https://doi.org/10.1016/j.energy.2016.06.120

Assessment of energy performance of semi-transparent PV insulating glass units using a validated simulation model

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Abstract

This study evaluated the energy performance of an a-Si semi-transparent PV insulating glass unit (IGU) via numerical simulation and experimental tests. Combined with the measured optical and electrical characteristics of the PV laminate, an integrated model was developed to simulate the overall energy performance of the PV IGU in EnergyPlus. Outdoor experiments were conducted to validate the accuracy of the simulation model. The proper consistency between the simulation results and the experimental data indicated that the simulation model was reliable for predicting the overall energy performance of PV IGU. With the validated model, a sensitivity analysis was conducted to investigate the influences of air gap depth and rear side glass, and an optimal design scheme was proposed to maximize the energy efficiency of PV IGU in Hong Kong. Finally, the energy saving potential of the optimized PV IGU compared to the other commonly used window systems was evaluated. It was found that the energy saving potential of the optimized PV IGU was 25.3% and 10.7%, respectively, compared to the single clear glass window and the Low-E glass window. The methodology developed in this study is expected to provide a useful reference for simulating the energy performance of PV IGU.

Keywords: building integrated photovoltaic (BIPV), semi-transparent PV laminate, insulating glass unit (IGU), EnergyPlus, energy saving potential

1. Introduction

Energy shortage and environment pollution are the two urgent problems which are crucial for human survival and development around the world. To cope with these problems, researchers have been paying tremendous efforts. Solar energy is usually regarded as an effective way to mitigate these two problems due to its natures of clean, abundant, and inexhaustible. Solar photovoltaic (PV) technology can be combined with building envelope to constitute building integrated photovoltaic (BIPV) systems, which refers to using PV material to replace conventional building materials and then achieve the goal of saving energy [1-3]. Usually, PV modules can be integrated into façades, roofs or fenestration products without causing any aesthetic problem.

As an essential contact component between the interior and exterior environment of buildings, windows possess many functions, including providing daylight, ventilation as well as visual access to the external environment. However, due to the poor insulating performance of windows, a large amount of heat transfers through windows in summer and winter, resulting in a considerable increase of cooling/heating load for air conditioning. Thus, it is an urgent task for researchers to develop new types of energy-efficient windows. Semi-transparent PV (STPV) window is an effective solution which can provide daylight illuminance and electricity power generation simultaneously. Various experimental and simulation studies have been carried out for single-plate STPV windows in recent years, and the results demonstrated that they not only generated electricity on the site of buildings but also saved energy by reducing the energy uses of air conditioning and artificial lighting [4-9].

PV windows with ventilation flow also attracted many researchers' attentions due to their relatively high energy conversion efficiency which was achieved by the ventilation effect. It is well known that the ventilation air flow reduces the PV module's temperature and in turn improves the energy conversion efficiency. Chow et al. [10-12] evaluated the performance of a ventilated PV window installed on an office building in Hong Kong. Han et al. [13-15] investigated the air flow properties in the cavity of a double-pane PV window. He et al. [16] compared the energy performance between a PV double-glazing window and a PV single-glazing window. The results indicated that the double-glazing PV window had larger energy saving potential than the single-glazing PV window when employing on office buildings on the premise that the cost is continuous decreasing and the efficiency is considerably increasing. Peng et al. [17, 18] developed a novel ventilated PV double skin façade (PV-DSF) and reported its energy performance under different ventilation modes. A simulation model was also developed to further evaluate the overall performance of the ventilated PV-DSF as well as its energy saving potential in a cool-summer Mediterranean climate zone [19-21].

However, PV ventilated windows also have obvious shortages, such as occupying a large area, requiring high initial investment, and not suitable for building retrofit. Thus, another kind of PV window, i.e. PV insulating glass unit (IGU) which consists of an STPV panel, an air gap and a glass sheet, was investigated in this paper. It possesses the merits of simple installation, low cost, and is suitable for new and retrofit buildings. The gas sealed in the cavity is capable of increasing the window's thermal insulation considerably. Thus, a good thermal performance is expected for this kind of PV IGU.

A few simulation studies were conducted to evaluate the overall performance of PV IGU recently. Miyazaki et al. [22] investigated the impacts of solar cell transmittance and window to wall ratio (WWR) on the energy performance of PV IGU using EnergyPlus. The solar cell transmittance was assumed varying from 10% to 80%, and the optimal solar cell transmittance was 40% corresponding to the 50% WWR. Didone and Wagner [23] reported that a considerable energy saving potential was achieved by using PV IGU on office buildings in Brazilian. The simulations about daylight and energy performance were separately conducted based on Daysim/Radiance program and EnergyPlus. Ng et al. [24] proposed many design strategies to optimize the WWR under different orientations such that to achieve the highest electricity benefit for various sizes of modules. Chae et al. [25] evaluated the impacts of electrical and optical parameters of BIPV windows on the overall energy performance of a typical midsize commercial building in various climate conditions. However, it was found that almost all the above simulation works were conducted based on assumed parameters, such as optical transmittance, emittance, reflectance, absorptivity, energy conversion efficiency, thermal conductivity and so on. Although simulation studies were convenient ways to evaluate the overall performance of PV IGU, the assumed properties for simulation made the results hard to be validated. Simulation studies based on real measured parameters were rarely reported. Wong et al. [26] measured the properties of PV panels and proposed to use semi-transparent PV as a skylight for residential buildings. In his study, the power generation model, thermal balance model and daylight model were validated separately, but the integration model was not validated comprehensively.

Experimental studies were also conducted to investigate the performance of PV IGU. A mock-up facility equipped with both BIPV windows and normal clear windows was built in South Korea [27, 28]. Song et al. [27] analyzed the effects of both the inclined slope and the azimuth angle on the output power performance of a double pane thin-film PV window. With the same test bed, Yoon et al. [28] measured and reported the long-term temperature characteristics of the PV window. These two experimental studies focused on the output power performance and thermal performance, respectively. Young et al. [29-32] proposed a heat insulation solar glass (HISG)-BIPV module which was characterized by multiple functions, including power generation, heat insulation, self-cleaning and energy-saving. The electricity generation, thermal insulation and optical performance characteristics of the HISG system were tested separately. Although the results indicated that the HISG system had great potential to replace normal glass windows, the overall energy performance was not evaluated in their studies. As the thermal, power and daylight performances of the PV IGU affect each other, separately performance evaluation could not effectively reflect the real energy performance.

