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An experimental study of building thermal environment in building integrated photovoltaic (BIPV) installation

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A 120kWp building integrated photovoltaic (BIPV) system was installed on the south facade of the building of Solar Energy Research Institute in Yunnan Normal University in October 2014. The area of curtain wall was 1560m^2(26m×60m), which consists of 720 semi-transparent monocrystalline silicon double glazing PV panels. The windows of many rooms from the fifth to the ground floors were covered by the PV curtain wall. The PV light transmittance was about 47%. Therefore, this paper studied the monthly and seasonal variations of thermal environment for building in terms of solar data and meteorological parameters. In summer and winter, the ambient temperatures and the indoor temperatures of the covered rooms by the PV curtain wall in different floors were tested and compared to the reference rooms without PV curtain wall. Results showed that the indoor temperature was 6℃ higher than the ambient temperature in winter. Therefore, it can be concluded that the integration of semi-transparent BIPV reduces the heating demand in winter.

Keywords: building-integrated photovoltaic system, building thermal environment, experimental study

INTRODUCTION

In the last 20 years, the world's energy consumption has sharply increased (40%) and is expected to continue to grow by one-third in the period to 2035 [1]. Buildings can be classified among the leading energy consumers and CO_2 emitters [2]. Especially, building energy consumption has been continuously increased, which has been doubled during the last decades in China [3]. According to the growing trend of developed countries, the building energy consumption will account for at least 40% of all social total energy consumption in China [4]. In this situation, the development of alternative, cost effective sources of renewable energy for residential and non-residential buildings should be given the priority for further research and solutions to these challenges. Therefore, designing energy efficient and affordable solutions integrated in buildings dealing with summer and winter climate challenges represents a very ambitious goal. The integration of PV systems into buildings becomes an imperative [5]. Building integrated photovoltaics (BIPV) have a prominent position due to the availability of large building surface areas and PV's ability to transform sunlight directly to electricity [6]. The BIPV may represent an important component of a zero net energy building, which produces as much energy as it consumes [7]. Norton et al. [8] mentioned that BIPV can serve as a shading device for a window, a semi-transparent glass facade, a building exterior cladding panel, a skylight, and parapet unit or roofing system. Moreover, BIPV can be designed to generate electricity at a building's peak usage times and reduce the building's peak grid electricity demand [9]. The peak power cost for large-scale BIPV systems could drop down, which also lead to PV electricity costs comparable to large centralized power plants and then by 2025, more that 3.6% of the world's electricity could be generated by PV power [10]. Furthermore, Li et al. [11] investigated the energy performance of a semi-transparent a-Si PV facade. The simulation results revealed that the semi-transparent PV facade was able to reduce the annual building energy use and peak cooling load by 1203 MWh and 450 kW, respectively. It was reported that the embodied energy pay-back period for photovoltaic system integrated with building was within the range of 12-13 years for the southern and western facades in the United Arab of Emirates [12]. James et al. [13] conducted a critical evaluation of semi-transparent PV roof glazing elements in the UK climate. They reported that taking the electricity generated, shading provided and comfort enhanced into account could render the total system viable both economically and in regard to averted carbon dioxide emissions. On the other hand, it was found that ventilated semi-transparent photovoltaic double-skin facades could improve the daily energy output by 3% because of its lower operating temperature [14]. Most of the previous

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studies considered the energy harvested of the PV panels as a key performance parameter of BIPV [15-17]. However, due to the "greenhouse effect", the heat from solar radiation in air channel between the building façade and the PV panels can be helpful to decrease the heating load in winter condition. But it is also associated with problems such as over-heating of the building in summertime [18] and the increase of the air conditioning loads, lack of visual and thermal comfort. Since 33% of the average building's cooling load is relate to solar heat gain through the windows. Therefore, the PV curtain wall has been used to cover the windows as a passive cooling for buildings. The experiment was the first and largest BIPV application installed on the building facade of Solar Energy Research Institute of Yunnan Normal University, which covered many windows of different floors and rooms, although Yunnan Normal University has built many rooftop PV systems, as shown in Fig.1. With the installed PV, Yunnan Normal University can save money on one million kWh electricity bill each year. Thus, the aim of this paper is to analyse and investigate the influence the semi-transparent BIPV system in the indoor thermal environment, from the point of view of indoor thermal environment as well as to provide useful information on the operating temperatures under natural convection in different seasons for more applications of semi-transparent BIPV.


