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Investigation on the overall energy performance of a novel vacuum semi-transparent photovoltaic glazing in cold regions of China

Changyu Qiu
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China
cy.qiu@connect.polyu.hk

Hongxing Yang*
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China
hong-xing.yang@polyu.edu.hk

Abstract— In recent years, as a multifunctional application of photovoltaic technologies, building-integrated photovoltaic (BIPV) glazing is used to generate power while natural lighting is provided as part of building façade. Unlike those PV windows made by crystalline silicon solar cells, the semi-transparent cadmium telluride (CdTe) photovoltaic (STPV) windows can admit natural daylight with a certain degree of transmittance without any shading. Therefore, it can provide better visual comfort to occupants. Adopting STPV windows will also affect the overall building energy consumption due to the low solar heat gain coefficient (SHGC). The thermal feature of common STPV windows can be beneficial for reducing the cooling load in the summer. However, when adopting the STPV windows in the heating-dominated regions, it will increase the heating load as most of the solar heat gain will be blocked by the solar cells in the PV windows. To improve the thermal insulation performance of STPV glazing, a novel vacuum photovoltaic insulated glass unit (VPV IGU) is proposed. This paper investigated the overall energy performance of a typical office in Harbin mounted with the innovative vacuum PV glazing systems. Two different configurations of the vacuum PV glazing were compared by the simulation work conducted by EnergyPlus. The results show that the first configuration, which the vacuum glazing is the internal layer, has better thermal performance from April to October, while the second configuration, the one with the vacuum glazing as an external layer, has superior thermal performance in winter as solar heat gain through PV glazing can contribute to indoor heating. The combination of STPV glazing and vacuum glazing may provide a significant energy saving potential in cold regions of China.

Keywords— semi-transparent photovoltaic (STPV) glazing, vacuum glazing, overall energy performance

I. Introduction

Building-integrated photovoltaics (BIPV) technology provides a promising approach to achieve net-zero energy buildings, especially in the urban areas. With the rapid development of photovoltaic materials, the application of Building-integrated photovoltaics (BIPV) glazing has been developed from the silicon-based PV glazing to the thin-film PV glazing which can generate renewable energy in situ and admit a certain level of daylighting [1]. Unlike the silicon-based PV glazing, semi-transparent photovoltaic windows which integrated with thin-film solar cells can achieve a uniform appearance and provide the daylighting into the indoor environment without casting any shadow inside the room [2]. In term of the thermal performance of fenestration products, STPV window has a superior advantage in the cooling dominant regions because of its low solar heat gain coefficient [3]. In order to enhance the thermal performance of the STPV windows, the combination of the PV glazing and the vacuum glazing with four-layer structure is proposed [4, 5]. The simulation results suggested that the vacuum PV glazing combines the advantage of low SHGC of PV glazing and low U-value of vacuum glazing to reduce the cooling consumption in Hong Kong. However, the thermal insulation performance of the conventional STPV windows limits its application in the heating-dominated regions [6]. As one of the best thermal insulation glazing, the combination of the vacuum glazing and PV glazing may enhance the adaptability of the STPV windows when applying this kind of BIPV technology in the cold regions. Therefore, this study proposes a novel three-layer vacuum PV glazing with two different configurations and conducted an investigation on the overall performance of the combination of the vacuum glazing and the PV glazing by different approaches.

II. Methodology

A. *Structure of the three-layer vacuum PV glazing*

A typical CdTe-based PV glazing consists of a stack of thin photovoltaic absorbing layers laminated between a glass coated with transparent conducting oxide (TCO) and another glass sheet as the covering plate. The proposed vacuum PV glazing combines the CdTe PV glazing with superstrate configuration and the vacuum glazing by replacing the backplate with the vacuum glazing. Fig.1 illustrates the cross-section of the purposed vacuum PV glazing with three-layer structure. With the superstrate configuration, the active absorbing layers are deposited on a glass superstrate with TCO coating and the vacuum PV glazing then is laminated on the back. As shown in Fig. 2, another alternative configuration of the vacuum PV glazing is so-called the reversed vacuum PV glazing which is manufactured based on the CdTe PV glazing with substrate structure. In both configurations, the vacuum glazing comprises a narrow vacuum gap with only 0.1 mm width between two glass sheets. The vacuum space can eliminate the heat conduction and heat convection and the low-e coating, which is deployed on the inner surface of the vacuum glazing towards outside reduce the radiative heat transfer to an extremely low level. Therefore, the thermal insulation performance of the vacuum PV glazing can be enhanced for severe cold climatic regions like Harbin.

