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# Investigation on the energy performance of a novel semi-transparent BIPV system integrated with vacuum glazing

**Abstract**

The development of vacuum glazed windows in recent decades has provided a foreseeable energy saving opportunity in the design of low-energy consumption buildings and the application of building integrated photovoltaic (BIPV) has experienced rapid development for application in buildings. This paper reports our investigations on the combinations of the vacuum glazing and BIPV integration. Semi-transparent photovoltaic windows can convert solar energy into electricity, but most of absorbed solar heat is transferred into indoor environment which becomes additional cooling load. The proposed vacuum photovoltaic insulated glass unit (VPV IGU) in this paper combines vacuum glazing and solar photovoltaic technologies, which can utilize solar energy and reduce cooling load of buildings at the same time. Various experiments were conducted to evaluate the thermal performance and determine the key characteristics of the VPV IGU in this study. It was found that the VPV IGU can achieve very low total heat gain coefficient (U-value) of around 1.5 $W/m^2K$ and block most of undesired solar radiation from penetrating through the window. Compared with a common double-pane glass sheet, the vacuum PV glazing can maintain the indoor environment at a relatively low temperature due to its excellent thermal insulation performance in summer. A detailed simulation study has been conducted by EnergyPlus and Berkeley Lab WINDOW. The simulation work has indicated that the cooling load can be reduced by 14.2 % by a south-oriented VPV IGU compared with common glazing products while power generation is not compromised compared with normal BIPV systems. The results show that the application of the VPV IGU has a huge energy saving potential and can minimize the drawback of common PV insulating glass units.

Keywords: Building integrated photovoltaic (BIPV), Vacuum glazing, Semi-transparent photovoltaic, thermal insulation performance

## 1. Introduction

On a global scale, developing energy-efficient buildings has been an irresistible trend as the energy consumption of building takes a large proportion of the total energy demand. Especially in Hong Kong, about 90% of the annual electricity consumption was consumed in buildings according to The Hong Kong Year Book 2015 (Hong Kong Information Services Department, 2015). Buildings not only play a remarkable role in respect of energy shortage situation (Erdem Cuce & Saffa B. Riffat, 2015), but also are responsible for more than 30% of the greenhouse gas emissions in many developed countries (Baetens, Jelle, & Gustavsen, 2011). To address these issues, development of energy-saving technology in building and utilization of renewable energy are two different attempts which have attracted the most attention of many researchers to mitigate energy consumed in buildings (Chen, Yang, & Lu, 2015; Omer, 2008).

For a typical building, the glazing area is responsible for the greatest energy loss which is up to 71% and 48% in summer and winter, respectively (Gustavsen, 2008). Due to the significantly high overall heat transfer coefficient (U-values) of conventional window technologies, the highly thermal resistive fenestration products have an appreciable potential to provide large energy savings and improve thermal comfort of the occupants as well. As the weakest link in the heat insulation of the building envelope, the thermal resistance enhancement of glazing area is the most promising research and development trends to achieve energy-efficient building in the future. Vacuum glazing is a competitive idea for energy saving purpose, which is able to present a low heat loss and noise cancellation as well.

The initial concept is not new, firstly being introduced and claimed a patent by Zoller in 1913 (F, 1924). The principles of a typical double vacuum glazing with an evacuated gap are the same behind a

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conventional Dewar flask: an evacuated gap between two glass panel can minimize heat conduction and convection through glass sheets. The first reported successful method to manufacture vacuum glazing in the laboratory was presented by R.E. Collins at the University of Sydney in 1989 (R. E. Collins et al., 1995). In the recent decade, significant effort has been made by many researchers to investigate and optimize the thermal performance of vacuum glazing. Collins and Simko (R. Collins & Simko, 1998) indicate that the radiative heat, which is the primary heat transfer remaining between the outside and inside of a vacuum glazing can be reduced enormously by adopting low-e coating. However, the fabrication method developed by the University of Sydney can only admit the utilization of hard low-e coating (Simko & Collins, 2014). Another approach to fabricate vacuum glazing was developed by the University of Ulster in 2000s (Fang et al., 2014). An indium alloy edge seal method was used to manufacture the vacuum glazing at a relative low temperature in a vacuum chamber. Therefore, it allows the use of soft low-e coating which has lower emissivity and much more complex structure of vacuum glazing (Simko & Collins, 2014). In this respect, a hybrid vacuum glazing with an air gap (R. Collins, Asano, Misonou, Katoh, & Nagasaka, 1999) and a triple vacuum glazing with two vacuum gap (Fang, Hyde, & Hewitt, 2010; Manz, Brunner, & Wullschleger, 2006) was proposed to achieve better thermal insulation performance. Manz, et al. (Manz et al., 2006) predicted that the U-value of a triple vacuum glazing with four low-e coatings can be less than 0.20 $W/m^2$ K. Fang, et al. (Fang, Hyde, Arya, & Hewitt, 2013) investigated the thermal performance of hybrid vacuum glazing and triple vacuum glazing theoretically and experimentally. It was found out that the minimum U-value of the triple vacuum glazing is around 0.24 $W/m^2K$ with three low-e coatings with an emittance of 0.03. The best vacuum glazing product in the commercial market was reported with the U-value of 0.86$W/m^2K$ (Erdem Cuce & Cuce, 2016). Besides the research on the performance of vacuum glazing, many researchers also explored various possibilities for combining the vacuum glazing with other advanced window technologies, such as electrochromic glazing, aerogel glazing and suspended particle device glazing (E. Cuce & S. B. Riffat, 2015; Fang, Hyde, Hewitt, Eames, & Norton, 2010; Ghosh, Norton, & Duffy, 2016; Schultz & Jensen, 2008).

