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Experimental Investigations on the Thermal Performance of Ventilated BIPV Curtain Walls

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Abstract

In this study, we integrated photovoltaic panels, building structures and heat transfer mechanism to design ventilated BIPV curtain walls that could hopefully dissipate the solar heat gain of the PV using the buoyant force and a double skin structure. Full-scale experiments were conducted to investigate the thermal performance of the ventilated BIPV curtain walls under various heating conditions, wall thicknesses, and types of openings. The results show that the developed ventilated BIPV curtain walls effectively remove their solar heat gain while maintaining adequate wall thermal performance.

Keywords - building integrated PV (BIPV); ventilated BIPV; curtain wall; thermal performance; building energy

1. Introduction

A BIPV integrates photovoltaic (PV) panels with façade material into a building structure such that the PV panel generates electricity and is incorporated into the building envelope, thereby replacing existing exterior wall materials. In short, a BIPV converts a building from a passive energy-consuming object to an active energy-generating subject. Norton et al. [1] conducted a strategic review on an optimum PV module installation in the building envelope to generate electricity.

Numerous factors affect the amount of electricity generated by a PV system, including the area of the solar cells, solar radiation energy received on the surface of the solar cells, spectral distribution of solar radiation, the solar incident angle, sunlight shading conditions, temperature of the solar cells, dust collected on the surface of the PV, wiring loss, DC/AC conversion, etc. The electricity conversion efficiency of a PV module is related to the temperature of the solar cells; the electricity conversion efficiency of a PV module decreases as the temperature of the solar cells increases [2]. The temperature coefficient (the change in the PV electricity generation efficiency with temperature) is approximately 0.11-0.63 %/K [3]. Therefore, it is imperative to include a heat-dissipation mechanism in the design stage during the development of a PV system [4-5].

The objectives of this study are to develop innovative ventilated BIPV curtain walls and evaluate their thermal performance. We used full-scale prototyping experiments, which have not been examined previously, to observe the channel effects, overall heat transfer coefficients and thermal penetration ratios of the proposed prototypes for different solar heating conditions, wall thicknesses and channel outlet configurations.

2. Research method

A full-scale curtain wall unit was used to develop the investigated ventilated BIPV prototype, based on the double skin structure, the solar chimney design concept and local construction practice, as shown in Fig. 1.

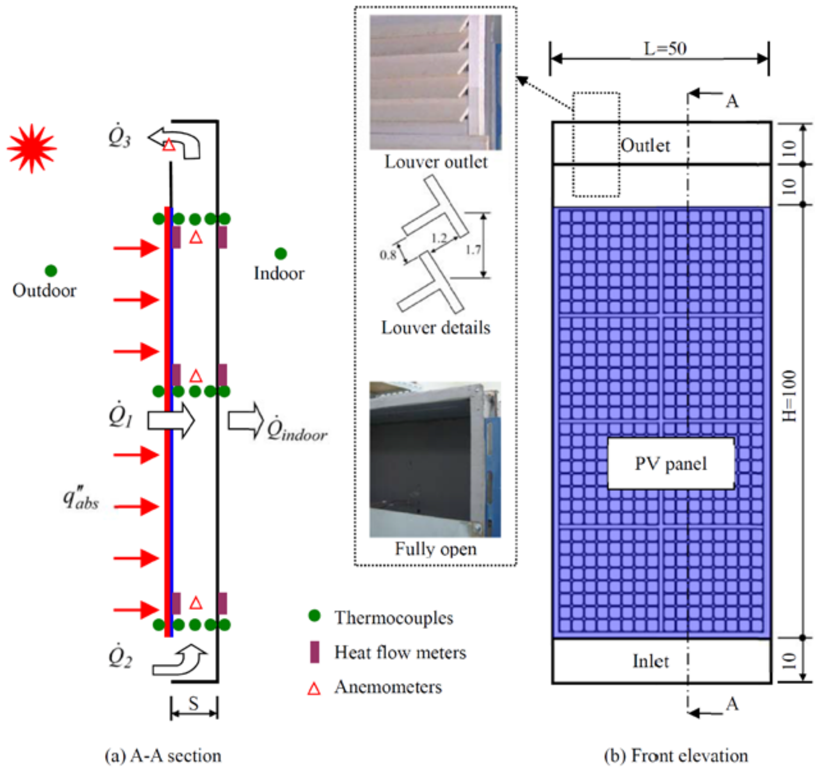

Fig.1 The tested ventilated BIPV curtain walls and measurement locations (unit: cm)

