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Investigation on the thermal performance of a novel vacuum PV glazing in different climates

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Abstract

With the rapid development of photovoltaic technologies, building-integrated photovoltaic (BIPV) windows could be used to replace traditional glazing, especially semi-transparent amorphous silicon (a-Si) photovoltaic (STPV) windows which can generate electricity in situ and admit daylight into the indoor environment. The utilization of semi-transparent PV modules provides the benefit of low solar heat gain coefficient (SHGC) as a key characteristic of window products. Meanwhile, it also produces a drawback as the remaining solar energy could be converted into heat gain which increases cooling load. Due to the excellent thermal insulation performance of vacuum glazing, the integration of STPV and vacuum glazing provides the potential to achieve the best energy-efficient performance by the low solar heat gain of the PV modules and low heat losses of the vacuum glazing. However, the determination of a suitable glazing of a building in different locations must consider the climate background. In this paper, the thermal performance of the proposed vacuum photovoltaic insulated glass unit (VPV IGU) in different climate zones has been investigated. The simulation work has shown that the vacuum PV glazing can provide a significant energy saving potential in Harbin, Beijing, Wuhan and Hong Kong, which represent the severe cold, cold, hot summer and cold winter, and hot summer and warm winter regions, respectively. However, it is not suitable for the moderate climatic region like Kunming. The results have indicated the advantages of utilizing the vacuum PV glazing in different climates as well as its limitations.

Keywords: Building integrated photovoltaic (BIPV); Vacuum glazing; Thermal performance

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1. Introduction

At the current phase of urbanization in China, developing energy-efficient and environmentally friendly buildings is becoming a requisite design criterion to deal with the energy shortage problem. As one of innovative window technologies, semi-transparent photovoltaic (STPV) windows can generate renewable energy in situ and admit a certain level of daylighting [1]. STPV window is also an implementation of solar controlling which is important for the window glazing selection in the cooling dominant regions [2]. However, the solar cell only converts a small proportion of solar energy into electricity and the remaining energy will transfer to indoor as undesired waste heat in the cooling season [3]. Besides solar controlled glazing, vacuum glazing is one of the best thermal insulation glazing, which consists an evacuated gap between two glass sheets [4]. The reported best commercial product of vacuum glazing has the overall heat transfer coefficient (U-value) of 0.86 W/m^2K [5].

Generally, solar controlled glazing with low solar heat gain coefficient (SHGC) is more suitable for the cooling dominated region and thermal insulating glazing with low U-value is more suitable for the heating dominated region. In order to enhance the thermal performance of the weakest link of a building envelope, a novel vacuum PV insulated glass unit is proposed to combine two advanced glazing technologies. This paper conducted an investigation on the thermal performance of the proposed vacuum PV glazing under different climate conditions.

2. Methodology

2.1. Structure of vacuum PV glazing

Fig. 1. shows the cross section of the structure of the vacuum PV glazing. The outside layer is a laminated semi-transparent a-Si PV module within two glass sheets with the transmittance of 20% and the inside layer is the vacuum glazing with low-e coating. A layer of polyvinyl butyral (PVB) was used as adhesive to combine the semi-transparent PV glazing and vacuum glazing into an integrated glass unit. The evacuated gap of vacuum glazing is only 0.1 mm wide, which is much smaller than the air gap of the conventional double-pane window. Nevertheless, the vacuum space can minimize the heat conduction and heat convection between the outside and inside glass, which contributes to better thermal insulation performance. In order to reduce the heat radiation through the vacuum glazing, a low-e coating with the emissivity of 0.042 was adopted on the inner surface towards outside. As shown in Table 1, the electrical characteristics had been obtained by experiment under standard condition test [6], namely 1.5 of air mass, 1000W/m^2 of solar irradiation and 25 ℃ of cell temperature.