Through the literature review, it was found that almost all the previous studies evaluated the overall performance of PV IGU by either simulating with the assumed physical properties [22-25] or evaluating the overall energy performance separately [27-32]. Validated simulation studies based on measured physical properties were rarely reported for semi-transparent PV IGU. Thus, a comprehensive study was needed to better understand the energy performance of PV IGU. In this study, the overall energy performance of PV IGU was investigated based on measured electrical, optical and thermal properties. An integrated simulation model which can simulate the thermal, power and daylight performance simultaneously was developed and validated against experimental data. With the validated model, sensitivity studies on the air gap depth and the rear side glass characteristics were conducted to optimize the PV IGU structure. Lastly, the energy saving potential of the optimized PV IGU was also evaluated compared to other commonly used windows.

2. Model developing

The simulation model of PV IGU was developed based on the measured physical characteristics of the semi-transparent a-Si PV laminate. The measured physical parameters, including the electrical, optical and thermal properties, were firstly imported into the WINDOW Software [33] for creating a physical characteristics file which can be compiled by EnergyPlus; then the physical characteristic file together with the building geometry and the weather data file were inputted into EnergyPlus; lastly the solar power generation model, heat transfer model, daylighting model, as well as the HVAC model, were adopted to simulate the overall energy performance of the semi-transparent PV IGU.

2.1 Physical Characteristics measurement

The optical characteristic of the semi-transparent a-Si PV laminate was measured by using a spectrometer. Fig. 1 shows the specific optical characteristic from 300 nm to 2500 nm. The TT, TD, RT, RD, and A were abbreviations of the total transmittance, the diffuse transmittance, the total reflectance, the diffuse reflectance, and the absorptivity, respectively. The subscripts s and v stand for the total solar radiation and the visible sunlight, respectively. The mean of the diffuse solar reflectance (RD_s), the total solar reflectance (RT_s), the total solar transmittance (TT_s) and the diffuse solar transmittance (TD_s) were 0.035, 0.115, 0.213 and 0.006, respectively. The visible transmittance of the semi-transparent PV laminate was about 5.7%. The front side and back side emittances of the PV laminate were measured by an emissometer, and the results were 0.853 and 0.834, respectively. The thermal conductivity of the PV laminate was measured by a thermal conductivity meter; it was about 0.486 W/(m·k).

The electrical characteristics of the semi-transparent a-Si PV laminate were tested under the standard testing conditions (STC, viz. 1000 W/m^2, 25 °C, AM 1.5) with an AAA class steady state solar simulator. The key electrical characteristics are listed in Table 1. The maximum power of the semi-transparent a-Si PV laminate was 88.1 W under STC, and the corresponding energy conversion efficiency was 6.2%. All the above measured characteristics of the PV laminate were inputted into the model for simulating the overall energy performance of the PV IGU.

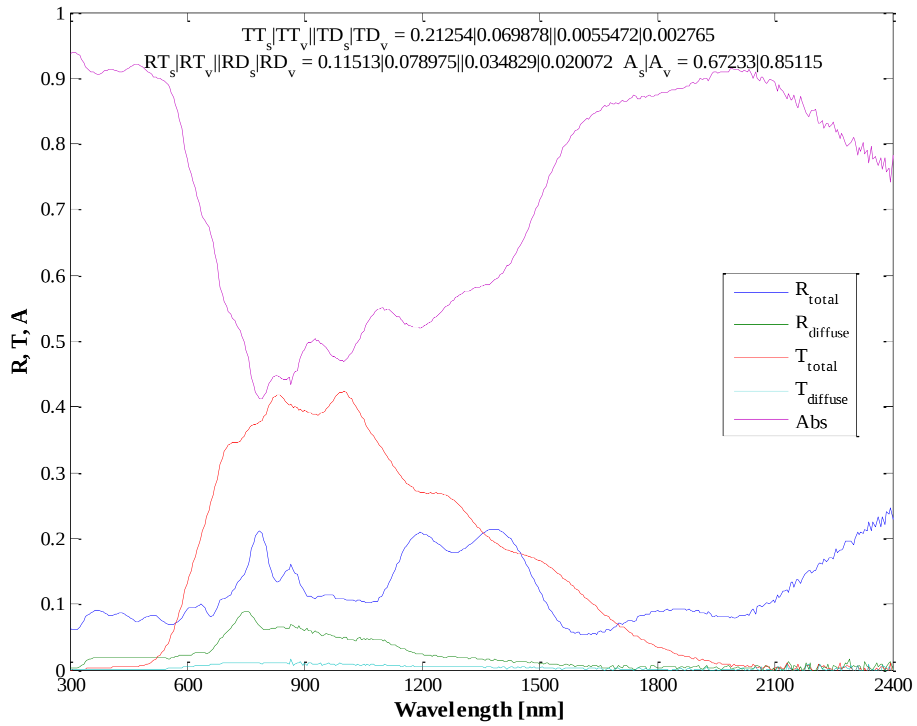

Fig.1. Optical characteristics of the semi-transparent a-Si PV laminate [20]

Table 1 The key electrical characteristics of the PV laminate under STC

Parameters	Value
Maximum Power at STC (P_{max})	88.1 (W)
Voltage at the maximum power point (V_{mp})	102.5 (V)
Current at the maximum power point (I_{mp})	0.86 (A)
Open Circuit Voltage (V_{oc})	139.2 (V)
Short Circuit Current (I_{sc})	1.04 (A)
Module Efficiency (η_c)	6.2%
Fill factor (FF)	0.61

2.2 PV IGU model

Fig.2 illustrates the schematic diagram of the PV IGU. It consisted of an outside layer of semi-transparent a-Si PV laminate, an inside layer of glass sheet and an intermediate sealed air cavity. The above measured physical characteristics were used for PV IGU model developing. The measured optical data was inputted into the OPTICS [34] and the WINDOW [33] software step by step. These two software tools were developed by Lawrence Berkeley National Laboratory for analyzing the performance of various glazing systems. OPTICS can be used to analyze and recreate optical properties of glazing systems and WINDOW aims to calculate window's thermal and optical performance. In this study, OPTICS was used to convert the measured data into a physical parameter file which can be recognized and compiled by Window. Window then exported the spectral file of the PV laminate to EnergyPlus. Except for the spectral data of PV laminate, both the geometric dimensions of the test bed and a customized weather data file need to be imported into EnergyPlus for simulation.