The heat transfer rate for each section is given below:

$$\dot{Q}_1 = K_o A_o (T_e - T_b) \tag{1}$$

$$\dot{Q}_2 = c\gamma\dot{V}T_o \,. \tag{2}$$

$$\dot{Q}_3 = c\gamma\dot{V}T_c \tag{3}$$

$$\dot{Q}_{indoor} = K_i A_i (T_b - T_i) \,. \tag{4}$$

$$\dot{Q}_{indoor} = K_i A (T_b - T_i) = A \frac{1}{\frac{1}{K_i} + \frac{1}{K_o + \frac{2c\gamma\dot{V}}{A}}} \left[\left(T_o + \frac{1}{1 + \frac{2c\gamma\dot{V}}{K_o A}} \left(\frac{\alpha}{h_o}\right) E \right) - T_i \right] \tag{5}$$

where $\dot{Q}_1$ is the rate of heat transfer through the exterior wall (W); $\dot{Q}_2$ is the rate of heat transfer from the air inflow (W); $\dot{Q}_3$ is the rate of heat transfer from the outflowing air (W); $\dot{Q}_{indoor}$ is the rate of heat transfer through the interior wall (W); T_o is the outdoor air temperature (K); T_c is the air temperature at the channel outlet (K); T_i is the indoor air temperature (K); T_e is the sol-air temperature (K); T_b is the representative channel air temperature (K); K_o is the heat conductance of the exterior wall (W/m^2 K); A_o is the surface area of the exterior wall (m^2); K_i is the heat conductance of the interior wall (W/m^{2}K); A_i is the surface area of the interior wall (m^2); c is the specific heat of air (J/kg K); γ is the density of air (kg/m^3); and $\dot{V}$ is the volumetric channel airflow rate (m^3/s).

Let the reciprocal channel effect $e_{ch} = \frac{1}{1 + \frac{2c\gamma\dot{V}}{K_o A}}$, which incorporates the influence of the proposed channel design on thermal performance of the prototypes. Please note that in order to have an intuitive expression in equations, e_{ch} is the reciprocal of the channel airflow effect. Then,

$$\dot{Q}_{indoor} = A \frac{1}{\frac{1}{K_i} + \frac{e_{ch}}{K_o}} \left[\left(T_o + e_{ch} \left(\frac{\alpha}{h_o}\right) E \right) - T_i \right] = A \frac{1}{\frac{1}{K_i} + \frac{e_{ch}}{K_o}} \left[\left(T_o + e_{ch} T_e^{*} \right) - T_i \right] \tag{6}$$

The conventional overall heat transfer coefficient (U-value) of the prototype can be written as follows:

$$\dot{Q}_{indoor} = UA\left(T_o + (\frac{\alpha}{h_o})E - T_i\right) \quad (7)$$

The height, length (L) and width of the prototype used in the experiment were 1.3 m, 0.5 m and S, respectively (Fig. 1). The commonly used local external wall construction produced a ventilated BIPV wall width between 0.05 m and 0.2 m. Therefore, in this study, the width of the prototype, S, (i.e., the width of the flow channel) was set as S=0.05, 0.1, 0.15 and 0.2 m. There was an outlet at the top of the prototype and an inlet at the bottom of the prototype. The heights of both the outlet and the inlet were 0.1 m. In practice, we often placed a louver above the outlet to prevent rain from entering the prototype. We first discuss the thermal performance of the prototype without an additional device installed above the outlet (namely, with a fully open outlet) and use this prototype as a baseline. Then, we test the thermal performance of a prototype for which the louver was placed above the outlet. Please check the details in our previous work [6].

3. Results and discussion

The control parameters included the solar heating flux on the prototype, q''_{abs} (to simulate the typical solar heat gain of about 200, 400, 600 and 800 W/m^2), the width of the prototype, S (to investigate the effect of different wall thicknesses of 0.05, 0.1, 0.15 and 0.2 m), and the channel outlet configurations (a fully open outlet and the louver outlet).

Fig. 2 shows that increasing the solar heating decreased the e_{ch} values for both the cases with the fully open outlet and the louver outlet. The e_{ch} values for the cases with the louver outlet were also affected by S: when S increased, e_{ch} first decreased and then increased. The e_{ch} values for cases with a fully open outlet were not significantly affected by S: for S = 0.1 m and 0.15 m, e_{ch} was slightly greater than that for the other thicknesses. Equation (8) shows the relationship between e_{ch} and the aspect ratio S/H and between e_{ch} and the Rayleigh number ($Ra_s^* = \frac{g\beta q''_{abs} S^4}{\nu^2 k} Pr$).