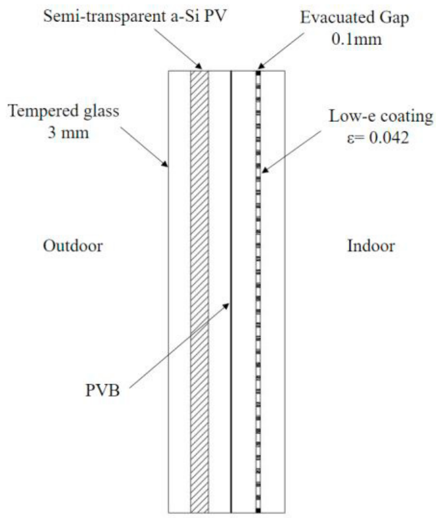

Fig. 1. Structure of the vacuum PV glazing

Table 1. Key electrical characteristic of the vacuum PV glazing under STC.

Parameters	Value
Maximum 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
Module efficiency	5.2%
Fill factor	0.62

2.2. Simulation model

The simulation model is based on EnergyPlus [7] which can model building energy performance and Berkley Lab WINDOW [8] which are used to calculate the thermal and optical properties of varies glazing systems. At the first stage of simulation, the measured optical and electrical characteristics of the vacuum PV glazing were introduced into the Berkley Lab WINDOW for the calculation of thermal properties. A input file which can be recognized by EnergyPlus was created by the former software. At the second stage, a simplified small office room with the dimension of 2.3 m × 2.5 m × 2.5 m (L×W×H) was built in this simulation to evaluate the adaptability and limitation of the vacuum PV glazing under different climatic background. Only one wall is set as the external wall while other walls, ceiling and floor are considered as internal surfaces. An alternative window is mounted on the external wall with the WWR of 65%. For cooling and heating in this typical office room, the COP of an air conditioning system and the heating of a gas boiler were fixed at 2.78 and 0.8, respectively. Comprehensive heat transfer model, HVAC model and surface heat balance model were adopted to simulate the annual thermal performance. All simulations in different climate regions were conducted in five different orientations, viz., east, southeast, south, southwest and west. For comparison purpose, conventional double-pane windows, vacuum glazing and double PV glazing were selected regarding to different climatic conditions.

The selection of window should comprehensively consider the glazing properties and the climatic profile of different site locations. Five cities, Harbin, Beijing, Wuhan, Hong Kong and Kunming were selected to represent five different climate zones of China, as known as, severe cold, cold, hot summer and cold winter, hot summer and warm winter, and moderate. According to the national standard of China, "Design standard for energy efficiency of public buildings" (GB 50189-2015) [9], the conventional double-pane windows and exterior wall were chosen to satisfy the standard requirement about U-value, as shown in Table 2. The key properties of the vacuum PV glazing and vacuum glazing with low-e coating that were adopted in those five cities are shown in Table 3.

Table 2. The properties of building envelope of representative city of different climate regions.

City	Climatic region	Conventional window	U-value of window (W/m^2*K)	SHGC of window	U-value of exterior wall (W/m^2*K)
Harbin	Severe Cold	6 mm low-e+7 mm air+ 6 mm low-e	1.5	0.35	0.38
Beijing	Cold	6 mm clear+6 mm air+6 mm low-e	1.9	0.45	0.5
Wuhan	Hot summer and cold winter	3 mm clear+3 mm air+3 mm low-e	2.2	0.45	0.6
Hong Kong	Hot summer and warm winter	3 mm clear+1.5 mm air+3 mm low-e	2.5	0.44	0.8
Kunming	Moderate	3 mm clear+1.5 mm air+3 mm low-e	2.5	0.44	0.8

Table 3. The key thermal properties of the vacuum glazing and vacuum PV glazing.