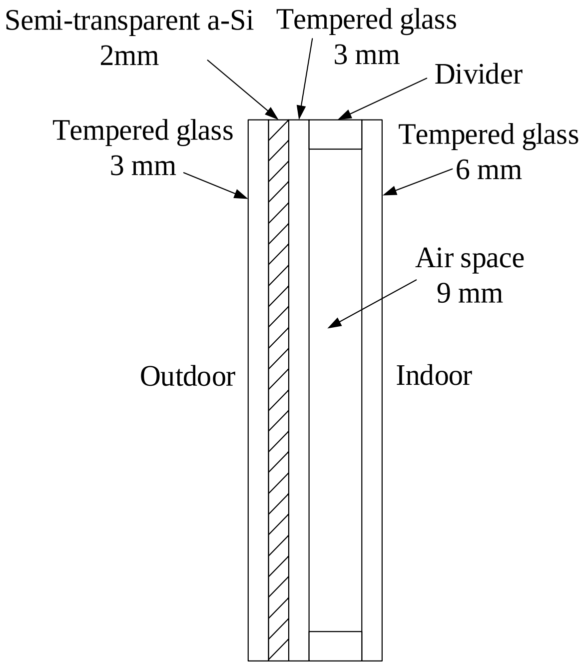

Fig. 2. Schematic diagram of the PV insulated glass unit (IGU)

2.3 Modeling in EnergyPlus

Fig. 3 illustrates the developed PV IGU and the test bed model in EnergyPlus. It was an air-conditioned office room with two pieces of PV IGUs mounted on the south facing facade. Different models and sub-model, including heat transfer model, daylight model and the Sandia PV power model, were employed to calculate the overall energy performance of the PV IGU in this simulation. The heat transfer model, i.e. glazing heat balance model, was adopted to calculate the thermal performance of the PV insulating glazing unit, including conduction, convection and radiation heat transfer simultaneously [35]. The daylighting performance under different weather conditions was simulated by the daylighting model in EnergyPlus [36]. With this model, the daylight illuminance and glare index at any locations of the room can be determined. For power output, the Sandia power model [37] was chosen to simulate the hourly dynamic power output of the PV IGU under arbitrary weather conditions because this model considered the impacts of many factors on the power output, such as the solar spectrum, incidence angle, operating temperature and so on. Thus, it is very suitable for simulating the output power performance of a-Si based PV windows, which are affected significantly by the environmental factors. Combined with the measured physical characteristics, the developed simulation model was capable of predicting the overall performance of PV IGU.

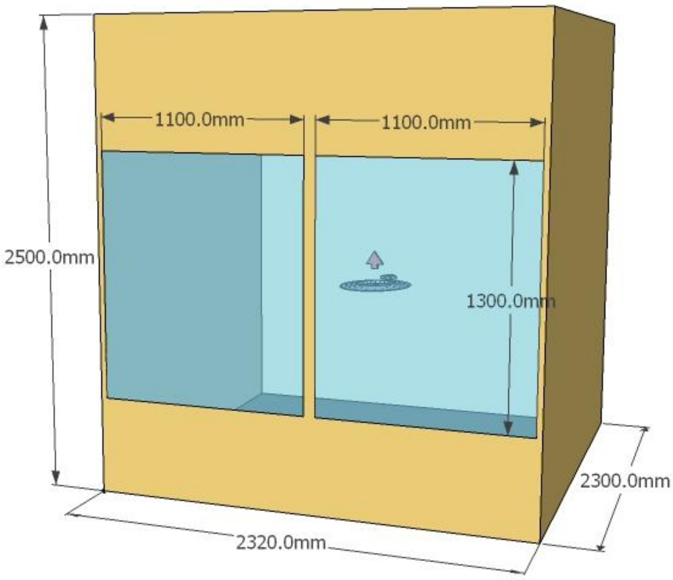

Fig. 3. Simulation model in EnergyPlus

3. Experimental studies

3.1 Testbed

To validate the accuracy of the developed simulation model, outdoor experiments were conducted at the campus of Hong Kong Polytechnic University, where the geographical location is 22.3°N (latitude), 114.2°E (longitude). As shown in Fig. 4, the test cell was south facing and had a shape of 2.32 m wide, 2.3 m long and 2.5 m high. It was located on the rooftop of a building, which eliminated the possibility of surrounding shading. The surrounding rooftop was cement floor with a rough diffuse surface. The PV IGUs were installed on the south facing façade of the test bed; the azimuth angle was 0°.

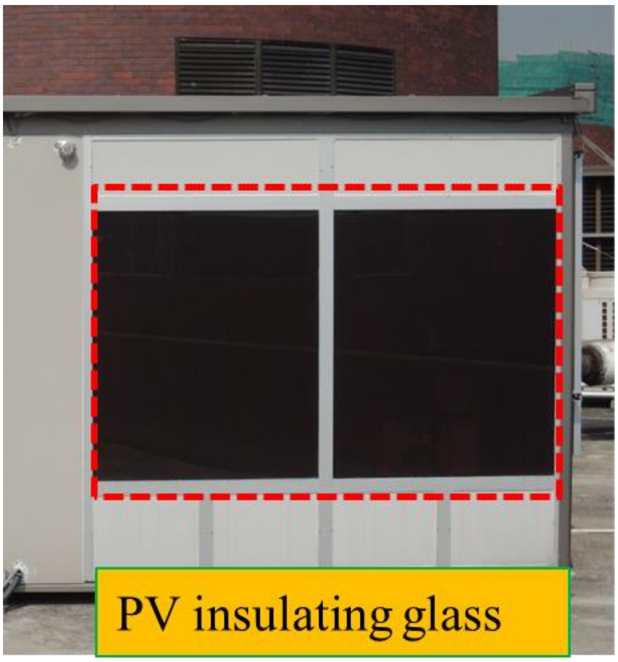

Fig. 4. Front elevation of the experiment rig

3.2 Measurement setup

An outdoor experiment was conducted from Oct. 2012 to Feb. 2013 to validate the simulation model's accuracy. The instruments adopted in the testing campaign are showed in Table 2. Fig.5 illustrates the outdoor measurement instruments, including the sun tracker, the pyranometers and the weather station. The sun tracker and the pyranometers mounted on it were used for measuring the horizontal global and diffuse solar radiations. The pyranometer installed on the south facing façade was employed to measure the incident solar radiation. The weather station can record the ambient temperature & humidity, wind speed, wind direction, and so on. During the measurement period, the environment parameters mentioned above were measured and then inputted into the simulation model as boundary conditions. Meanwhile, the real-time power output was recorded and compared against the simulated power output to validate the model's accuracy.