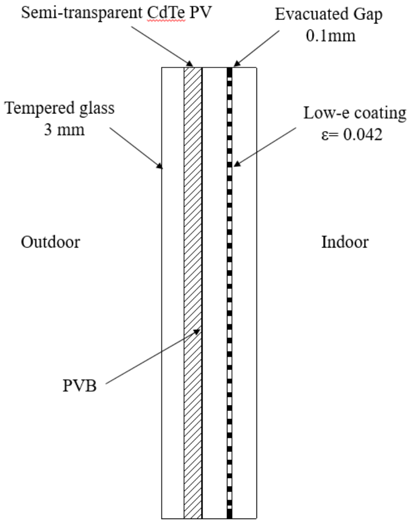

Fig. 1. The cross-section of the vacuum PV glazing

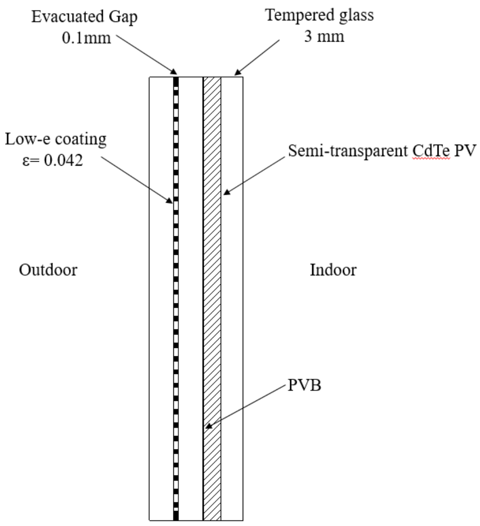

Fig. 2. The cross-section of the reversed vacuum PV glazing

In this study, a small scale sample of the proposed vacuum PV glazing was made by a solar PV manufacturer named ASP in Hangzhou, China. A vacuum glazing as the inner layer is used as the backside panel of the CdTe PV glazing. The size of the sample is 300 mm * 300 mm. As can be seen from Fig. 3, the semi-transparent effect of the PV glazing provides a certain degree of daylighting without blocking the outdoor view. From the lateral view of the vacuum PV glazing as shown in Fig. 4, it can be seen that the vacuum PV glazing consists of three glass panes which one of the glasses is the TCO glass with the CdTe solar cells and the other two glass panes compose the vacuum glazing.

Fig. 3. The front view of the vacuum PV glazing

Fig. 4. The lateral view of the vacuum PV glazing

The electrical characteristics of the vacuum PV glazing under standard test condition are provided by the manufacturer as listed in Table I.

TABLE I. ELECTRICAL CHARECTERISTICS OF THE VACUUM PV GLAZING

Parameters	**Values**
Maximum power output (W)	48
Voltage at the maximum power point (V)	87
Current at the maximum power point (A)	0.55
Open circuit voltage (V)	116
Short circuit current (A)	0.59
Fill factor	0.70
Module efficiency	6.7%

The optical characteristics of the sample of the vacuum PV glazing were obtained by the measurement. A Hitachi UV-VIS-NIR spectrophotometer was used to determine the spectral transmittance, reflectance, and absorption of the vacuum PV glazing within the solar spectrum from 300 nm to 2500 nm. From Fig. 5. It can be seen the average solar transmittance (T), reflectance (R) and absorption (A) for vacuum PV glazing were 6.0%, 14.3%, and 79.6%, respectively. The visible transmittance was around 18.3%. In the visible range, the highest transmittance was around 600 nm.