Nowadays, building-integrated photovoltaic (BIPV) system becomes an optional building element to replace the conventional building rooftop or facades and act as power generator as well (Chow, Qiu, & Li, 2009; E. Cuce, Riffat, & Young, 2015; Skandalos & Karamanis, 2015; Wong, Shimoda, Nonaka, Inoue, & Mizuno, 2008). Normally, solar cells can be integrated into fenestration products or building façade and generate power from solar energy resource without any aesthetic problem occurring. One of the BIPV applications, semi-transparent photovoltaic (STPV) windows, which can admit a portion of daylight into indoor environment and generate electricity simultaneously, have been widely used as a part of building envelope in recent years (Lu & Law, 2013; Jinqing Peng, Lu, & Yang, 2013). Many researchers have done numerous experimental and simulation study about semi-transparent PV windows during last decade. Fung and Yang (Fung & Yang, 2008) introduced a one-dimensional transient heat transfer model to evaluate the thermal performance of a c-Si semi-transparent photovoltaic modules for the building-integrated application. The simulation results show that solar heat gain dominates the total heat gain. Lu and Law (Lu & Law, 2013) evaluated the overall energy performance of a single-glazed semi-transparent photovoltaic window for office buildings in Hong Kong by simulation work. Their results indicated that the energy saving potential of the semi-transparent PV window was mainly due to the reduction of total heat gain by using this application. The comparison of energy performance between PV glazing and traditional glazing was also shown the energy saving potential of semi-transparent PV windows (Li, Lam, Chan, & Mak, 2009; Liao & Xu, 2015). Wang et al. (Wang et al., 2016; Wang et al., 2017) investigated the overall energy performance of PV insulating glass unit (PV-IGU) by experimental tests and simulation works in Hong Kong. The results suggested that the PV-IGU has better thermal insulation than the PV double skin façade (PV-DSF) while the PV-DSF is better in reducing solar heat gain. Zhang et al. (Weilong Zhang, Lu, Peng, & Song, 2016) compared the overall energy performance of semi-transparent photovoltaic (STPV) windows with common energy-efficient windows in Hong Kong via simulation study. It was found that STPV glazing has better overall energy performance compared with other commonly used windows, such as, clear single glazing and double-pane glazing.

However, the solar energy irradiated on the PV windows can only be utilized for power generation by a small proportion and the remaining energy will be absorbed by solar cells then transform into waste heat (Jinqing Peng et al., 2016). Thus, one of the drawbacks of PV windows is that the waste heat would increase the heat gain of indoors. On the other hand, the vacuum glazing technology is mainly applied to cold region due to its excellent thermal insulation which is more suitable for heating dominated area (Hee et al., 2015). Not like the cold region where the temperature difference between indoor and outdoor is quite large, in the subtropical zone like Hong Kong, solar heat gain is the major part of total heat transfer through the glazing area, especially for those buildings with a large area of curtain wall (J. Peng, Lu, Yang, & Ma, 2015a).

Therefore, a novel vacuum PV insulated glass unit (VPV IGU) is proposed to combine the advantage of the high thermal insulation performance of vacuum glazing and the power generation capability of PV glazing. The PV windows can utilize the solar energy to generated electricity and reduce the solar heat gain at the same time. Meanwhile, the vacuum glazing can resist the waste heat from solar cells to become the undesired cooling demand. This study aims to investigate the overall energy performance including thermal performance and power generation performance of this novel BIPV system integrated with vacuum glazing.

# 2. Structure of VPV IGU

The proposed VPV IGU was combined with vacuum glazing and PV module into an integral glass unit. As illustrated in Fig. 1, the exterior layer of the panel is a semi-transparent a-Si PV laminated glass with the transmittance of 20% and the interior layer is an insulated vacuum glazing with two layers of glass sheet and an evacuated gap. The external PV laminated glass was adhered to the internal vacuum glass by a layer of polyvinyl butyral (PVB).

In the practical application of the vacuum PV glazing integrated into building façade, a large portion of the incident solar radiation can be absorbed by the a-Si solar cell layers. Besides the reflected and absorbed part of solar radiation, the remaining solar radiation enters into indoor room providing natural daylight. When the solar cell utilizes the sunlight to generate electricity, the unused solar energy transfers into waste heat and can increase the cooling demand in summer. As one of the best thermal insulation fenestration products, the inner layer of vacuum glazing can minimize the heat gain and heat loss through the window. In summer, the waste heat from the solar radiation absorbed by solar cell can be blocked from indoor. In winter, it can reduce the heat loss from inside to outside. As radiation is the only mode of heat transfer that not affected by the vacuum gap, a low-E coating with the emittance of 0.042 was deposited on the inner surface (toward the outside) of the vacuum glazing to minimize the total heat transfer. However, the excellent thermal insulation performance of the vacuum glazing will also increase the temperature of PV modules so that the PV conversion efficiency will decrease. Therefore, the type of solar cells used in the vacuum PV glazing must be selected with the consideration of the temperature coefficient of PV modules. According to the characteristics provided by the manufacture, the a-Si PV used in the vacuum PV glazing has the temperature coefficient of -0.19%/°C. In contrast, the temperature coefficient of the typical crystalline silicon PV, which generally ranges from -0.4%/°C to -0.65%/°C (Ma, Yang, Zhang, Lu, & Wang, 2015; J. Peng, Lu, Yang, & Ma, 2015b), is much higher. The combination of the vacuum glazing and a-Si PV is expected to offer the best thermal performance and uncompromised power performance. Besides the power performance of PV glazing, the cost of generation is also essential to the selection of solar cell. The cost of generation of a-Si PV glazing is \$0.3/W*yr, which is much lower than that of similar PV glazing products used mC-Si PV (Youssef, Zhai, & Reffat, 2015).

