Numerical evaluation and sensitivity analysis on dynamic heat transfer of a novel CdTe-base vacuum PV glazing

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Abstract— Building-integrated photovoltaic (BIPV) technology plays an important role on the path to carbon neutral society. The CdTe-based vacuum PV glazing is proposed to improve the thermal performance of the PV glazing. Therefore, the goals of renewable energy production and energy-efficient building can be achieved at the same time. To fully understand the dynamic heat transfer process and thermal behaviour, this study conducted a comprehensive numerical evaluation based on a mathematic heat transfer model for the CdTe-based vacuum PV glazing. It was found the average dynamic solar heat gain coefficient (SHGC) of the CdTe-based vacuum PV glazing is 0.147 and will increase with the increment of incident solar radiation. The dynamic overall heat transfer coefficient (U-value) varies from 0.451 to 0.467 W/m^{2}K under summer conditions which are higher than which under winter conditions. The solar radiation dominates the total heat transfer compared with the temperature difference in the daytime. The solar radiation and ambient temperature have a negative effect on the PV efficiency and a distinctly positive effect on the outside surface temperature. However, the inside surface temperature is much more stable. A sensitivity analysis was also conducted to investigate the thermal response of the vacuum PV glazing with different design parameters and various environmental conditions. The emissivity of low-e coating is the most effective design parameter. The results indicate that the vacuum PV glazing can perform an excellent thermal insulation performance and contribute to the optimization of the design parameters in future studies.

Keywords— semi-transparent photovoltaic window, vacuum glazing, dynamic heat transfer, numerical evaluation, sensitivity analysis

I. Introduction

In the past decades, building-integrated photovoltaic (BIPV) windows drew attention to both building industry and academic [1]. As a multifunctional application of photovoltaic technologies, it can generate renewable energy in situ and play the role of typical windows [2, 3]. 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 [4]. Therefore, it can provide better visual comfort to occupants. However, typical BIPV windows are not suitable for the cold region due to the inferior thermal insulation [5]. To improve the thermal performance of the BIPV glazing, a novel CdTe-based vacuum PV glazing (VPV) is developed with a highly integrate three-layer structure [6]. The previous studies [7, 8] indicated that the vacuum PV glazing not only has an excellent thermal performance but also can provide better visual comfort than common windows. However, the comprehensive thermal response of the vacuum PV glazing under different environmental conditions should be studied for in-depth understanding of the heat transfer mechanism. Moreover, the impact of the design parameters of this innovative technologies still needs further investigation. In this study, the numerical evaluation and sensitivity analysis are conducted based on a dynamic heat transfer model of the vacuum PV glazing.

II. Methodology

A. *Structure of the CdTe-based vacuum PV glazing*

The novel CdTe-based vacuum PV glazing has a three-layer structure, which a lighter and thinner than the first prototype as the four-layer a-Si-based vacuum PV glazing [9]. The CdTe-based vacuum PV glazing is constructed based on the superstrate configuration of thin-film PV glazing, where the single glass backplate is replaced by the vacuum glazing, as shown in Fig. 1. The 0.1 mm wide vacuum gap of the vacuum glazing can reduce the heat conduction and convection to a negligible level. The low-e coating deposited on the inner surface of the vacuum glazing helps to prevent the incoming heat radiation. Regarding to the unique feature of the vacuum PV glazing, it is expected to provide an outstanding thermal performance. Fig. 2 shows the front view of a sample of the CdTe-based vacuum PV glazing, which demonstrates the semi-transparent effect. In the previous study [7], it was found that the vacuum PV glazing has a superior daylighting performance compared with the vacuum glazing.