Table 2 The key experimental instruments and their specifications

Equipment	Manufacturer and model	Sensitivity and/or technical data	Measurement uncertainty
Weather station	Thies Clima	Wind speed: 0.1m/s; Wind direction: 1°; Temperature: 0.1°C; Humidity: 0.1%;	
Pyranometers	EKO instruments (MS-802)	Sensitivity: about 7 μV/(W/m^2);	Non-linearity<0.2 % (at 1000W/m^2);
Thermocouples	RS components (T type thermocouple)	Temperature range: -50 ~ 400°C;	±0.5°C;
Lightmeter	Casella	20 (M129005), 200, 2000, 20000, 200000 Lux	±3%;
Heat flux meter	Captec Enterprise (RS-30)	Sensitivity: 2.0 μV/(W/m^2); Response time: 0.3 seconds;	<3%
Data logger	Graphtec (GL820 Midi DataLogger)	Accepts Voltage (20mv to 50V), temperature, humidity, pulse and logic signals;	The minimum resolutions are 1 μV and 0.1 °C;
Micro-inverter	Involar (MAC250B)	Recommended input power (STC), 250W/200-260W; DC voltage operating range, 60–150 V;MPPT voltage range, 72–120 V;Maximum DC current, 3.47 A;	Power factor > 0.99 Peak inverter efficiency, 94.5%; CEC weighted efficiency, 93.2%

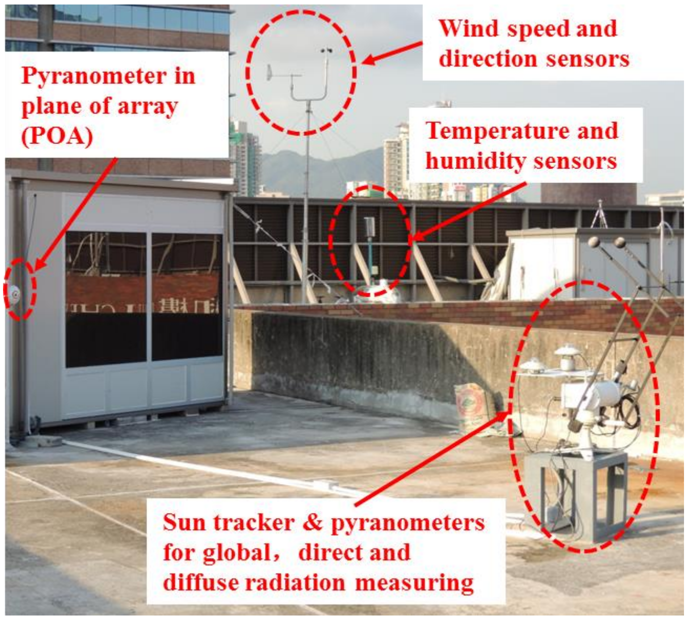

Fig. 5. Outdoor measurement instruments

Fig. 6 shows the indoor measurement instruments. Thermocouples and heat flux meters were used to measure the temperature and the heat flux of the PV IGU, respectively. The measured data directly demonstrated the thermal performance of the PV IGU. The daylight performance of the PV IGU was evaluated by measuring the daylight illuminance at a reference point inside the experimental rig. The selected daylight reference point located in the middle of the room with the work plane height (1 m). For the power output performance testing, the direct current (DC) power output from the PV IGU was firstly converted into alternative current (AC) power by micro-inverters, and then the AC power was transferred to the main distribution box. The dynamic power output of the PV IGUs was measured and recorded by micro-inverters. The generated electricity was firstly used to fulfill the energy requirements of the test rig itself, such as for lighting, computer, and air-conditioning. The surplus electricity, if any, was then transferred to the utility grid and this part of electricity was recorded by a smart energy meter. The monthly power generation during the test period is showed in Fig.7. The maximum monthly power generation was 12.1 kWh, occurred in Jan 2013. With a portable data logger, the above measured data was recorded at a time interval of 1 min.

Fig. 6. Indoor measurement instruments

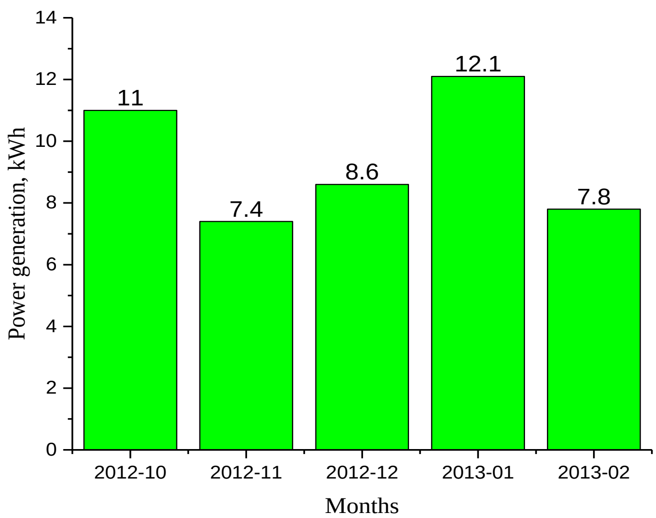

Fig.7. Monthly power generation of the PV IGU

4. Model Validation

To assess the accuracy of the simulation model, two statistical indices, viz. mean bias error (MBE) and the coefficient of variation of root mean square error (Cv(RMSE)), were chosen to evaluate the deviation between the simulated results and the measured data. The reason we chose these two indices is that they can definitively quantify the consistency between the simulation results and the measured data, they are also recommended by ASHRAE Guideline 14 [38] and have a wide application in various error analyses. MBE indicates how well the result predicted by the simulation model is as compared to the measured data. The positive value of MBE shows that the simulation result was overestimated compared to the actual value, and instead the negative value means an underestimated value. Cv(RMSE) indicates the overall uncertainty of the simulation prediction. The lower the value, the better the model accuracy, and the value of Cv(RMSE) is always positive. ASHRAE Guideline 14 suggests that if the MBE and Cv(RMSE) of a building energy simulation model fall within 10% and 30%, respectively, it can be regarded as an acceptable model in accuracy [38, 39]. Equations of calculating MBE and Cv(RMSE) are as follows:

$$\mathrm{MBE}(\%) = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N}(m_i)} \quad (1)$$

$$\mathrm{Cv(RMSE)}(\%) = \frac{\sqrt{\left(\sum_{i=1}^{N}(m_i - s_i)^2/N\right)}}{\bar{m}} \quad (2)$$

Where, m_i and s_i are the measured and simulated data for the instance "i", respectively; N is the number of data points; $\bar{m}$ is the average value of the all measured data.

Since the energy performance of PV IGU was concerned on sunny days and cloudy days rather than on rainy days, the measured data from Oct.20 to Oct.26 2012 were chosen to validate against the simulation results. Fig.8 illustrates the measured global and diffuse solar irradiances on the horizontal surface. It is seen that the frist six days were sunny days and the last day was a typical cloudy day. With the experimental data on typical sunny days and cloudy day, a comprehensive understanding of the overall energy performance of the PV IGU under different weather conditions was obtained.