Fig. 2 presents the pictures of the sample of vacuum PV glazing, which the thickness is 20.8 mm, thinner than common double-pane glazing. The thinner thickness of the vacuum PV glazing is also an advantage when retrofitting conventional glazing system of existing building. Based on the previous research on the VPV IGU (Weilong Zhang, Lu, & Chen, 2016), the key electrical specification of the VPV IGU was measured under standard test conditions (STC: air mass 1.5, solar irradiation 1000W/$m^2$ and cell temperature 25 °C) as shown in Table 1.

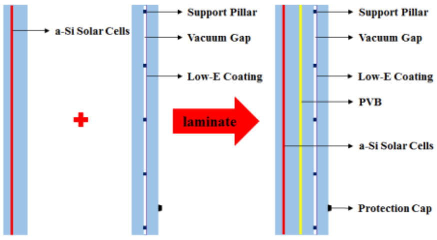


Fig 1. The cross-sectional view of vacuum PV insulated glass unit (Weilong Zhang, Lin Lu, & Xi Chen, 2016)

Fig 2. The pictures of vacuum PV insulated glass unit

Table 1: The key electrical specification of the VPV IGU under STC

| Parameters | Value |
|---|---|
| Rated power output (W) | 74 |
| Voltage at the maximum power point (V) | 94 |
| Current at the maximum power point (A) | 0.78 |
| Open circuit voltage (V) | 120 |

| | |
|---|---|
| Short circuit current (A) | 0.98 |
| Fill Factor | 0.62 |

## 3. Experimental study

To compare the thermal performance of the proposed vacuum PV glazing with other glazing products, two test rigs with the same dimension, which is 300 mm (length) × 300 mm (width) × 400 mm (height), were built. As shown in Fig. 3, the test rigs are covered with thermal insulation material on the vertical faces and the bottom to reduce the heat transfer through these surfaces except the top. Samples of different types of glazing were mounted on the top of test rigs to implement both indoor and outdoor test.

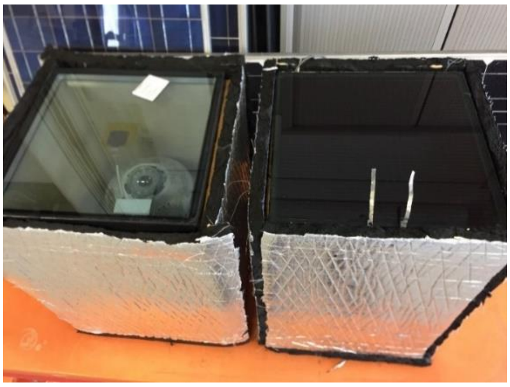

Fig. 3 The picture of the test rigs in the solar simulation test

The key specifications of the experimental instruments are listed in Table 2. Three pyranometers were employed to measure the horizontal solar radiation in the two test rigs and the incident solar radiation. Thermocouples and heat flux sensors were adopted on the surface of glazing and both sides of test rigs to evaluate the thermal performance of vacuum PV glazing and other types of glasses as well. All the data measured by these sensors were collected by a GL 840 Midi Data Logger with a sample interval of 1min.

Table 2: The key specifications of the experimental instruments

| Equipment | Function | Manufacture and Model | Accuracy/sensitivity |
|---|---|---|---|
| Pyranometers | Solar irradiation measuring | EKO instruments(MS-802) | Sensitivity: about 7 μV/(W/m$^2$); Non-linearity < 0.2%(at 1000W/m$^2$) |
| Thermocouples | Temperature measuring | RS Components(T type thermocouple) | Temperature range: -50 ℃ to 400 ℃; Accuracy: ±0.2 ℃ |
| Heat flux meter | Heat flux measuring | Captec Enterprise(RS-30) | Sensitivity: about 5 μV/(W/m$^2$); Response time: 0.3s |
| Data logger | Data acquisition | Graphtec (GL840 Midi Data Logger) | Accepts voltage (20 mV to 100 V), temperature, humidity, pulse and logic signals; The minimum resolution: 1 μV and 0.1 ℃ |

Regarding the overall thermal performance of building envelops, solar heat gain coefficient (SHGC) and

U-value are the two most popular indices for the evaluation purpose. SHGC of glazing in building is the fraction of the total heat from the sun and the sky entering through the window. Besides the reflection proportion, the solar radiation that transfers to the indoor heat gain can be classified into two parts, the primary transmittance which is the direct solar energy transmitted through the glass, and the secondary transmittance which is the proportion of the energy absorbed and re-emitted by the glazing to the indoor environment. U-value is the total heat transfer coefficient, namely, the heat flow rate per unit area due to the temperature difference between the inside and outside of building façade. According to ISO 15099 ("Thermal Performance of Windows, Doors and Shading Devices-Detailed Calculations," 2003), the U-value of any glazing is assumed to the thermal transmittance without solar radiation by definition. Consequently, the SHGC is calculated as the difference in net heat gain between the situation with and without solar radiation. Therefore, the U-value and SHGC can be expressed by the following equation:

$$U_{value} = \frac{Q_{in,no\_sun}}{T_i - T_o}$$

$$SHGC = \frac{Q_{in} - Q_{in,no\_sun}}{I_s}$$

where $Q_{in}$ and $Q_{in,\ no\_sun}$ are the total heat transfer through the glazing area in the situation with and without solar radiation, respectively, (W/m$^2$). $T_i$ and $T_o$ are the air temperature of indoor and outdoor ambient, respectively, (°C). $I_s$ is the total incident solar radiation on the glazing area, (W/m$^2$).