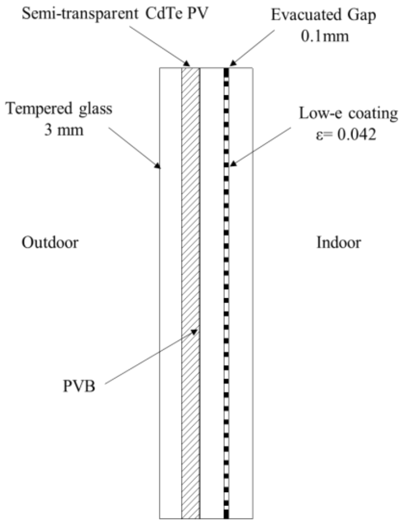


Fig. 1. The structure of the CdTe-based vacuum PV glazing

Fig. 2. The picture of the CdTe-based vacuum PV glazing

B. *Dynamic Heat transfer model*

To investigate the dynamic heat transfer behaviour of the CdTe-based vacuum PV glazing, a mathematic model was developed. This model integrates transient conductive heat transfer through the VPV, and radiative and convective heat transfer between the exterior/interior surface and outdoor/indoor environment. The power generation of the solar cells is also taken into account when the PV module is active. The governing equations for the dynamic heat transfer through the vacuum PV glazing are established as follows,

$$\rho C_p \frac{\partial T(x,t)}{\partial t} = \lambda \frac{\partial^2 T(x,t)}{\partial x^2} + \frac{dF}{dx} \quad (1)$$

$$\frac{A_{pv}}{A_g}(\alpha_{pv}\tau_{fg}G - \eta_{pv}\tau_{fg}G) = \lambda_{fvg}\frac{\partial T_{fvg}(x,t)}{\partial x} - \lambda_{fg}\frac{\partial T_{fg}(x,t)}{\partial x} \quad (2)$$

$$-\lambda_{fvg}\frac{\partial T_{fvg}(x,t)}{\partial x} = \varepsilon_s \sigma[(T_{fvg}(L_1,t))^4 - (T_{bvg}(L_1,t))^4] \quad (3)$$

$$-\lambda_{bvg}\frac{\partial T_{bvg}(x,t)}{\partial x} = \varepsilon_s \sigma[(T_{bvg}(L_1,t))^4 - (T_{fvg}(L_1,t))^4] \quad (4)$$

where *T(x, t)* is the node temperature of the substance at distance x and time t; λ, ρ and C_p are the thermal conductivity (W/(mK)), the density (kg/m3) and specific heat capacity (J/(kgK)) of the material, respectively; F is the attenuated function of the solar energy in the glass; α, τ and ε are the absorbance, transmittance and emissivity, respectively; η is the efficiency of the PV solar cell; and σ is the Stefan-Boltzmann constant. The subscript, *pv*, *fg*, *fvg* and *bvg* stand for the PV solar cell, the front glass of VPV, the front glass of the vacuum glazing and the back glass of the vacuum glazing, respectively.

The boundary conditions are given by,

$$-\lambda_{fg}\frac{\partial T_{fg}(x,t)}{\partial x} = h_o[T_{fg}(L,t) - T_o] + \varepsilon_{fg}\sigma[(T_{fg}(L,t))^4 - T_o^{\ 4}] \quad (5)$$

$$-\lambda_{bvg}\frac{\partial T_{bvg}(0,t)}{\partial x} = h_i[T_{bvg}(0,t) - T_{in}] + \varepsilon_{bvg}\sigma[(T_{bvg}(0,t))^4 - T_{in}^{\ 4}] \quad (6)$$

where h_o and h_i are the convective heat transfer coefficient of the exterior and interior surface of the VPV; T_o and T_i are the outdoor temperature and indoor temperature, respectively.

The transient heat transfer model of the VPV are solved by the explicit finite difference method (FDM). Based on numerical solutions, the temperature profile across the VPV for given boundary conditions can be determined accordingly. Subsequently, the heat gain or heat loss from the VPV can be calculated after the determination of the inside surface temperature for each time step.