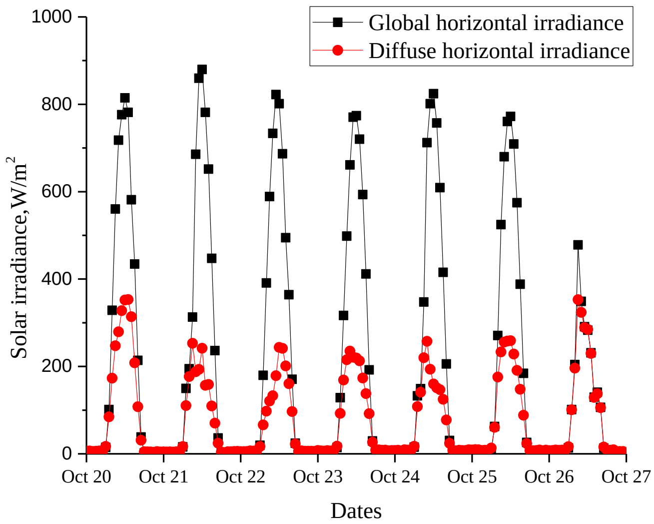

Fig. 8. Global and diffuse solar irradiances on the horizontal surface

4.1 Validation of incident solar radiation

Fig.9 compares the simulated and the measured solar radiations incident on the south-facing PV IGUs. It is seen that the simulated incident solar radiation agreed well with the measured data no matter on sunny days or overcast days. The MBE and Cv(RMSE) between the simulated and the measured incident solar radiations are 0.6% and 25.5%, respectively. The good consistency indicates that the solar radiation model can accurately convert the horizontal global solar radiation into incident solar radiation on a vertical surface.

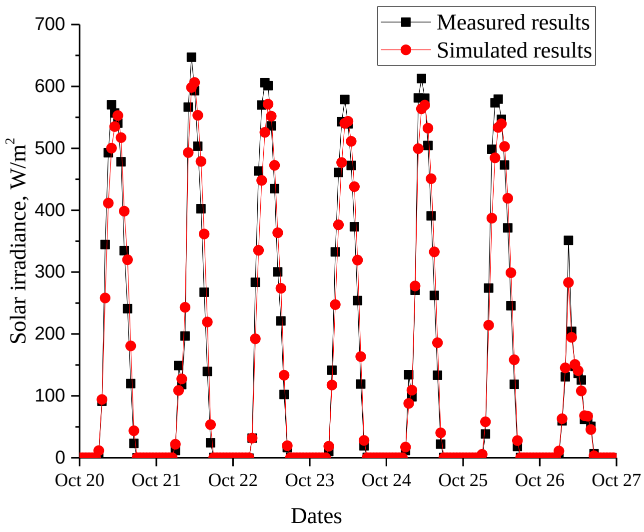

Fig. 9. Comparison of the simulated and measured solar radiation incident on the south facing PV IGU

4.2 Validation of PV IGU temperature

A comparison between the simulated solar cell temperature and the measured back-surface temperature of the PV IGU are presented in Fig.10. It is found that the maximum temperature deviation is about 3.5 °C, occurred in the morning. At other time, the deviation is less than 1 °C and the MBE and Cv(RMSE) between the simulated and measured temperature results are -1.2% and 2.8%, respectively. The errors are much lower than the thresholds stipulated by ASHRAE Guideline 14. In other words, the integrated model predicted the PV IGU temperature well.

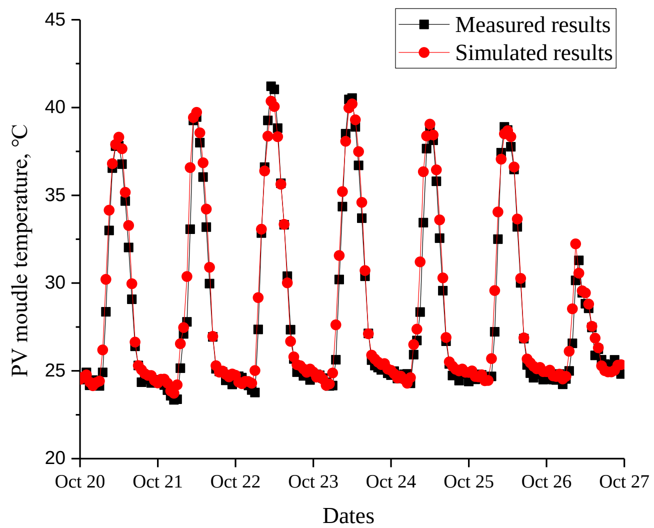

Fig. 10. Comparison between the simulated and measured PV IGU temperature

4.3 Validation of daylight illuminance

Fig.11 presents the comparison results between the simulated and the measured indoor daylight illuminance at the reference point 1. The maximum daylight illuminance is close to 400 lux, occurred at noon on sunny days. This value is close to the design illuminance level (500 lux) and could meet the lighting requirements for most indoor activities. If taking full use of daylight illuminance of the semi-transparent PV IGU, the artificial lighting energy use can be reduced considerably. The MBE and Cv(RMSE) between the simulated and the measured daylight illuminance are -1.7% and 28.1%, respectively. As the wavelength-based spectrum data was employed in the model, the simulated daylight performance agreed well with the measured daylight illuminance in this study.

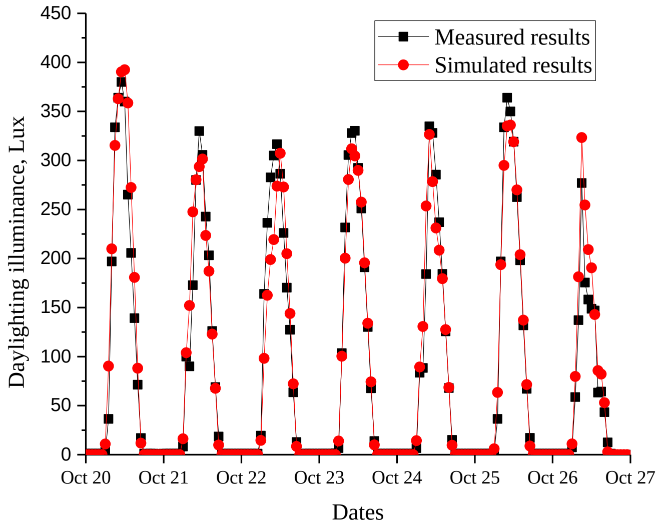

Fig. 11. Comparison between the simulated and measured daylight illuminance

4.4 Validation of heat gains through the PV IGU

The simulated heat gain through the PV IGU was also validated against the measured heat flux, which was measured by heat flux meters. As shown in Fig. 12, the simulated heat gains are slightly higher than the measured data in the morning, but on the contrary in the afternoon. At night, since the indoor air temperature was higher than the ambient air temperature, the heat flux values were negative, which meant that heat loss transferred from indoor room to external environment. The MBE and Cv(RMSE) of heat gain through the PV IGU are -6.9% and 22.1%, respectively. In general, although there is a little overestimation for the heat fluxes, the heat transfer model is acceptable to simulate the real heat transfer situation of the PV IGU.