(a)


(b)


(c)

Fig.1. Yunnan Normal University rooftop PV systems. (a) The 256.50kWp installation capacity on the roof of the library, (b) The 90 kWp installation capacity on the roof of the indoor swimming pool, (c) The 652kWp installation capacity on the roof of the sports training centre

SYSTEM UNDER STUDY

This experiment has been conducted in Kunming city at the southwest of China (24°23′N to 26°22′N, 102°10′E to 103°40′E, 1950m above MSL), which has a mildest climate characterized by short, cool dry winter with mild days and crisp night, and long, warm and humid summers. It is controlled by a subtropical highland climate and the average temperature is around 15℃ in winter and 24℃ in summer. It also receivers an annual total solar radiation of ~5508.87MJ/m^2, and the monthly total solar radiation is shown in Fig.2 based on the data of typical meteorological year (TMY). Therefore, the climate and location of Kunming are suitable for solar installations. The BIPV system in this study (Fig.3) was installed outside of the south facade of the building of Solar Energy Research Institute building in Yunnan Normal University. The system was built in June 2014 and completed the installation and test in October 2014. Totally 720 monocrystalline silicon double glazing PV modules were used on the facade of five floors, which were installed on 60m length and 26m height with south facing of the building with a total area of 1560m^2. The modules were installed using specially designed mounting with 85° tilt angles and 6 m apart from the building for the ventilation. The PV arrays were comprised of 30 parallel strings where each string has 24 modules, and the peak power and voltage of each string were 4080Wp and 796V, respectively. The 120kWp power generated was synchronized and supplied to the 400V campus grid through a grid export conditioner built with a Maximum Power Point Tracker (MPPT).

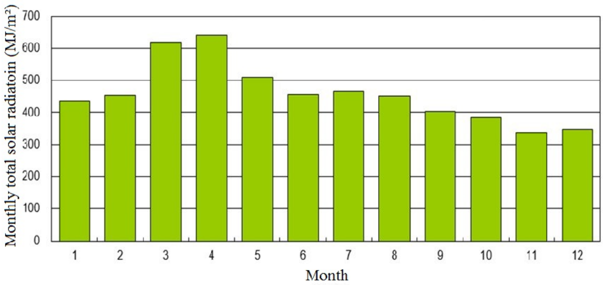


Fig.2. The monthly total solar radiation of TMY in Kunming

Fig.3. Yunnan Normal University BIPV system

Table 1. The PV module specifications under STC

No.	item	parameter
1	Dimension(mm)	1985 × 1038 × 13.52
2	Light transmittance	47%
3	Nominal power(Wp)	170
4	I_{sc}(A)	5.65
5	U_{oc}(V)	39.6
6	Efficiency	8.25%
7	Layer structure	Toughened glass(6mm)+PVB(2.28mm)+(125 × 125mm) sc-Si cells+toughened glass(6mm)

The specifications of the semi-transparent PV modules are given in Table 1. The PV modules have a 6mm transparent glass covers, a 6mm glass backside and a maintain space between the PV cells in order to transmit light, so that the light transmittance was 47%. And each PV module consisted of 64 pieces of solar cells, and its dimensions was 1985×1038mm. Solar cells adopted in the PV module were monocrystalline silicon wafer cells and the dimension of each cell was 125×125mm as shown in Fig.4. The efficiency of the monocrystalline silicon PV modules was 8.25%, which was lower than conventional monocrystalline silicon modules. The reason was that the areas of 64 pieces of solar cells in a module was just 48.5% of the total area of a PV module. It was based on the cost of sacrificing the efficiency of PV module to ensure partial light transmission.