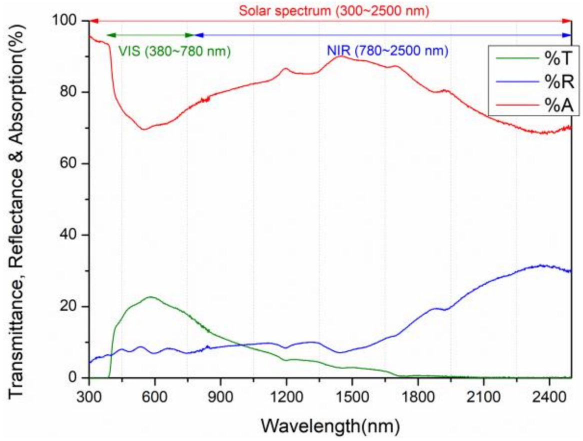

Fig. 5. The cross-section of the reversed vacuum PV glazing

B. *Weather condtions of Harbin*

In terms of weather conditions, there are five different climatic regions in China, namely, severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and moderate zone. Harbin has been selected to represent the severe cold zone which locates at 45.7° N latitude and 126.7° E longitude. The summer average temperature is 21.5 ℃ and the winter average temperature is -16.5 ℃ in Harbin. In this study, the building energy simulations were conducted based on hourly time-steps of a whole year weather data from the World Meteorological Organization (WMO).

C. *Development of the simulation model*

In order to investigate the overall energy performance of the vacuum PV glazing, EnergyPlus [7] was used in this study to simulate the building energy performance including the cooling consumption, the heating consumption, the lighting consumption and the power generation by PV solar cells. Firstly, as shown in Fig.6, a 3D model which represents a typical small office was built up with the dimension of 2.3 m wide, 2.5 deep and 2.5 m high. The only external wall is mounted with a window as the window to wall ratio (WWR) is 65%. The ceiling, the floor, and the other walls are considered as interior surfaces.

Secondly, in the aspect of window types used in the simulation, the conventional double-pane window with low-e coating, the vacuum glazing, double PV glazing were selected for comparison purpose. According to the national standard of China, “Design standard for energy efficiency of public buildings” (GB 50189-2015) [8], the conventional double-pane windows were chosen be two 5.7 mm low-e glass panes with 7 mm air gap to satisfy the standard requirement about U-value. The double PV glazing was adopted the same CdTe-based PV glazing as the vacuum PV glazing and the same configuration as the double-pane window. The vacuum glazing is identical to those used in manufacturing the vacuum PV glazing and the reversed vacuum PV glazing. The Berkley Lab WINDOW [9] was used to determine the thermal and optical properties of different glazing systems. It can create the glazing system layer by layer and generate a physical characteristics file of the glazing as an input file that can be imported to EnergyPlus. The measured optical properties of the vacuum PV glazing were introduced into the Berkley Lab WINDOW for the calculation of U-value and solar heat gain coefficient (SHGC). The key properties of all glazing systems adopted in the simulations were listed in Table II.

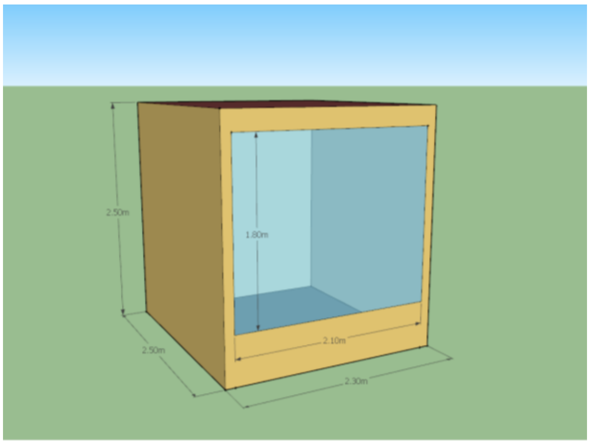

Fig. 6. Geometry of the model as a typical office

TABLE II. KEY PROPERTIES OF DIFFERENT TYPES OF GLAZING

Glazing	Thickness (mm)	Visible transmittance	U-value (W/m2k)	SHGC
Double-pane window	18.4	0.612	1.471	0.348
Vacuum glazing	11.5	0.693	0.648	0.396
Double PV glazing	25.7	0.136	1.717	0.162
Vacuum PV glazing	14.2	0.127	0.647	0.121
Reversed vacuum PV glazing	14.2	0.148	0.648	0.374