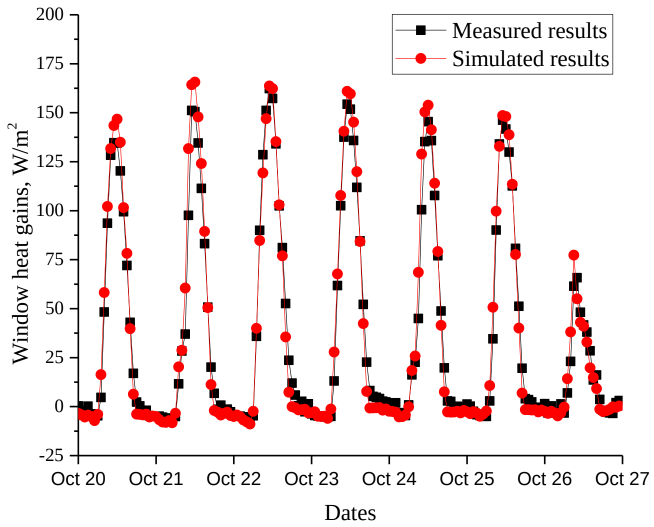

Fig. 12. Comparison between the simulated and measured heat gains

4.5 Validation of power generation

During the outdoor test campaign, the DC power generated by the PV IGU was converted into AC power with the same voltage and frequency as the utility grid electricity by micro-inverters. The daily DC and AC energy output of the PV IGU were also measured and recorded by the micro-inverters, but the net uploaded electricity was recorded by a smart energy meter. In the integrated model, the energy output of the PV IGUs was simulated by the Sandia array performance model, and the performance ratio of converting DC into AC electrical power was determined by the electric load center in EnergyPlus. The load center took all energy losses into account from DC power yielding to AC demand, including the inverter loss, wiring loss, and mismatch loss. Fig. 13 shows the comparison results between the simulated results and the measured data. The MBE and Cv(RMSE) for power generation are 0.2% and 22.8%, respectively.

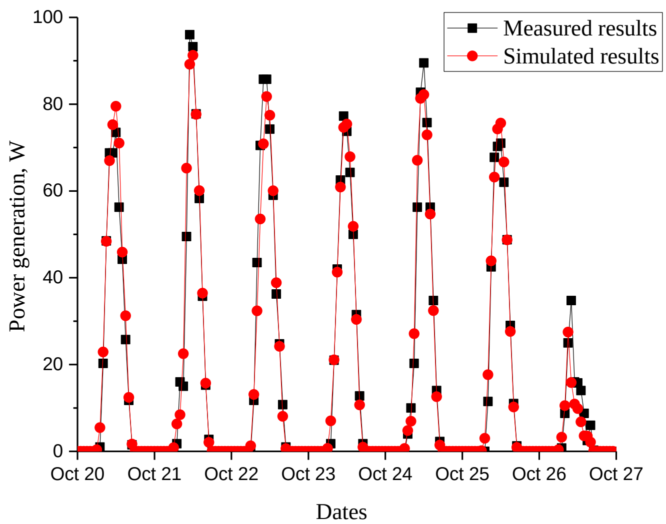

Fig. 13. Comparison between the simulated and measured hourly power generation

5. Results and discussion

The above validation results indicated that the model developed was reliable for predicting the overall energy performance of PV IGU. In this section, the structure of PV IGU was optimized with this validated model. Then the energy saving potential of the optimized PV IGU was evaluated compared to commonly used window systems. The simulation procedures were all the same except the window configuration. The typical meteorological year (TMY) weather data in Hong Kong was utilized in this study for evaluating the annual overall energy performance of the PV IGU. The overall energy performance, including energy uses of air conditioning and lighting, as well as PV power generation, is evaluated using the following equation.

$$\mathrm{E}_{year} = \mathrm{E}_{heating} + \mathrm{E}_{cooling} + \mathrm{E}_{lighting} - \mathrm{E}_{power} \quad (3)$$

Where, E_{year} is the annual end-use electricity consumption (kWh), $\mathrm{E}_{heating}$, $\mathrm{E}_{cooling}$, and $\mathrm{E}_{lighting}$ are the energy demands (kWh) for heating, cooling and lighting, respectively. E_{power} is the annual power generation from the PV IGU (kWh).

In this simulation, a direct expansion cooling coil (COP=2.78) was used for cooling and an electric heating coil (COP=1) was adopted for heating. Meanwhile, a continuous lighting control model was assumed to regulate the artificial light output according to the variation of daylight illuminance.

5.1 Optimization of PV insulating glass unit

Different rear side glass sheets can be integrated with the semi-transparent PV laminate to constitute PV IGUs with different thermal and daylight performance. Table 3 shows the properties of various types of rear side glasses. Clear glass is the most commonly used glass, which has good daylight performance but bad thermal insulation performance. Low-E glass is produced by depositing a low-emittance coating on clear glasses or tinted float glasses. Low-E glass possesses advanced thermal insulation performance because this Low-E coating has a high reflectance to long-wave heat radiation. Low-iron glass is an ultra clear float glass. The transparency of low iron glass can reach up to 91%. In contrast, tinted glass is a glass that has been treated with certain technology to reduce the visible light transmittance. Except for various rear side glass sheets, different air gap (3 mm, 6 mm, 9 mm, 12 mm and 15 mm) was also adopted to investigate the impact of air gap depth on the thermal performance of PV IGU in this study.

Table 3 Thermal and optical properties of different rear side glasses

Glazing type	ID in IGDB[1]	Thickness	T_{sol}[2]	R_{sol}[2]	T_{vis}[2]	E_{mis}[2]	U (W/m^2K)	SHGC[3]
Clear glass	103	5.72mm	0.77	0.07	0.88	0.84	5.82	0.82
Low-e glass	1616	5.85mm	0.36	0.24	0.56	0.01	3.44	0.43
Low-iron glass	2924	5.82mm	0.90	0.08	0.92	0.84	5.82	0.91
Tinted glass	17037	5.84mm	0.32	0.04	0.16	0.84	5.82	0.52

1. IGDB stands for International Glazing Database. ID in IGDB represent the identification no. of the glass in International Glazing Database.
2. T_{sol}, R_{sol}, T_{vis} and E_{mis} stand for the solar transmittance, solar reflection, visible transmittance and emissivity of the glass layer, respectively.