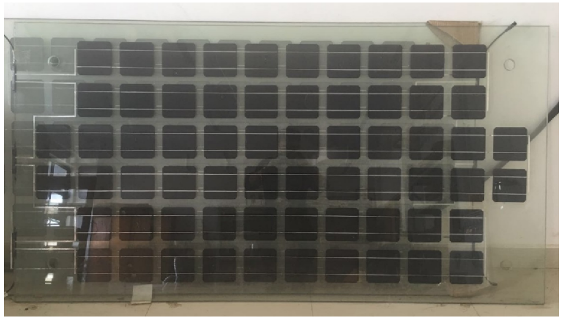


Fig.4. The semi-transparent double glazing PV module

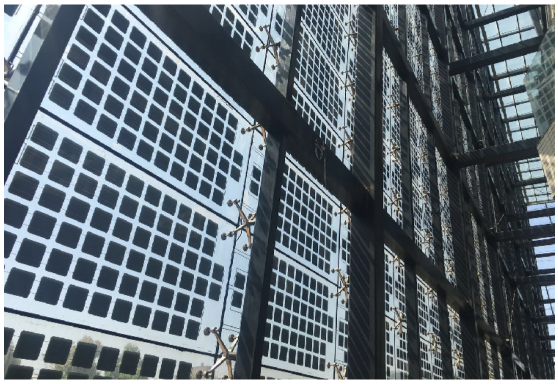


Fig.5. The inside view of the PV curtain wall

The laminated glasses forms were installed on both west and east directions and on the rooftops of the PV curtain wall. Meanwhile, there was a space of 6 m between the building facade and PV curtain wall (Fig.5). Some ventilation blinds were placed at the top and the bottom of the PV curtain wall for a proper ventilation (Fig.6). The windows of many rooms from 5th-floor to ground floor were covered by the PV curtain wall. Therefore, the rooms' temperature would be affected around the year. However, the room temperature will be controlled or affected according to the adjustment of these ventilation blinds by opening or closing it in different seasons. As schematically shown, the BIPV system considered in the present study consisted of a PV curtain wall which was separated by air space from the building facade. Once the PV curtain wall heated by the solar radiation, the air within the space rises due to buoyancy, thus allowing ambient air to flow through the space via chimney effect. No mechanical ventilation for the air gap between the PV panels and building external envelope surface was provided. Thus only natural convective flow and heat transfer in the space were considered in the present study.

Fig.6. The ventilation blinds at the top and bottom of the PV curtain wall

"T" type (copper-constantan) thermocouples with accuracy of ±0.3℃ were installed to measure temperatures at different floors and rooms. Two rooms with window facing the south were chosen on each floor from the 1st floor to the 5th floor, one room with window covered by the PV curtain wall and the other room with window not covered, which was regarded as the reference room. Each room had the similar characteristics and same dimensions (10.2m long, 8.4 m wide and 3.5m high). The room temperature had not been influenced by any HVAC (Heating, Ventilating and Air Conditioning) system during the measurements. The indoor and outdoor temperature of each floor also was tested. The arrangement of test points is shown in Fig.7. Each floor had three tested rooms, the points 2B-5B were the average temperature of each floor. Each temperature test points were about 2m high of the ground and at the centre of each tested room, which has window towards to the PV curtain wall, and the air between PV curtain wall and building exterior wall can enter each tested room through window. Similarly, the point 1A-5A were the average temperature of each floor and these test points were about 2 m apart from the exterior wall of the building, each floor had three test points and each one was 15 meters apart. Two pyranometers were used to measure the solar irradiance on the surface of the PV curtain wall and through the curtain wall, respectively. These data were recorded by Agilent 34970A data acquisition instrument every 10 minutes automatically. The comparative tests were carried out from June 5th to July 11st, 2015 for summer and from October 3rd to October 29th, 2015 for winter.

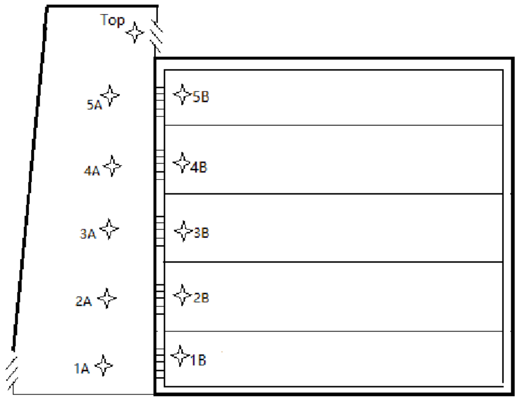
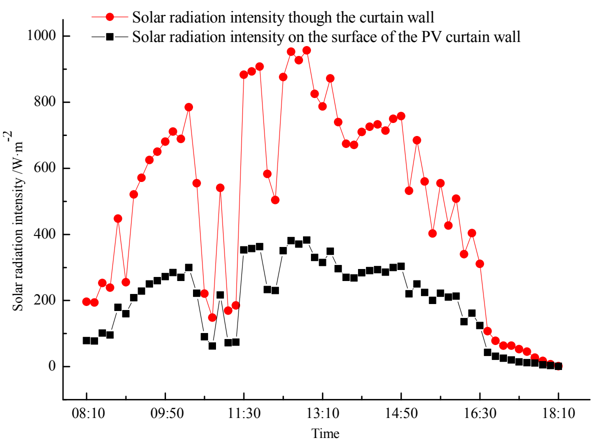