From the energy balance between indoor and outdoor environment, the heat gain of an indoor room is mainly contributed by the incident solar radiation and the temperature difference between indoor and outdoor. On account of the definition of U-value and SHGC discussed before, it can be asserted that the U-value of glazing represents the thermal insulation capability dealing with the temperature difference, while the SHGC of glazing represents the thermal insulation capability dealing with the incident solar radiation. However, in the dynamic outdoor test, the radiant flux through the glazing area is practically impossible to separate into the effect of U-value and SHGC. In this study, the heat flux measured by heat flux sensor was used to calculate the U-value. The direct solar transmittance and indoor air temperature were used for comprehensive analysis of the overall thermal performance of different types of glazing.

In order to determine the thermal performance and characteristics of vacuum PV glazing, the experimental study consists of three parts. Firstly, a co-heating test methodology was adopted for thermal analysis of the vacuum PV glazing. The test rig was filled with the ice-water mixture to ensure the temperature difference between the inside and outside of glazing surface larger than 5 °C. After both sides of the test rig fulfilled the steady-state conditions, data acquisition was started for the further analyses. Heat flux meter and thermalcouples were used at the center of the vacuum PV sample to calculate the U-value. Secondly, the solar simulation test can provide considerable steady horizontal incident solar radiation. The test rig is located in the same spot to ensure each window sample under the same steady solar irradiation. The direct solar transmittance of the vacuum PV glazing sample was obtained and compared with that of three other advanced glazing technologies (double pane glass, single pane PV window, and vacuum glazing) in the solar simulation laboratory. Lastly, a comparative outdoor test lasted for 4 days from September 26 to September 30. Two test rigs were located on the platform of Block Z in the Hong Kong Polytechnic University without shading from the surrounding. During this experimental period, the heat flux through the glazing area of samples as well as the temperatures of vacuum PV glazing and the internal temperature of the test rigs were measured simultaneously under the same weather conditions. Therefore, the data related to U-value and SHGC were collected continuously to indicate the overall thermal performance of vacuum PV glazing. A conventional double clear pane glazing was also tested in the outdoor test for comparison purpose.

# 4. Simulation study

EnergyPlus and Berkeley Lab WINDOW were introduced in this study to simulate the overall energy performance of different windows including the proposed vacuum glazing integrated with photovoltaic module. EnergyPlus is widely used to simulate energy performance of a specific building envelope (Hong, Langevin, & Sun, 2018) and Berkeley Lab WINDOW is a professional software to calculate the window thermal properties such as U-factor and solar heat gain coefficient (SHGC).

## 4.1 Model development

In order to compare the overall energy performance of different windows, EnergyPlus and Berkeley Lab WINDOW were employed to investigate the thermal performance and power generation performance of the vacuum PV glazing and other common fenestration products. Berkeley Lab WINDOW is a professional software developed by Lawrence Berkeley National Laboratory ("Berkeley Lab WINDOW," 2018). It aims to calculate the thermal and optical performance indices of complex glazing systems which can be formed by the combination of different glass layers and gas layers. An integrated glazing system library is provided by this software to assist the users to select the required windows or build up the proposed complex windows. EnergyPlus is a whole building energy simulation programme, which can model both energy consumption and on-site renewable power generation ("EnergyPlus," 2018).

In this study, the measured physical characteristics of VPV IGU, which are the optical, thermal and electrical properties, were firstly introduced into the Berkeley Lab WINDOW to generate a physical characteristics file. The physical characteristics file containing all the key parameters for next step simulation, such as U-value, SHGC and spectral data, can be recognized by EnergyPlus as input data. The heat transfer model, daylight model, HVAC model, as well as solar power generation model, were employed to calculate the overall energy performance of the vacuum PV glazing. The surface heat balance model, i.e the window glass module, was adopted to simulate the thermal performance of the VPV IGU and other comparative windows, including heat conduction, convection and radiation through the glazing area. In the case of the application of vacuum glazing, the thermal conductance of the low-pressure gas ($P<0.1Pa$) was also taken into account. For the photovoltaic power generation, the equivalent one-diode model was selected to simulate the hourly dynamic power output of the PV modules with the consideration of the solar spectrum, incidence angle and operation temperature. As different glazing systems will perform different outside surface temperature, which would affect the power output of PV modules, the applicable heat transfer integration mode was chosen to couple the operation temperature of the semi-transparent PV module and the surface temperature of the glass sheet. Based on these models and sub-models, the comprehensive simulation model was able to predict the overall energy performance of the VPV IGU application and other alternative windows.

## 4.2 Description of simulation model

The comparison of the overall energy performance of different windows is the main focus of the simulation study. Therefore, the simulation model was simplified to a generic office room instead of a whole building with the detailed configuration. Fig. 4 illustrates the generic model used in this study to represent a typical Hong Kong office room with an air-conditioning system. The dimension of the office was 2.3 m × 2.5 m × 2.5 m (L×W×H). Only one wall of the office room was exposed to the outdoor environment while other walls were defined as the internal surface with the same conditions. One uniform window was mounted on the exterior wall. The properties of the building envelopes were followed the instruction of the Hong Kong standard (Authority, 1995). An air-conditioning system was set to maintain the fixed coefficient of performance of 2.78, so that the electricity consumption for cooling can be calculated. Weather data file for the location and climate was represented by the typical meteorological year (TMY) data in Hong Kong (Chan, Chow, Fong, & Lin, 2006). Simulations were conducted for different orientations, i.e. south (S), west (W), North (N) and east (E).