3. SHGC stands for solar heat gain coefficient. U-value and SHGC are used to describe the thermal properties of windows.

Fig. 14 shows the overall energy performance of the test cell which equipped with the PV IGUs with different air gap depths. It is seen that the power consumption of the test cell decreases as the PV IGU air gap depth increasing. This reduction is due to the improvement of thermal insulation, which influences the cooling energy consumption. The variations of lighting and heating energy consumptions were ignorable. However, this improvement has limited effect since the majority of solar heat gain was solar radiation which had no relationship with thermal insulation effect. In general, the influence of air gap on the overall energy performance was not significant in Hong Kong. When the air gap depth increased from 3 mm to 15 mm, the overall power consumption only decreased by 1.4%. Thus, a conclusion can be drawn that the air gap depth has limited effect on the overall energy performance of PV IGU in Hong Kong.

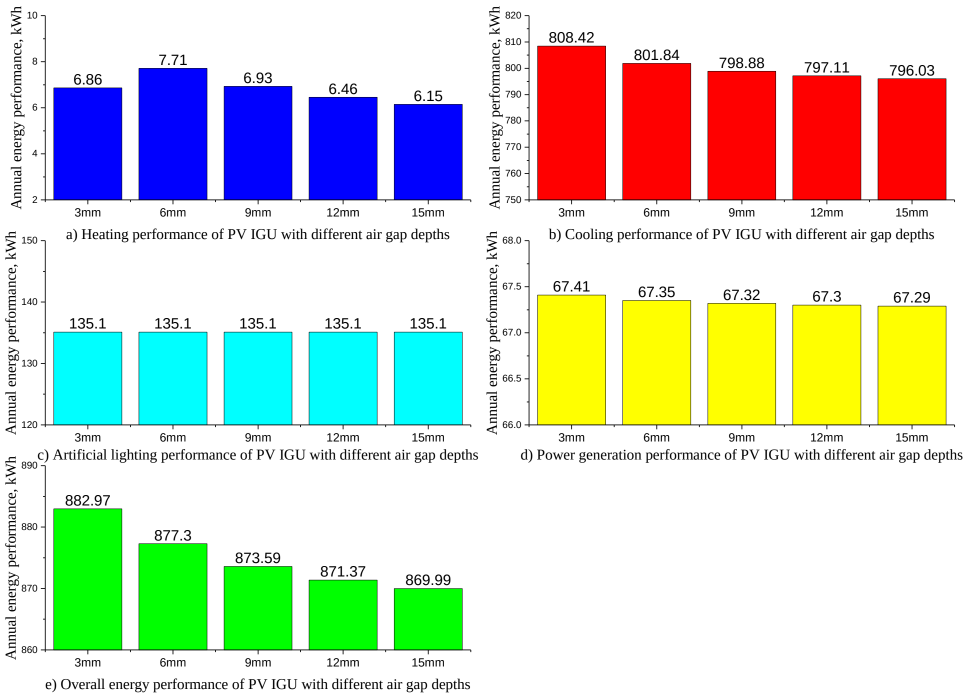

Fig. 14. Comparison of annual energy performance of PV IGU with different air gap depths

The overall energy performance of PV IGUs with different rear side glass sheets are showed in Fig. 15. In general, the PV-IGU with Low-E glass sheet performs best because it can reduce the cooling energy demand. Compare to the case of the clear glass sheet, the PV IGU with Low-E glass saves 3% energy. The low-iron glass represents the improvement of transmittance. Even though it can reduce the lighting energy consumption, the improvement in energy saving is not too much; it is only 2.49kWh. Meanwhile, the high transmittance leads to an increase of cooling load, which deteriorates the thermal performance of the PV IGU. The tinted glass means a decrease of transmittance. It was found that the lighting energy consumption of the

PV IGU with tinted glass went up a lot, and the overall performance was the worst among all glasses. It was found that the transmittance of rear side glass influence the solar heat gain significantly. A low transmittance is needed to reduce the cooling load, which would increase the lighting consumption. A compromise should be made to balance the pros and cons. In this study, the PV IGU combined with Low-E glass sheet possessed the best overall energy efficiency. Thus, the best option of PV IGUs evaluated in this study is composed of a semi-transparent PV laminate and a Low-E rear glass sheet in this study.

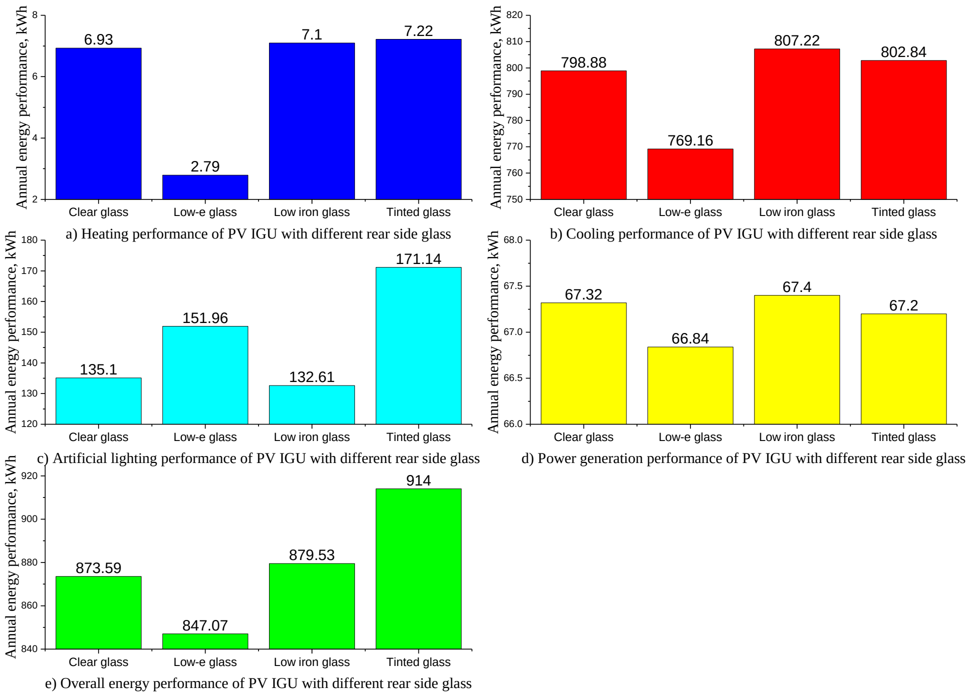

Fig. 15. Comparison of annual energy performance of PV IGU with different rear side glass sheets

5.2 Energy saving potential of the optimized PV IGU

The energy saving potential of the optimized PV IGU was evaluated compared with the other commonly used windows. The glazing systems chosen for comparison are showed in Table 4. Fig. 16 presents the annual energy performance of different windows in Hong Kong. It is found that Scenario G (i.e. the optimized PV IGU) consume the least energy, it is 847.07 kWh/yr. Compared to the single glass and the Low-E glass windows, the energy saving potentials of the optimized IGU are 25.3% and 10.7%, respectively. The main source of energy conservation was coming from the reduction of cooling energy use, which accounted for the largest fraction of the overall energy consumption in Hong Kong. However, it is found that the electricity generated by the PV IGU is partially offset by the increasing artificial lighting use, which was due to the relatively low visible transmittance. If high efficiency and transmittance PV laminates are utilized, the energy saving potential of PV IGU is expected to become larger in the future.