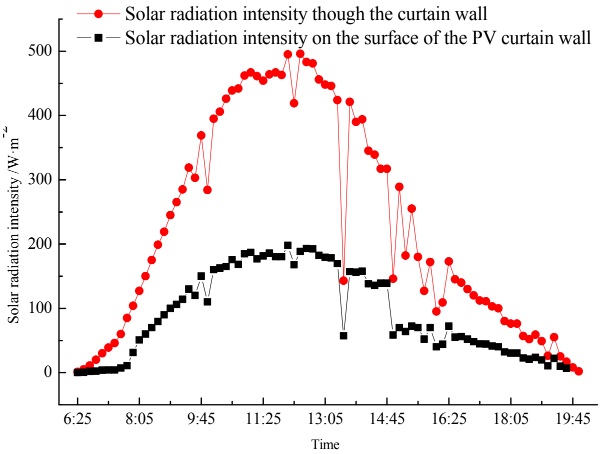
Fig.7. The measure spots

RESULTS AND DISCUSSION

Results showed that the average daily sunshine duration was 10h in winter and 13h in summer during the test periods. The average daily solar radiation intensity was 0.55kW/m^2 and 0.19 kW/m^2 on the vertical surface of the PV curtain wall and through the curtain wall during October 3rd to 29th, respectively. However, during June 5th to July 11st, the average daily solar radiation intensity on the vertical surface of the PV curtain wall and through the curtain wall was 0.23kW/m^2 and 0.09 kW/m^2, respectively as shown in Fig.8. The reason why the total solar radiation on June is less than October is that the solar zenith angel is lower in winter than summer in Kunming, which means that the vertical south surface of the PV curtain wall can receive more solar radiation on October. Furthermore, the solar radiation intensity though the PV curtain wall is around 40% of what it is before though the PV curtain wall. Maybe due to closing to the curtain wall, the pyranometer which was used to measure the solar radiation intensity through the curtain wall could be shield by some solar cells or columns of curtain wall sometimes with the sun moving during the test periods. However, the solar energy received by the building through the PV curtain wall was 40%~47%, it could be considered to reduce the heat load in summer.



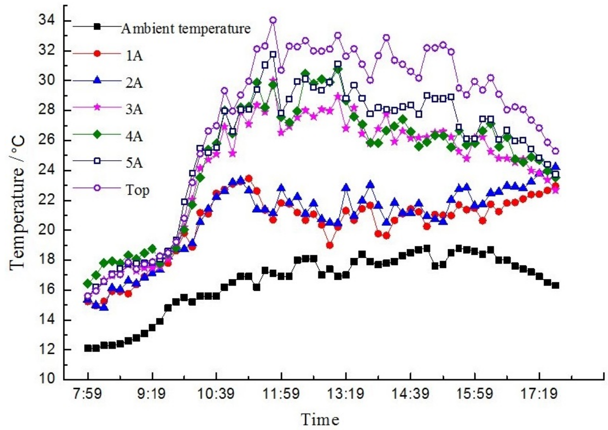
(a)



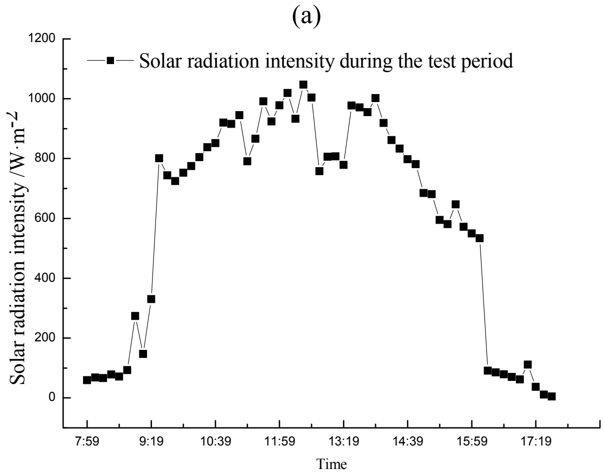
(b)