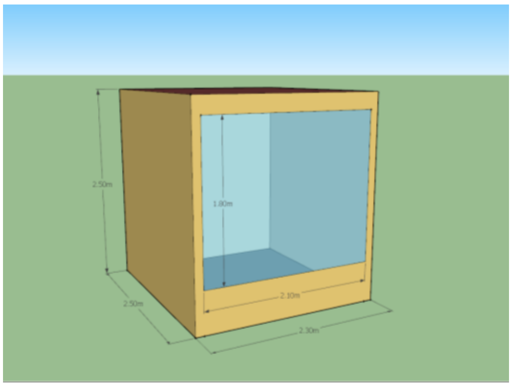


Figure 4: A generic simulation model in EnergyPlus

## 4.3 Properties of glazing materials

The overall energy performance of VPV IGU was compared with other common glazing systems to identify the energy saving potential as well as the solar power output ability. The single-pane clear glass was introduced as a baseline model. Double-pane glazing is widely used for energy-efficient building envelope which is made up of two 5.7 mm single clear glass with 12.7mm air cavity between the double-pane. A standard vacuum glazing including 0.1 mm evacuated gap between two 5.7 mm glass sheets was also adopted in this study. The support pillars are 0.5 mm in diameter and positioned in a square array, separated by 50 mm. A low-E coating is applied on the internal surface of the outer layer of the vacuum glazing for the solar control purpose which is essential for the building envelop design in the subtropics. The combination of the same semi-transparent a-Si PV laminate with single-pane and double-pane glass was also taken into account for the comparison of photovoltaic power generation. The key properties of different types of glazing material are shown in Table 3.

Table 3: Key properties of different types of glazing

| Glazing type | Thickness (mm) | Visible transmittance | Solar transmittance | U-value ($W/m^2k$) | SHGC |
|---|---|---|---|---|---|
| Single-pane clear glazing | 5.7 | 0.884 | 0.771 | 5.54 | 0.817 |
| Double-pane clear glazing | 24.1 | 0.786 | 0.607 | 2.63 | 0.703 |

| | | | | | |
|---|---|---|---|---|---|
| Vacuum glazing (low-E) | 11.5 | 0.693 | 0.344 | 0.648 | 0.391 |
| Single-pane PV glazing | 8.0 | 0.153 | 0.268 | 5.254 | 0.489 |
| Double-pane PV glazing | 25.7 | 0.136 | 0.195 | 2.584 | 0.354 |
| Vacuum PV glazing | 20.8 | 0.120 | 0.076 | 0.557 | 0.143 |

It is worth noting that the low visibility of all the three types of PV glazing would clearly affect the daylighting performance. Normally, the STPV windows have lower daylight autonomy (DA) and higher useful daylight illuminances (UDI) than conventional windows (Weilong Zhang, Lin Lu, Jinqing Peng, et al., 2016). However, high DA and low UDI tend to cause visual discomfort when the solar irradiation is excessively high. In Hong Kong, the internal sun-shading systems, such as Venetian blinds, are widely used in office buildings to reduce the solar heat gain and improve visual comfort during the daytime (W. Zhang, Lu, & Peng, 2016). The utilization of interior blind not only prevents the occupants from the sun exposure but also blocks the outdoor view. In comparison, the PV glazing can serve as a sun-blocking device and generate power at the same time (J. Peng et al., 2016). As shown in Fig. 2, the visual effect of the vacuum PV glazing is acceptable for occupants as the outdoor scenery is still can be seen.

# 5. Results and discussion

5.1 Experimental results

Fig. 5 shows the internal and external temperature of the vacuum PV glazing sample. The data for further calculation were selected after achieving the steady-state conditions, which the temperature difference was around 8 °C. At the next stage of the results, the heat flux through glazing samples and the U-value were determined as illustrated in Fig. 6. The average heat flux from vacuum glazing was measured to be 15.4 W/m$^2$. And the average U-value was calculated as 1.5 W/m$^2$*K which is much lower than a common double-pane window with the U-value of 2.5W/m$^2$*K. Considering the edge heat transfer which would strongly affect the heat flux measurement when the sample is small, it can be expected that the center U-valve of vacuum PV glazing should be lower than 1.5 W/m$^2$*K in a large-scale application.

