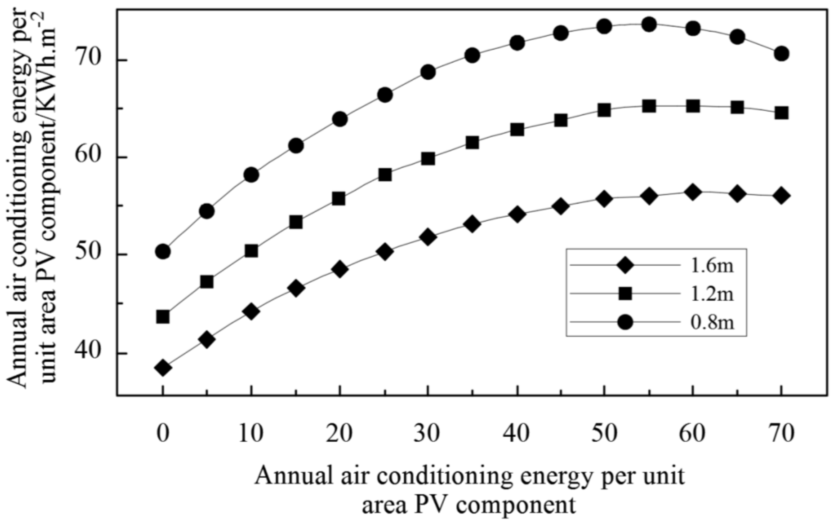

Fig. 6. Annual air conditioning energy per unit area solar photovoltaic component

temperature is 26.7 °. The reduction rate of building solar photovoltaic installation visor case and corresponding heat are respectively compared. The results of the simulation analysis are shown in Fig. 7.

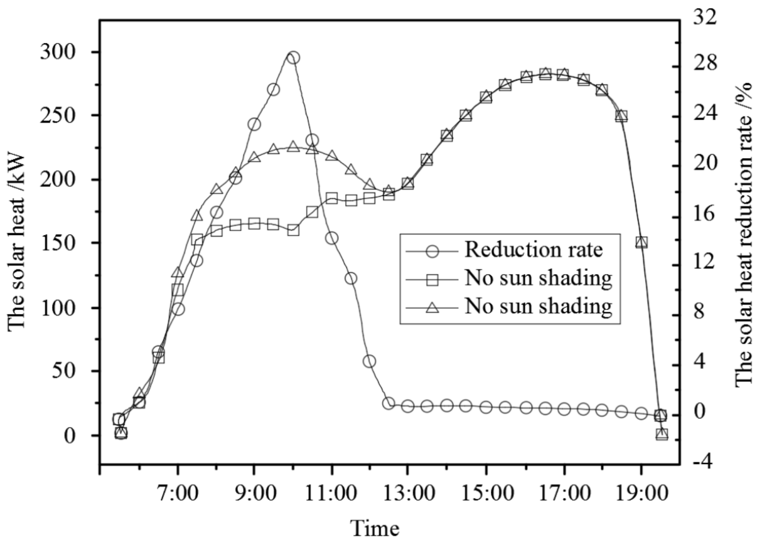

Fig. 7. The influence of the building photovoltaic sunshade window solar heat gain

It can be seen from the figures that without the installation of photovoltaic sun visor, the solar heat of the outside window has two peaks at 10:00 a.m. and 16:30, and the middle period is relatively low stage. It is because that the big sun elevation angle at noon forms a small plane angle between the building facade, and the direct radiation intensity outside the window on the reflection to the building is very small. In the morning and afternoon, the sun high angle is small, and the plane angle between the sun and the building facade is big with too large solar heat. The comparison of two peaks in the morning and afternoon shows that the afternoon heat insulation peak is higher than that of the solar heat morning peak because of greater sun radiation intensity in the afternoon.

From the reduction rate, the heat reduction rate during 7:00 a.m.–11:30 a.m. is around 12 %. At the time of 12:00, the solar thermal reduction rate is reduced to 0. This is because the sun has the smallest azimuth and the height angle at noon. In addition, the plane angle between sun and the building facade is large, which leads to large direct solar radiation intensity. But from the different installation orientations, the effect of installing photovoltaic panels on the east side is the best, far better than the south. Similarly, the effect of the installation of winter photovoltaic shading panels on buildings can also be obtained. Around the noon, there is little difference between the amount of heat and the rate of decrease in the days of winter, but the reduction rate is slightly higher point at noon. From the time all day long, the solar thermal reduction rate maintains at around 4 %. This is because the solar radiation in winter mainly presents scattered radiation, and there is very little direct radiation. Although the sun visor can play a very good shielding effect on the solar radiation, the effect of scatter radiation is not obvious. In conclusion, solar photovoltaic panels can effectively block solar radiation in summer and reduce indoor refrigeration energy consumption. In winter, solar photovoltaic panels have small effect on diffuse solar radiation and little influence on the indoor energy consumption.

5. Conclusion

In this paper, EnergyPlus software was used to simulate and analyze the energy consumption of the building integrated photovoltaic, so as to effectively carry out the data transmission and overall control simulation analysis of the building envelope and indoor. On this basis, an office building in a southern city of our country was chosen as a calculation model, and photovoltaic shading panels were installed in the east, south and west of the office building in three directions. Combined with the local weather data simulation results, it can be seen that no matter what width of photovoltaic shading board is adopted, the minimum energy consumption of air conditioning system can be obtained when the inclination angle is 60 °. However, the change of its width has different effects on the total energy saving of the air conditioning system and the energy per unit area, so that the width parameter should be considered in the design. Further analysis shows that in the summer time, photovoltaic solar panels can effectively prevent direct sunlight into the room, thereby effectively reducing the cooling energy consumption. In winter, the photovoltaic solar panels have little influence on the solar radiation, so the indoor heating energy consumption does not increase. On the whole, solar panels can effectively reduce the energy consumption of air-conditioning systems, and contribute to energy saving design. However, this study does not carry out in-depth study of the impact of photovoltaic power on the overall energy consumption, which is also a major part of the impact.

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