Fig.8. Solar radiation intensity on the vertical surface of the PV curtain wall and though the curtain wall (The (a) is a winter's data and the (b) is a summer's data)

The variation of the air average temperature in the gap (ATIG) between PV curtain wall and building exterior wall has been tested from October 3rd to October 29th, and then one day has been chosen as shown in Fig.9 to discuss the results. The trend of the ATIG was consistent with the ambient temperature that was the temperature of outside of the PV curtain wall, but the ambient temperature was the lowest. The temperature of each floor or each test spot has been clearly fluctuated, due to the ventilation blinds on top and bottom were opened during the test periods. Consequently, the internal temperatures were significantly influenced by wind speed. The air naturally moved into the gap between the PV curtain wall and building exterior wall through the bottom ventilation blinds. The wind speeds at the bottom and top ventilation blinds were 1.15m/s~1.58m/s and 0.21m/s~0.28m/s, respectively, tested by OMEGA's HHF91 digital anemometer with a velocity accuracy of 2%. However, it was clear that the ATIG increased from 1st floor to the top floor gradually. It was observed that the highest temperature of ATIG was around 32℃ on the top close to the outlet of top ventilation blinds. Meanwhile, the air temperature on the top was about 10℃ higher than on the 1st floor and the 2nd floor at noon. The 1A and 2A had a very small temperature difference all the day, because these test spots of 1st and 2nd floors in the gap were closer to the bottom ventilation blinds, thereby they became more sensitive to the environment at a better air fluidity.



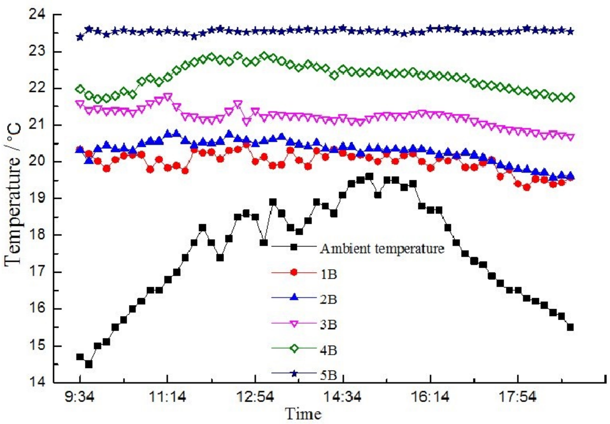
(a)



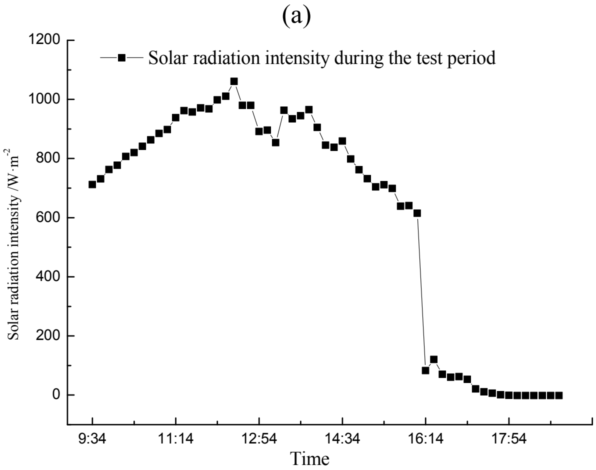
(b)

Fig.9. (a) The air temperature in the gap between PV curtain wall and the building exterior wall and (b) the solar radiation intensity on the surface of the PV curtain wall during the test period

Fig.9 shows the variations of internal and external air temperature on October. It was found that the ATIG at 7:59 in the morning of winter was about 4℃ higher than the ambient temperature, while in the afternoon, the ATIG was about 9℃ higher. Therefore, the ATIG increased rapidly from 9:29 then about 2 hours later, the ATIG reached the maximum temperature and no longer increased. The gradual increasing of solar radiation on the PV curtain wall from 330W/m^2 to 800 W/m^2 resulted in a gradual increasing of air temperatures. Subsequently, the ATIG started to decrease at 15:59 and the average of 1A~Top temperature eventually reached around 22℃ which was 6℃ higher than ambient temperatures as shown in Fig.9(a).