III. RESULTS AND DISCUSSIONS

Based on the transient heat transfer model, the dynamic thermal responses of the vacuum PV glazing can be predicted under the given specific boundary conditions. On the other hand, the design parameters of the vacuum PV glazing, such as PV efficiency, PV coverage and the emissivity of the low-e coating also affect the thermal performance. Therefore, this study quantitatively evaluates the effect of environmental conditions as well as the design parameters of the vacuum PV glazing.

A. *Effect of solar radiation on SHGC*

The solar heat gain coefficient (SHGC) consists of two parts, the directed solar transmitted radiation and the part of absorbed solar radiation transferred to indoors by heat convection and radiation. Therefore, the dynamic SHGC varies with the variation of the incident solar radiation on the glazing.

Fig. 3 shows the effect of solar radiation on SHGC of the vacuum PV glazing. In order to investigate the effect of solar radiation solely, the outdoor and indoor air temperature are set to be the same, at 25°C, and the wind speed is 3m/s. Therefore, the influence of temperature difference between the outdoor and the indoor can be eliminated. The total solar heat gain is 14.67 W/m^2 when the intensity of the incident solar radiation is 100 W/m^2. As the incident solar radiation reaches up to 1000 W/m^2, the total solar heat gain gradually increases to 148.23 W/m^2. However, the SHGC of the vacuum PV glazing not remains to be a steady value. It can be seen that the dynamic SHGC of the CdTe-based vacuum PV glazing slightly increases from 0.146 to 0.148 with the increment of incident solar radiation from 100 W/m^2 to 900 W/m^2. Meanwhile, the proportion of the absorbed solar radiation also increases from 18.19% to 19.05%.

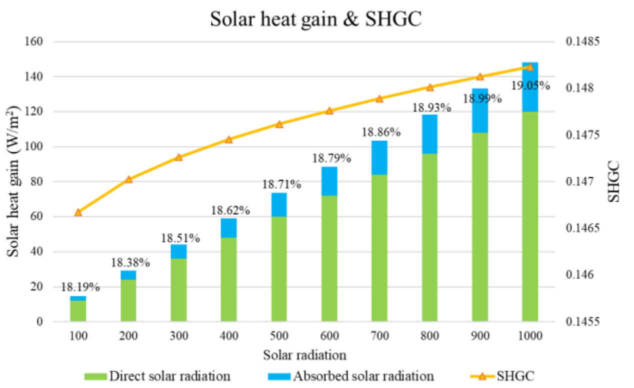


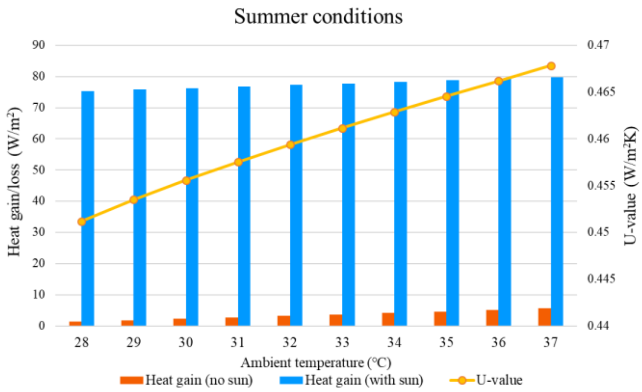
Fig. 3. Solar heat gain and SHGC of VPV under different solar radiation