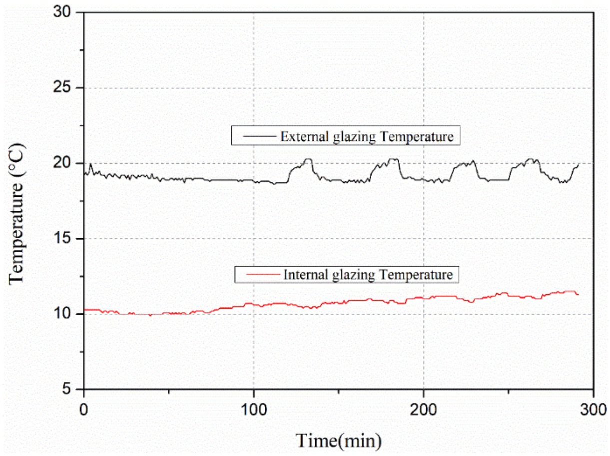


Fig. 5 Internal and external glazing temperature of vacuum PV glazing

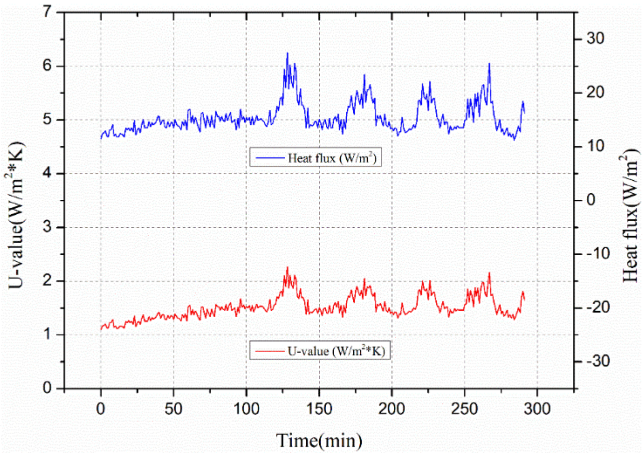

Fig. 6 Measured heat flux and calculated U-value of vacuum PV glazing

The solar simulator in the solar simulation laboratory can provide considerable steady horizontal incident solar radiation. The test rig is located in the same spot to ensure each window sample under the same steady solar irradiation. As shown in Fig. 7, the direct solar transmittance of vacuum PV glazing and double-pane PV glazing are much lower than which of the vacuum glazing and double clear glass. That is because the combination of PV module can absorb the majority solar irradiation. The vacuum PV glazing has the lowest direct solar transmittance as 0.10 which can be beneficial for thermal insulation when the solar irradiation is strong. These results suggest that the solar heat penetration through the vacuum PV glazing can be maintained at a very low level. Therefore, the fluctuation of indoor temperature is much more stable compared with the building envelope using other fenestration products when the solar irradiation changes dramatically.

Fig. 8 presents the temperature profile of the test rig mounted with vacuum PV glazing and other conventional window samples. The air temperature inside the test rig is closely related to the U-value and SHGC of each glazing samples. The solar energy penetration through the glazing area and part of the solar energy absorbed and re-emitted by the window samples are the main contributions of the increase of the inside air temperature of the test rig. In the solar simulation test, the highest inside air temperature of the test rig with vacuum glazing, double-pane glass and double PV glazing reached 63.1 °C, 58 °C and 50.9°C, respectively. After the same period of time, the indoor temperature of the test rig which mounts on vacuum PV glazing was only 39.8 °C under the same steady solar radiation. In this respect, it can be concluded that the vacuum PV glazing has the best thermal insulation performance and can achieve more comfortable indoor air temperature.

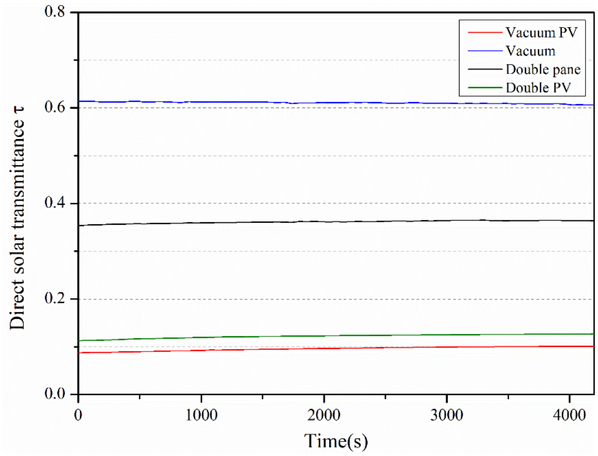


Fig. 7 The direct solar transmittance of different types of glazing

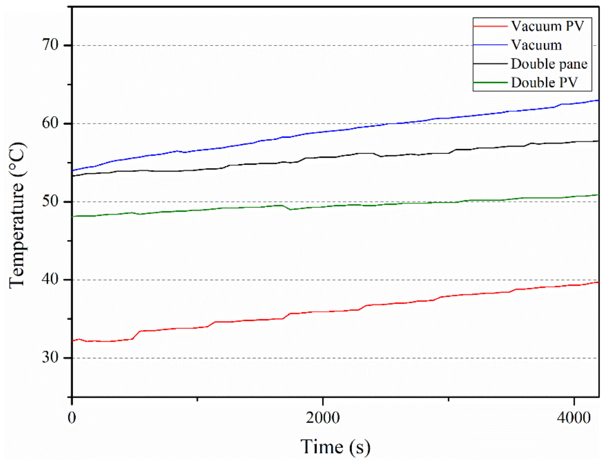


Fig. 8 Air temperature inside the test rig mounted with different types of glazing

The outdoor test lasted four days from September 26 to September 30. As shown in Fig. 9, September 26, 27 and 30 are cloudy days and September 28 can be considered as a sunny day. It can be found that the vacuum PV glazing blocked most of the solar irradiation while the double-pane glass allowed much more solar energy through the glazing area. From Fig. 10, it can be observed that the heat flux value of the vacuum PV glazing was much smaller than that of double-pane glass due to the better thermal insulation performance of vacuum PV glazing and less temperature difference between the outside and inside surface of vacuum PV glazing.

Fig. 11 presents the temperature profile of vacuum glazing and double-pane glass in the sunny day. The internal surface temperature of both vacuum PV glazing and double-pane glass is much higher than ambient temperature when the outside incident solar radiation is high. The internal surface temperature and the indoor temperature of test rig which mounts on vacuum glazing is lower than that of test rig with double-pane glass. The temperature difference between the indoor air temperature of test rig of two glazing system is much lower than the difference of internal surface temperature. Therefore, the application of vacuum PV glazing can achieve better indoor environment by reducing the heat gain from outside environment.