(a)



(b)

Fig.10. (a) The temperature of each tested room and (b) the solar radiation intensity on the surface of the PV curtain wall during the test period

Fig.10 shows the indoor temperature 1B to 5B and ambient temperature, which are the corresponding data of the same day as shown in Fig.9. It was found that the ambient temperature presented a first increases and then decreases trend while, the indoor average temperature of tested room from 1B to 5B remained stable at the beginning and then increased from 1st floor to 5th floor gradually. The test periods were during working hours and the 1B was the average temperature of the tested room, which was an office and some people worked in it, thereby the temperature was clearly fluctuated. Nevertheless, the internal air temperature at 1B (around 20℃) was the lowest indoor temperature of all the tested rooms. It was still higher than the ambient temperature all the time. In addition, there was a little difference in the average temperature at 1B and 2B comparing to the outdoor temperatures. The indoor temperature at 5B was the highest temperature (around 23.5℃) and it was higher than the 4B by 1℃. Consequently, it can be observed from Fig.10 that the indoor temperature at the upper floors was higher than the lower floors by 1℃, due to the chimney effect of the PV curtain wall, when the hot air density is lower than the cold air density so the hot air moves to the upper area and creates the temperature differences in different floors. These results will be helpful to keep the upper rooms warm without any heating facilities in winter.

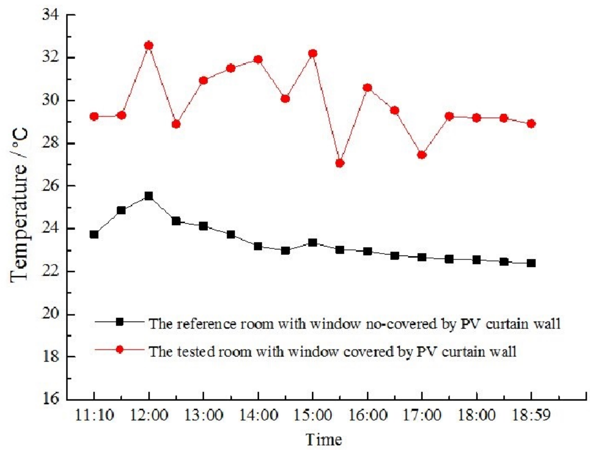


Fig.11. The temperature of test room and reference room

Fig.11 shows the indoor temperatures of the tested room and the reference room on the 4th floor from 11:00 to 19:00 on a sunny day, June 7th. During the comparative period, it can be clearly seen that the indoor temperature of the reference room was stable while the indoor temperature of the tested room was fluctuated and higher than the reference room by 6°C in average for most of the time. The strong fluctuations of the tested room temperature were caused by the doors opened or closed during the test periods which were the working hours. Thus, it was inevitable that there were some people working in the tested rooms and the reference rooms, admittedly, the doors were opened or closed for getting in or out of these rooms. However, the average ambient temperature was lower than the indoor temperature at 23℃. The average, maximum and minimum temperatures of the tested room was 29.8℃, 32.5℃ and 27.0℃ respectively. However, the average, the maximum and minimum temperatures of the reference room was 23.3℃, 25.7℃ and 22.2℃, respectively. Obviously, the greenhouse effect of PV curtain wall caused overheats in summer by increasing the indoor temperatures. Therefore, the ventilation blinds on top and bottom of PV curtain wall were opened to decrease the internal air temperatures.

CONCLUSIONS

This experiment was conducted to study the thermal environment of building and sunlight penetration in terms of the variation of air temperature in different seasons. Results revealed that the indoor thermal environment was comfortable and helpful to save energy for keeping the rooms warm in the winter season. The temperature of the tested rooms was varied from 20 ℃ to 24℃ according to different floors, and it was 6℃ higher than the ambient temperature in winter all the day. The solar radiation in the south side of the building which was shaded by the PV curtain wall has been measured and ranged from 40%~47% of the outside solar radiation on the PV curtain wall. Nevertheless, the ventilation blinds have been arranged on the top and the bottom of the PV curtain wall and were opened in summer, the phenomenon of overheat in the rooms with window covered by curtain wall was still inevitable. In conclusion, the proper design of the large PV curtain wall could be a good choice to save energy for decreasing the cooling and heating load of building.

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