B. *Effect of ambient temperature on U-value*

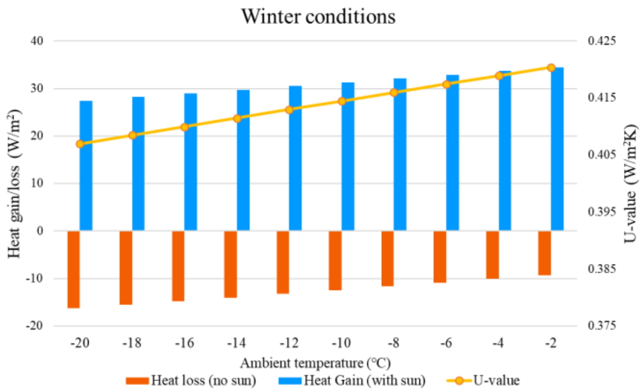
The overall heat transfer coefficient, as known as the U-value, is a key indicator of thermal insulation performance. The U-value is usually determined as a fixed index which using the reference boundary conditions, including summer conditions and winter conditions. In this study, the dynamic U-value of the vacuum PV glazing is calculated by the transient heat transfer model under different scenarios to evaluate the effect of ambient temperature, as shown in Fig. 4. The indoor air temperature is 25℃ for the summer conditions and 20℃ for the winter conditions. The incident solar radiation is 300 W/m^2 for both scenarios. The heat gain or heat loss can be determined based on different boundary conditions to reflect the impact of the solar radiation in summer and winter respectively. According to ISO 15099 [10], the definition of the U-value is assumed to be thermal transmittance without solar radiation.

As shown in Fig. 4(a), for summer conditions, it can be found that the heat gain dramatically increases when the solar radiation occurs. The average heat gain is 3.46 W/m^2 when there is no sun and 77.52 W/m^2 when the sun is up. It indicates that the solar radiation dominates the total heat transfer compared with the temperature difference in the daytime. The dynamic U-value varies from 0.451 to 0.467 W/m^{2}K with the increment of ambient temperature from 28℃ to 37℃.

Fig. 4(b) demonstrates the effect of the outdoor temperature on the U-value and net heat gain/loss under the winter conditions. When there is no solar radiation, the heat transfers from indoor to outdoor. The heat loss is -16.28 W/m^2 to -9.25 W/m^2 when the ambient temperature increases from -20℃ to -2℃. However, the solar radiation could convert the net heat loss to net heat gain. With the solar radiation, the heat gain is 27.45 W/m^2 ~ 34.50 W/m^2 in winter, which is much lower than the heat gain in summer. The dynamic U-value increases from 0.407 W/m^{2}K to 0.420 W/m^{2}K when the outdoor temperature increases. In conclusion, the U-value of the vacuum PV glazing is much lower than that of the common used double-pane window, which indicates that its excellent thermal insulation performance under both summer and winter conditions.



(a) Summer conditions



(b) Winter conditions

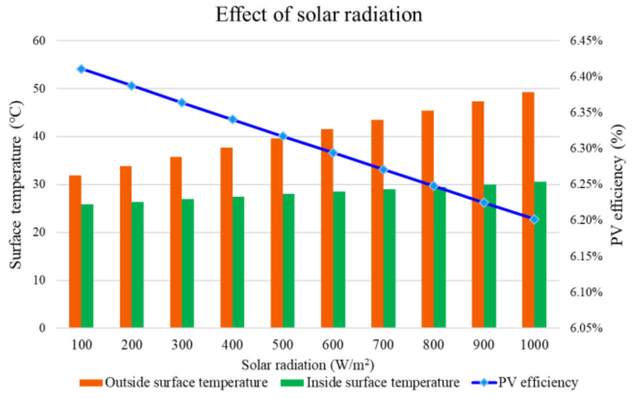
Fig. 4. Heat gain/loss and U-value of VPV under summer and winter conditions

C. *Effect of environmental conditions*

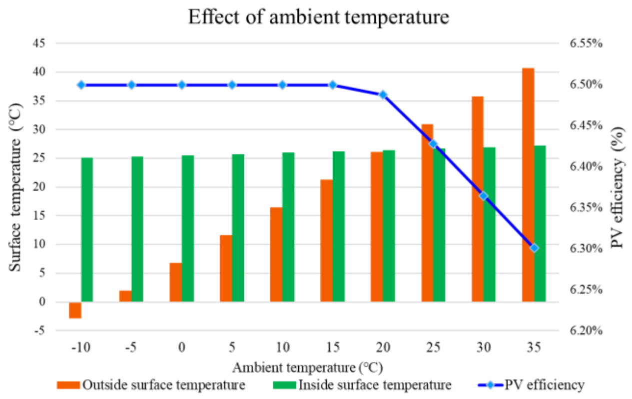
In order to investigate the effect of environmental conditions on the thermal behaviour and PV efficiency of the CdTe-based vacuum PV glazing, the simulations were carried out under different scenarios of environmental conditions.