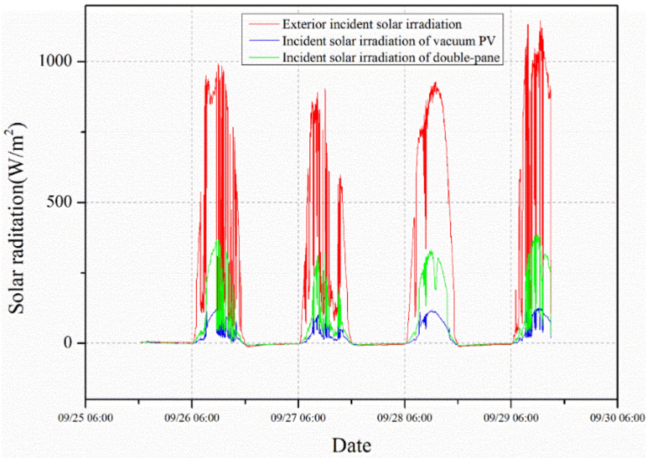


Fig. 9 The incident solar radiation of the vacuum PV glazing and double-pane glass

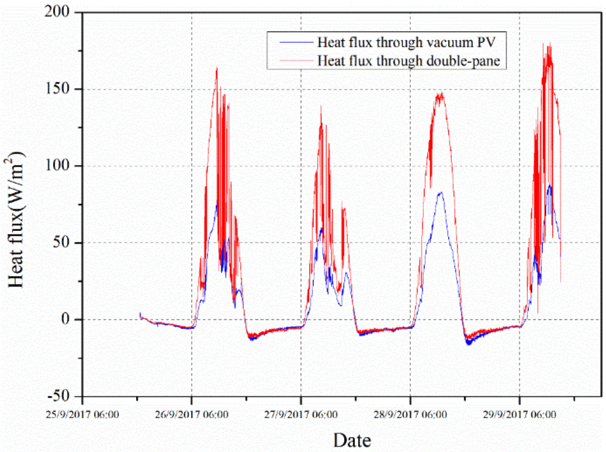


Fig. 10 The heat flux through the vacuum PV glazing and double-pane glass

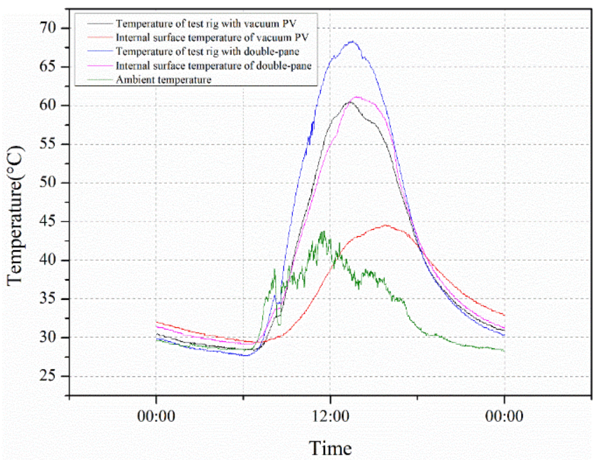


Fig. 11 The sunny day temperature profile of the vacuum PV glazing and double-pane glass

## 5.2 Simulation results

### 5.2.1 Thermal performance

To compare the thermal performance of different types of glazing system, Fig. 12 shows the annual electricity consumption used for cooling in different orientations in Hong Kong. It was found that the office using VPV IGU has the best thermal performance for all orientations. This is because the VPV IGU has much lower U-value and SHGC than the contrastive windows, as shown in Table 2. A lower U-value is the key index to achieve better heat insulation performance, and a lower SHGC indicates that less solar radiation will pass through the fenestration area. Consequently, the cooling load was reduced for the room installed VPV IGU so that the electricity consumption on cooling was reduced significantly. For instance, the south facing room with VPV IGU consumes about 705.6 kWh per year, which was approximately 14.2%. 9.0%, 10.2%, 7.6% and 5.2% less than the corresponding room with single-pane clear glazing, double-pane clear glazing, single-pane PV glazing, double-pane PV glazing and vacuum glazing, respectively. On the account of different orientations, the most cooling consumption of the office room occurs at the west orientation, followed by east, south and north. The energy saving of the west-oriented vacuum PV glazing was 25.4%, 16.5%, 14.0%, 20.1% and 14.9% compared with the cooling consumption of the room with single-pane clear glazing, double-pane clear glazing, single-pane PV glazing, double-pane PV glazing and vacuum glazing, respectively. Therefore, windows of east and west facades should have better thermal insulation performance and less solar radiation heat gain as energy saving purpose required.

Based on the characteristic of vacuum glazing with low-E coating, the VPV IGU will present the optimum performance in the area where has a big temperature difference between indoor and outdoor and high level of solar radiation intensity. As a result, the combination of vacuum glazing and semi-transparent PV modules can make the most of the thermal performance of vacuum glazing technology since the backside of solar cell has much higher temperature than ambient temperature.