After the geometry of the simulation model and the glazing properties were determined, various simulation models were conducted in EnergyPlus. EnergyPlus is a validated and widely used tool for a whole building energy simulation [10]. For cooling and heating in the simulations, the COP of an air conditioning system and the heating of a gas boiler were fixed at 2.78 and 0.8, respectively. Air Heat Balance Module, HVAC Module, and Surface Heat Balance Module were used to determine the cooling and heating consumption. The electricity consumption from artificial lighting was calculated based on the integration of Daylighting Module, Sky Model Module, and Window Glass Module. Equivalent one-diode model was adopted to evaluate the PV power generation performance so that the temperature effect of the solar cells can be taken into considerations. All simulations for different types of glazing systems were carried out in five orientations, viz., east, southeast, south, southwest, and west.

III. RESULTS AND DISCUSSION

In terms of the overall energy consumption, the thermal performance and the power generation performance of the vacuum PV glazing were investigated by comparing the annual energy consumption and power generation of two kinds of vacuum PV glazing with which of other alternatives. The conventional double glazing was used to be the baseline as it is the most common fenestration product in severe cold regions. As part of the vacuum PV glazing components, the PV glazing which has a relatively low SHGC and the vacuum glazing which has a very low U-value would affect the thermal behavior through different approaches. The double PV glazing and the vacuum glazing were used to indicate the thermal performance of the two components of the vacuum PV glazing respectively. The power generation performance of double PV glazing was used to indicate the effect of utilizing the vacuum glazing on the PV power generation.

A. *Thermal Performance*

Fig. 7 presents the annual cooling consumption and heating consumption of the simulation model adopted different glazing systems when facing different orientations. In terms of heating consumption, the vacuum PV glazing has the best performance by saving 34% - 47% cooling energy compared with the double-pane window in different orientations. The double PV glazing is also beneficial for the cooling seasons by providing the energy saving potential of 29% - 36%. However, the vacuum glazing and the reversed vacuum PV glazing perform the adverse effects in summer since the cooling consumption of the vacuum glazing and the reversed vacuum PV glazing would increase 6% - 18 % and 11% - 17%, respectively.

For the heat consumption in Harbin, it can be found that the utilization of the vacuum glazing can reduce the heating consumption dramatically. Meanwhile, the use of the PV glazing may have a certain negative impact on the heating consumption. The heating consumption of the double PV glazing is 27%, 40%, 50%, 42% and 27% more compared with the conventional double-pane window of the room facing east, southeast, south, southwest, and west, respectively. The reversed vacuum PV glazing can achieve 51% - 59% energy saving in terms of heating consumption while the vacuum PV glazing can save 13% - 27% energy consumption for heating.

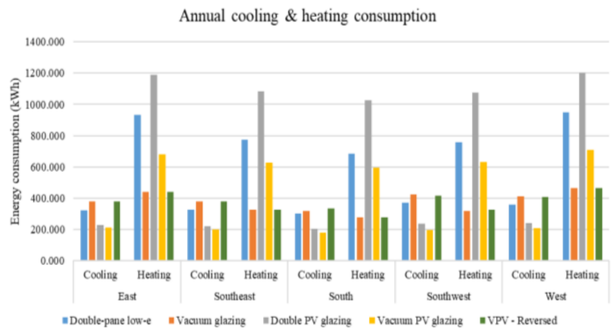

Fig. 7. Annual cooling and heating consumption

The different configurations of the vacuum PV glazing have different thermal behavior. Fig. 8 presents the monthly consumption for cooling and heating of the vacuum PV glazing and the reversed vacuum PV glazing in Harbin when facing southwest. It can be observed that the vacuum PV glazing consumes less energy in the cooling seasons from April to October. From November to March, the reversed vacuum PV glazing can save more energy than the vacuum PV glazing. It is mainly due to the difference between the structures of the vacuum PV glazing and the reversed vacuum PV glazing. When adopting the vacuum glazing in the cooling season, the excellent thermal insulation performance may become the drawback when there is free cooling occurs during the night time. Because of the low SHGC of the PV glazing as part of the vacuum PV glazing, the solar heat gain can be reduced when the sun is up in cooling seasons. Meanwhile, the vacuum glazing as the inner layer the vacuum PV glazing can contribute to reducing the cooling consumption because the waste heat from the absorbed solar energy can be blocked by the vacuum glazing. On the contrary, when the vacuum glazing is the external layer of the reversed vacuum PV glazing, the part of solar energy which is not used to generate electricity will transfer to indoor directly, so that the solar heat gain will increase. However, in the heating season, the solar heat gain can contribute to reducing the heating load. Therefore, the structure of the reverse vacuum PV glazing is beneficial for the heating. Additionally, the excellent thermal insulation is crucial for fenestration products in winter, especially in those severe cold regions. Hence, both types of vacuum PV glazing have the best thermal performance in the respect of the weather conditions in Harbin.