Table 4 Information of the chosen glazing system

Scenarios	Glazing name	Structure	ID in IGDB
A	Single clear glass	Clear (5.72mm)	103
B	Insulated glass unit	Clear (5.72mm) + air gap (9mm) + Clear (5.72mm)	103/103
C	Low-e glass	Low-e (5.85mm)	1616
D	low-e insulated glass unit	Clear (5.72mm) + air gap (9mm) + Low-e (5.85mm)	103/1616
E	PV window	a-Si PV laminate (8mm)	60900
F	PV IGU	a-Si PV laminate (8mm) + air gap (9mm) + Clear (5.72mm)	60900/103
G	Optimal PV IGU	a-Si PV laminate (8mm) + air gap (9mm) + Low-e (5.85mm)	60900/1616

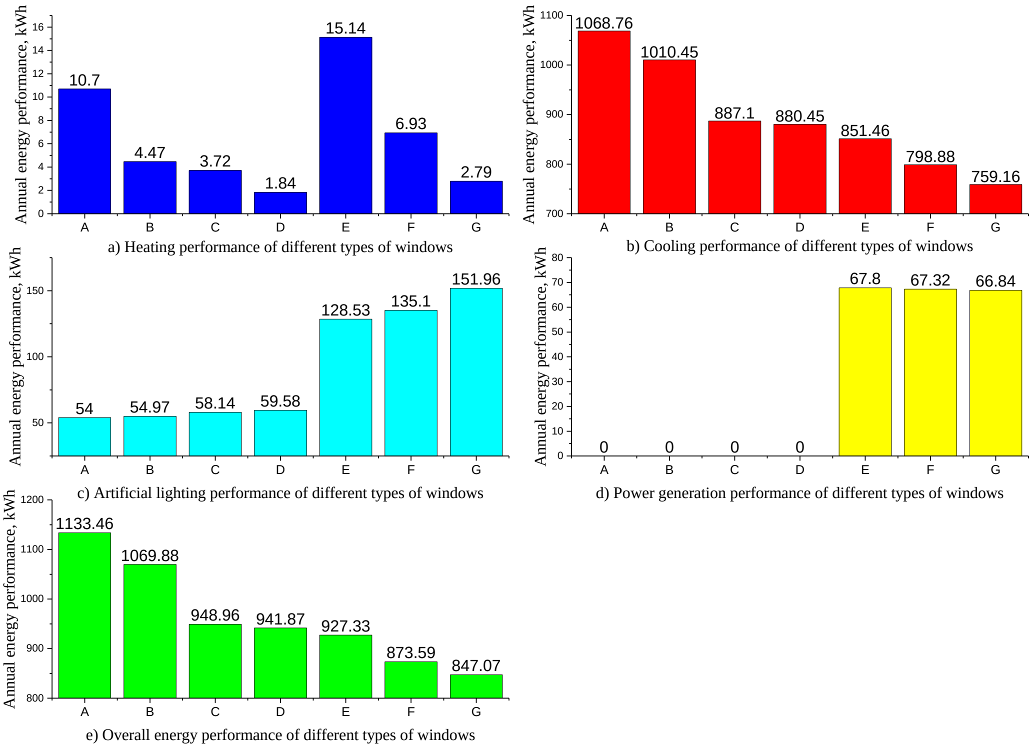

Fig. 16. Energy performance of different windows

In this study, the overall performance of PV IGU was investigated based on the actual product of PV IGU. Since the developed simulation model was comprehensively validated against experimental data, the simulation results obtained in this study was more reliable and accurate than the previous study. The results demonstrated the energy efficiency of PV IGU in the current application status and provided useful information for building engineers or architects to apply this kind of BIPV window system in buildings. On the one hand, the energy performance results could be employed for comparing with the energy performance of other types of windows when selecting suitable façades in Hong Kong. On the other hand, the optimization solution could be used for further optimization of PV IGU structure. Although this model was developed based on a low transmittance a-Si PV laminate and was only validated in Hong Kong in this study, it should be independent of climate conditions and also suitable for other kinds of semi-transparent PV windows. However, the PV technology is developing very quickly. The energy conversion efficiency of the a-Si PV laminate used in this paper was 6.2%, which was much lower than the recently emerging semi-transparent CdTe PV module. The efficiency of the semi-transparent CdTe PV module is approximately twice as high as that of the a-Si PV module, which means that the annual energy output of the PV-IGU could be doubled by using the CdTe PV module to replace the a-Si PV module. Further study should be conducted to develop new type high-efficiency PV products and improve the energy saving efficiency of PV windows.

6. Conclusions

In this paper, the energy performance and the energy saving potential of PV IGU were investigated via numerical simulation and experimental tests. The highlighted results and conclusions were summarized as follows.

1) An integrated model based on the measured properties was used to estimate the overall energy performance of PV IGU. Compared with previous models, the developed model had better accuracy in prediction.
2) The influence of air gap depth on the overall energy performance of PV IGU was investigated, and it was found that the impact of air gap depth was limited in Hong Kong.
3) The PV IGU combined with Low-E glass rear sheet can reduce the energy consumption by 3% compared to the PV IGU with clear glass. The replacement was found to be an excellent choice to save energy in Hong Kong.
4) The optimized PV IGU can reduce the energy consumption by 25.3% and 10.7% compared to the single clear glass and the Low-E glass windows in Hong Kong. These results provided useful references for architects when choosing the energy-efficient windows.
5) With the development of PV technology, higher efficiency PV laminate can promote the energy saving potential of PV IGU in the future. Further studies should be conducted to develop new types of high-efficiency PV products as well as improve the energy saving efficiency of PV windows.

Acknowledgements

The authors appreciate the financial supports provided by the Fundamental Research Funds for the Central Universities (Hunan University, Project No. 531107040899), the Hong Kong Construction Industry Council Research Fund (CIC Project: K-ZJK1), the National Natural Science Foundation of China (Project No. 51578220), Shenzhen Peacock Plan.

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