Glazing Type	Thickness (mm)	Visible Transmittance	U-value (W/m^2*K)	SHGC

Vacuum glazing (low-e)	11.5	0.693	0.648	0.391
Vacuum PV glazing	20.8	0.120	0.557	0.143

3. Results and discussion

The objective of this paper is to evaluate the energy saving potential of the vacuum PV glazing in different climate regions. The annual cooling and heating consumption of conventional windows is set as the baseline for comparison purpose. The double PV windows with the same air gap and inside low-e glass of double-pane windows under different climate conditions were used to indicate how relatively low solar heat gain of PV glazing would affect on the thermal performance. An identical vacuum PV glazing was used in all simulation models to investigate the applicability of this novel glazing system, which combines the best thermal resistance glazing and solar controlling glazing in an integral glass unit.

Fig. 2~6 presents simulation results of the thermal performance of different windows in different climates. Since Harbin is a typical city in the severe cold region, the heating consumption is much higher than the cooling consumption. As shown in Fig. 2, the vacuum glazing can save 58% heating energy in the southeast-oriented room while the vacuum PV glazing can save 30% heating energy compared with the double-pane window. It is worth noting that the double PV window requires the most heating consumption. It is mainly due to the low SHGC of the double PV window, which blocks the solar heat transfer into indoor in winter daytime. The same interpretation could explain why the vacuum glazing has the better thermal performance than the vacuum PV glazing regarding heating demand. On the other hand, the almost same U-value of the double PV window as that of double-pane window is responsible for a large amount of heat loss in the heating season. Therefore, the double PV window consumes 27%, 40%, 50%, 42% and 27% more heating energy compared with the conventional double-pane window of the room facing east, southeast, south, southwest and west, respectively. For the cooling consumption in Harbin, the energy saving of vacuum PV glazing is 27%~41% compared with the baseline in different orientations while the best thermal performance occurs in the southwest room.

From the simulation results of Beijing, Wuhan and Hong Kong shown in Fig. 3~5, it is seen that the cooling consumption of the vacuum PV glazing and double PV window are smaller than that of the double-pane window and vacuum glazing. Moreover, the heating consumption of the vacuum PV glazing and vacuum glazing are much smaller than that of the double-pane window and the double PV window. It can be observed that the utilization of vacuum glazing can reduce a large amount of heating energy in the regions that have a cold winter, such as Harbin, Beijing and Wuhan and the utilization of PV glazing can reduce the cooling energy in the regions that have a hot summer, such as Wuhan and Hong Kong. In the southwest room of Beijing, Wuhan and Hong Kong, the vacuum PV glazing can save the cooling energy by 45%, 33% and 27%, respectively. The vacuum glazing can also reduce the heating consumption by 42% and 74% in the southwest room in Beijing and Wuhan. However, the use of vacuum glazing and vacuum PV glazing in Kunming will increase the cooling consumption compared with the double-pane glazing and double PV glazing as shown in Fig. 6. Therefore, the double PV window is the best thermal performance product for moderate climatic zones.