Fig. 5 shows the effect of solar radiation, ambient temperature and wind speed on the outside and inside surface temperature of the vacuum PV glazing as well as the PV efficiency of the CdTe PV solar cell. Obviously, the outside surface temperature is sensible to the environmental conditional, especially the ambient temperature. When the solar radiation is fixed at 300 W/m^2, the outside surface temperature increases from -2.91℃ to 40.64℃ as the ambient temperature rises from -10℃ to 35℃. Similarly, when the outdoor air temperature is 30℃, the outside surface temperature increases from 31.9℃ to 49.2℃ with the increasing solar radiation of 100 W/m^2 to 1000 W/m^2. In contract, the wind speed has a negative effect, which lead to a decrease of the outside surface temperature of the vacuum PV glazing from 38.2℃ to 32.8℃ when the wind speed increases from 1 m/s to 10 m/s. However, due to the excellent thermal insulation ability of the vacuum PV glazing, the inside surface temperature is much more stable. Therefore, the vacuum PV glazing contributes to stabilizing the room temperature.

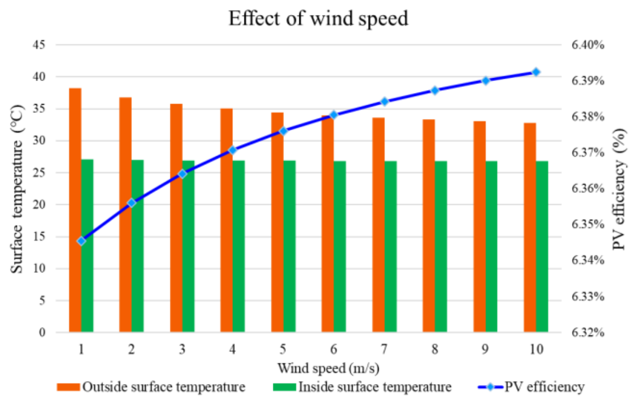
On the other hand, the opposite trends can be observed on the effect of environmental conditions on the PV efficiency. The PV efficiency will decrease with the increase of solar radiation and ambient temperature and will increase with higher wind speed. It is because the higher solar cell temperature have negative effect on the PV efficiency. As shown in Fig. 5, the PV efficiency decreases almost linearly with the increment of solar radiation. In the cases of different ambient temperatures, the PV efficiency dramatically decreases when the outdoor temperature exceeds 25℃. However, the increase of wind speed helps to improve the PV efficiency.



(a) Effect of solar radiation



(b) Effect of ambient temperature



(c) Effect of wind speed

Fig. 5. Surface temperatures and PV efficiency of VPV under different environmental conditions

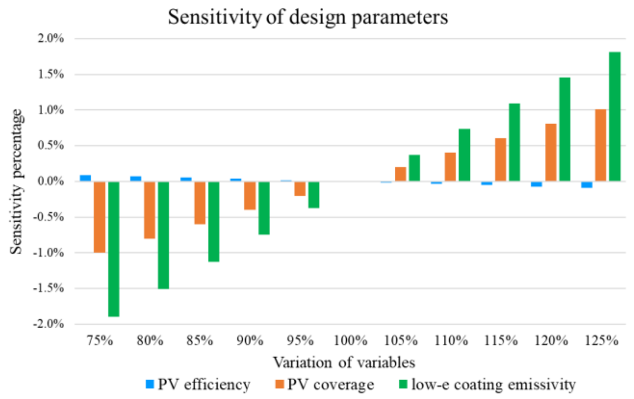
D. *Sensitivity analysis*

An excellent style manual for science writers is [7].