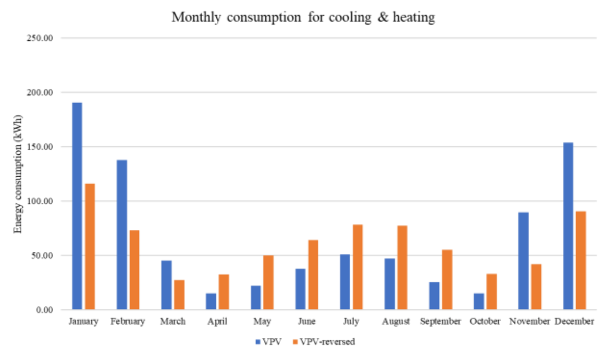

Fig. 8. Monthly consumption for cooling and heating of two configurations of the vacuum PV glazings

B. *Overall energy performance*

From the simulation results of the overall energy performance as shown in Fig. 9, it can be seen that, in general, the heating energy is much higher than the cooling energy for most of the cases, especially when the office is mounted with the double-pane low-e window or the double PV glazing. The average power generation of the vacuum PV glazing is 202 kWh per year. The power generation of the vacuum PV glazing and the reversed vacuum PV glazing is 14% - 16% less than which of the double PV glazing. The thermal insulation of the vacuum glazing may increase the temperature of the solar cells so that the power generation efficiency will be compromised. With regards to the overall energy performance, the annual energy saving potential of the vacuum glazing, the vacuum PV glazing, and the reversed vacuum PV glazing is 31% - 36%, 32% - 43%, and 37 – 54%, respectively. Although the reversed vacuum PV glazing may increase the cooling consumption, the results indicate that the reserved vacuum PV glazing can be considered as the best fenestration product regarding the overall energy performance. The main reason is that the heating takes the majority of the overall energy consumption. And the reversed vacuum PV glazing can reduce the heating consumption due to the thermal insulation of the vacuum glazing and utilize the solar heat gain absorbed the PV glazing to be part of the solar heating.

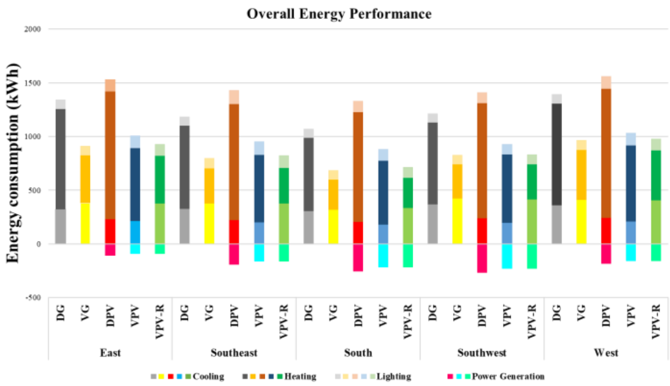

Fig. 9. Overall energy performance of different glazings

IV. CONCLUSIONS

This study proposed a novel vacuum PV glazing with two different configurations. An investigation on the overall energy performance of these two kinds of vacuum PV glazing in the severe cold regions in China was conducted by the simulation works. The results indicate that the vacuum PV glazing has the best performance in cooling seasons while the reversed vacuum PV glazing has the best performance in heating seasons. The application of vacuum glazing will increase the cooling consumption and the application of PV glazing will increase the heating consumption and lighting consumption. In terms of the overall energy performance, the vacuum PV glazing and the reversed vacuum PV glazing can provide the energy saving potential of 32%~43%, and 37%~54%, respectively. In the severe cold regions of China，the proposed BIPV system integrated with vacuum glazing not only has the best thermal performance but also can produce a considerable amount of electricity.

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