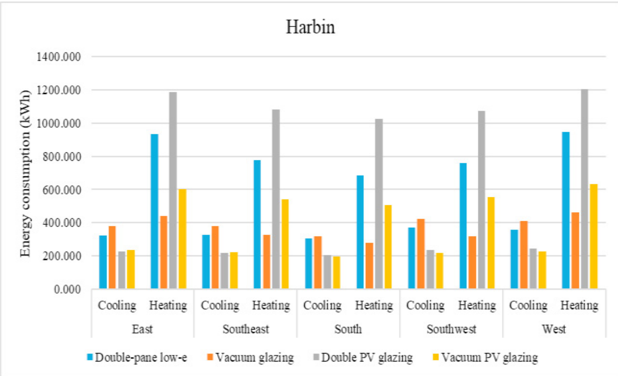

Fig. 2. Annual consumption of cooling and heating in Harbin

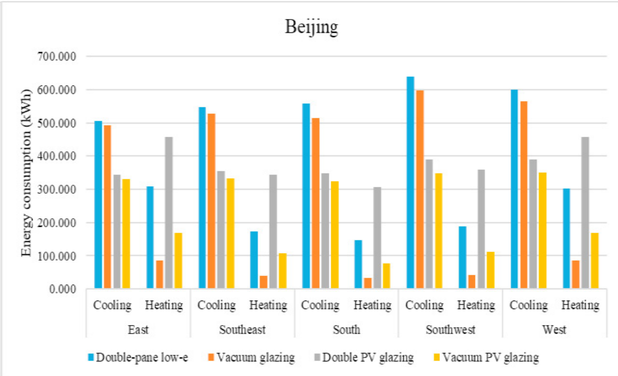

Fig. 3. Annual consumption of cooling and heating in Beijing

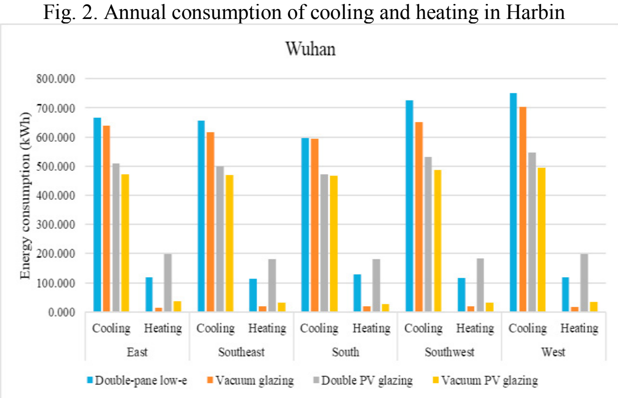

Fig. 4. Annual consumption of cooling and heating in Wuhan

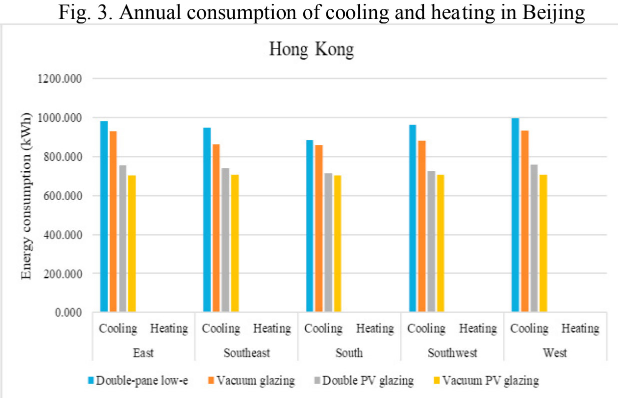

Fig. 5. Annual consumption of cooling and heating in Hong Kong

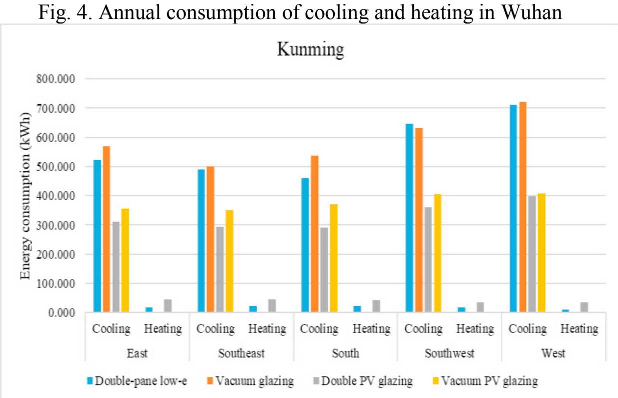

Fig. 6. Annual consumption of cooling and heating in Kunming

4. Conclusions

In this study, an investigation on the energy performance of the proposed semi-transparent PV glazing integrated with vacuum glazing under different climate zones was conducted. The results indicate that the vacuum PV glazing is an excellent fenestration product, which not only has high thermal resistance, but also can control solar heat gain by PV cells. In severe cold, cold, and hot summer/cold winter regions, the vacuum PV glazing can provide a large energy saving potential for space heating due to the best heat insulation performance. In hot summer/cold winter and hot summer/warm winter regions, the vacuum PV glazing can achieve the best thermal performance in cooling seasons and generate power by the PV modules. However, the utilization of vacuum glazing is not suitable for those cities in the moderated region, such as Kunming.

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