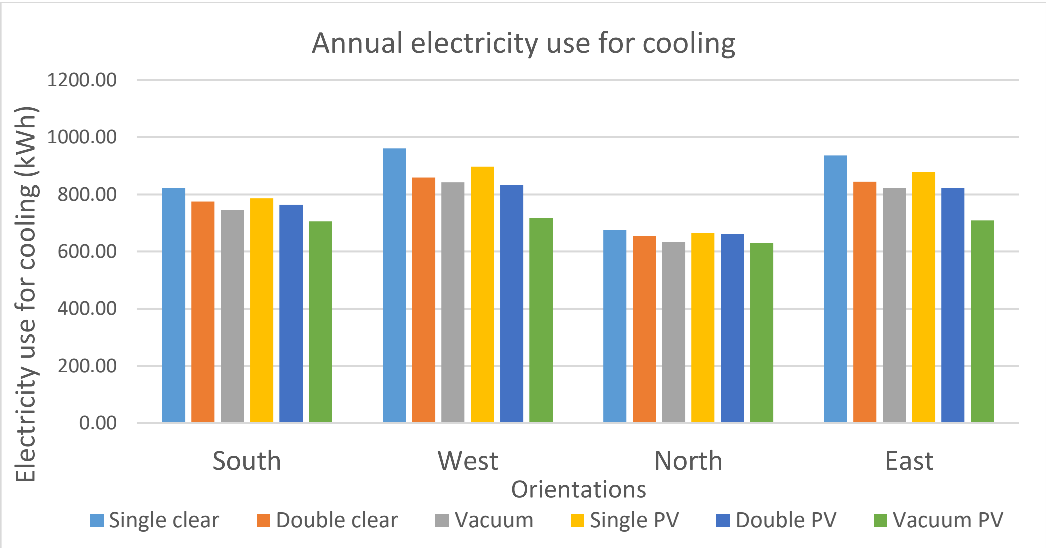


Figure 12: The annual electricity use for cooling of different types of glazing

### 5.2.2 Power generation performance

In order to utilize the solar energy and reduce the cooling load at the same time, the PV glazing was applied to generate electricity in situ. As shown in Fig. 13, the monthly electricity generation of different BIPV systems on the south façade was in agreement with the incident solar radiation. The difference of the power generation among different BIPV systems is less than 1%, and the single-pane PV glazing produced the most electricity output. For the case of VPV IGU, the simulated monthly output energy ranges from 2.10 kWh in June to 22.17 kWh in December. The highest energy generated in December is mainly due to the highest solar radiation received and high conversion efficiency of solar cells as a result of low ambient temperature. In contrast, the lowest solar radiation and high outdoor temperature in June contribute the lowest energy output.

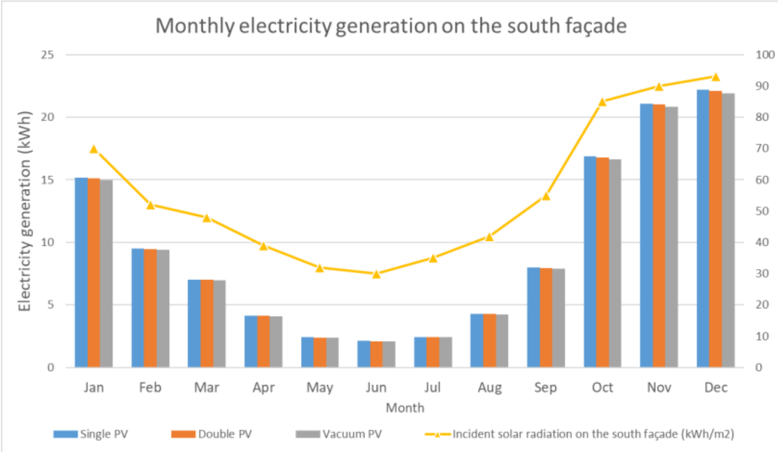


Figure 13: The monthly electricity generation of BIPV systems and incident solar radiation on the south façade

The annual electricity generation of three types of PV glazing are shown in Fig. 14. It can be observed that the annual electricity generation of three types of PV glazing is similar to each other. The electricity generation from VPV IGU was only 0.4% - 1% less than that from the single-pane PV glazing due to the higher cell temperature related to the better thermal insulation of vacuum glazing. Because of the relatively small value of the temperature coefficient of thin-film a-Si solar cells, the PV conversion efficiency is not compromised. The south-oriented semi-transparent a-Si PV glazing with 20% transmittance produced the most electricity annually among all orientations, at around 113.8 kWh per year. Thus, it is recommended to install PV glazing on the south and west façade in order to maximize the productivity of PV glazing in Hong Kong. In contrast, the north façade is considered unsuitable for PV installation in terms of power generation.

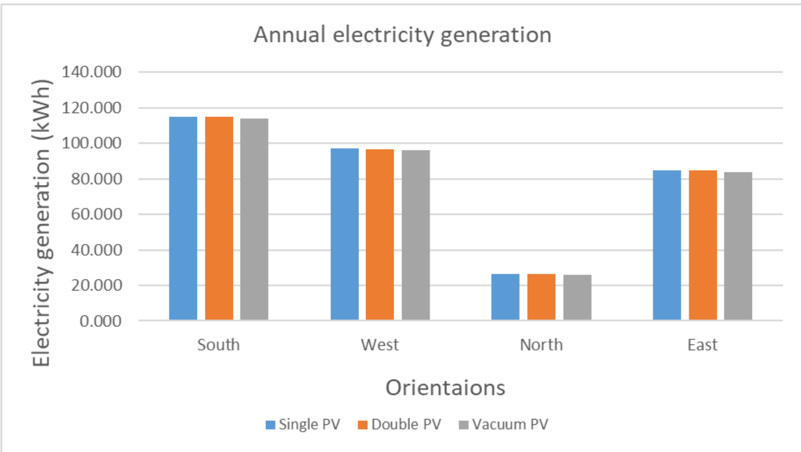


Figure 14: The annual electricity generation of BIPV systems

## 6. Conclusion

The proposed BIPV system integrated with vacuum glazing not only has the best thermal performance among all types of widely used fenestration products but also can produce a considerable amount of electricity. In this study, the thermal insulation performance and the overall energy performance of the vacuum PV glazing were investigated by experimental work and simulation work. The laboratory tests and outdoor test indicated that the VPV IGU has the best thermal insulation performance compared with other common windows due to its lowest U-value and direct solar transmittance. The simulation study for the comparison of the overall energy performance of the vacuum PV glazing and other commonly used glazing products was carried out by using two types of professional software, EnergyPlus and Berkeley Lab WINDOW. The VPV IGU combines the advantage of low SHGC of semi-transparent solar cells and low U-value of vacuum glazing. It can be found that the west facing façade installed with the vacuum PV glazing can reduce cooling electricity by at most 25.4% and 16.5% compared with the same oriented room with single-pane windows and double-pane windows. Therefore, it is better to install the vacuum PV glazing on the west, east and south façades to achieve better building energy efficiency. In Hong Kong, the south-oriented vacuum PV glazing produces the most electricity output in December. It is recommended to install the VPV IGU on the south-oriented façade in order to perform the best overall energy performance.

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