$e_{ch} = 47.2(\frac{S}{H})(Ra_s^*)^{-0.23}$ (prototype with a fully open outlet)

$e_{ch,L} = 151.5(\frac{S}{H})(Ra_s^*)^{-0.265}$ (prototype with the louver outlet) (8)

The overall heat transfer coefficient (U-value) is commonly used to describe the thermal performance of the building envelope. The lower the U-value is, the lower the heat transfer of the structure and the better its thermal insulation performance. Fig. 3 shows that low U values were determined for the ventilated BIPV walls (with a fully open outlet and the louver outlet). For cases with a fully open outlet and with the louver outlet, U was approximately 0.11-0.14 and 0.19-0.25 W/m^2 K respectively.

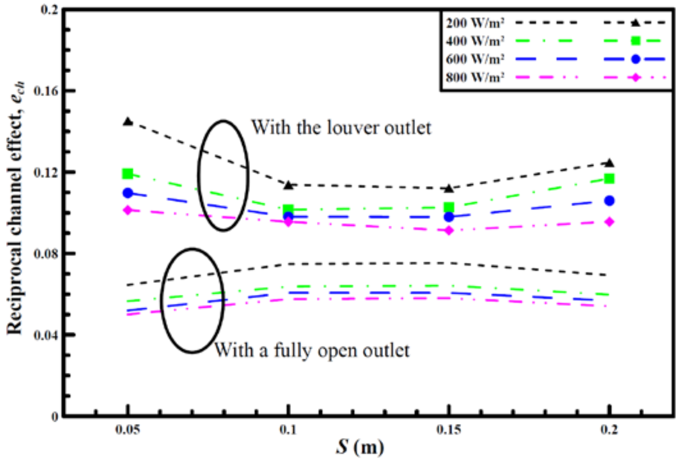

Fig. 2 Variations of the reciprocal channel effects (e_{ch}) with the channel widths (S) for various solar heating conditions and outlet configurations.

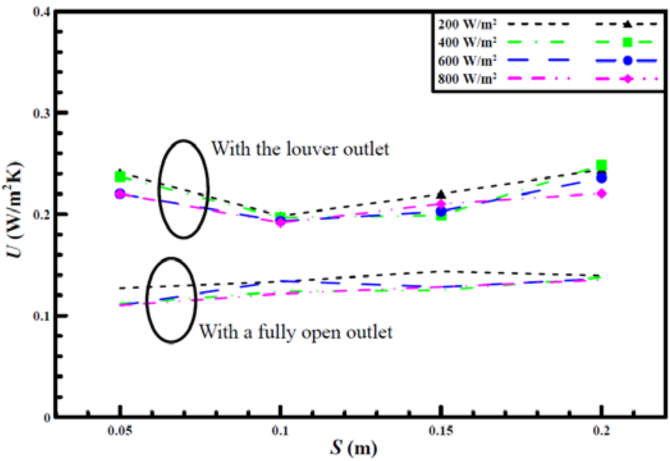

Fig. 3 Variations of the overall heat transfer coefficient (U) with the channel widths (S) for various solar heating conditions and outlet configurations.

The thermal penetration ratio of the ventilated BIPV curtain walls represents the ratio of the heat flux transferred indoors to the solar heating flux. The greater this ratio is, the poorer the insulation performance of the wall. In this study, the thermal penetration ratios and their trends were similar for the respective cases with a fully open outlet or the louver outlet. This ratio was not significantly affected by the solar heating power but was a parabolic function of *S* (data not shown). When *S* was gradually changed from 0.05 m to 0.1, 0.15 and 0.2 m, the ratios changed from 2.17% to 1.77, 1.67 and 1.87%, respectively; not much heat was transferred indoors.

4. Conclusions

Photovoltaic panels, building structures and heat transfer mechanism were integrated to develop ventilated BIPV curtain walls that could dissipate the solar heat gain of the PV using the buoyant force and a double skin structure, thereby successfully maintaining adequate solar cell temperature and external wall insulation.

The overall heat transfer coefficients (*U*-values) for exterior walls are limited to be 2-2.75 W/m^2 K (depends on the building type) in Taiwanese Building Code (2015). Compared with this requirement, the overall heat transfer coefficients of the proposed ventilated BIPV curtain walls with a fully open outlet or the louver outlet are very low. The thermal penetration ratio, which represents the ratio of heat flux being transferred indoors to solar heating, ranges from 1.67% to 2.17%; it is not significantly affected by solar heating but is by wall thickness. Within our investigated wall thickness (*S*=0.05, 0.1, 0.15 and 0.2m), we suggest using a 15 cm ventilated BIPV curtain wall, which can result in gains in both electricity efficiency enhancement and the low indoor heat gain.

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