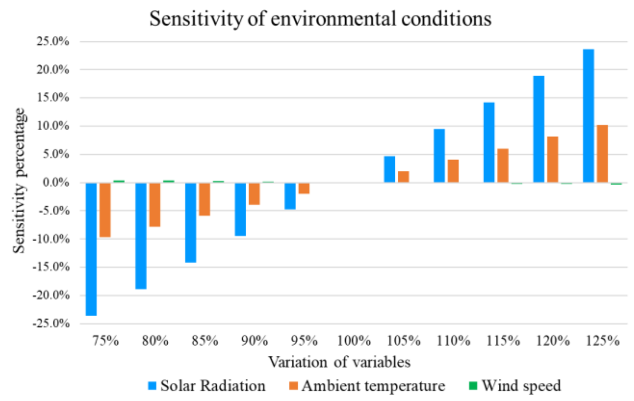
The sensitivity analysis was conducted to quantively evaluate the effect of design parameters and environmental conditions on the thermal performance of the vacuum PV glazing. The total heat flux of different scenarios with the variables changing within ±25% were compared. The input variables of the baseline case are $G = 300\ W/m^2$, $T_o = 30℃$, $T_i = 25℃$, $v = 3m/s$, $\eta_{pv} = 6.5\%$, *PV coverage = 50%*, and $\varepsilon = 0.1$.

As shown in Fig. 6(a), for design parameters, the emissivity of low-e coating is the most effective parameter on the heat transfer of the vacuum PV glazing. The variation of the total heat flux is ±1.9% and ±1% along with the variation of the low-e coating emissivity and PV coverage, respectively. On the other hand, the PV efficiency has much less influence compared with the other two design parameters.

Fig. 6(b) demonstrates the tornado diagram of the sensitivity of environmental conditions, including the solar radiation, outdoor temperature and wind speed. It can be seen that the dynamic heat transfer of the CdTe-base vacuum PV glazing is more sensitive to the environmental conditions than the design parameters. Especially, the solar radiation plays a prominent part in the heat transfer of the CdTe-based vacuum PV glazing, which has ±23.6% effect on the total heat flux. The ambient temperature also affects the total heat flux by -9.7% to 10.2%. However, the wind speed has insignificant influence on the heat transfer since it only affect the heat convection coefficient of the outside surface of the vacuum PV glazing.



(a) design parameters



(b) Environmental conditions

Fig. 6. Sensitivity of the vacuum PV glazing: (a) design parameters; (b) environmental conditions

IV. CONCLUSIONS

This study conducted a comprehensive numerical evaluation based on a mathematic heat transfer model for the CdTe-based vacuum PV glazing. It was found that the average dynamic solar heat gain coefficient (SHGC) of the CdTe-based vacuum PV glazing is 0.147 and will increase with the increment of incident solar radiation. The dynamic overall heat transfer coefficient (U-value) varies from 0.451 to 0.467 W/m^2K under summer conditions which are higher than which under winter conditions. In both summer and winter, the most of heat gain is due to solar radiation, while the contribution of temperature difference on the amount of heat gain or heat loss is much less. The solar radiation and ambient temperature have a negative effect on the PV efficiency and a distinctly positive effect on the outside surface temperature. However, the inside surface temperature is much more stable.

Based on the results of sensitivity analysis, the dynamic heat transfer mode is more sensitive to environmental conditions than the design parameter. Solar radiation plays a prominent part in the heat transfer of the CdTe-based vacuum PV glazing. For design parameters, the emissivity of low-e coating is the most effective parameter. The results indicate that the vacuum PV glazing can perform an excellent thermal insulation performance. For further development, an optimization of the design parameters should be conducted to enhance the solar heat gain control ability of the vacuum PV glazing.

ACKNOWLEDGMENT

The work described in this paper was supported by the Postdoctoral Fellowships Scheme of The Hong Kong Polytechnic University (Account No.: YW4W).

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