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Experimental Investigations on the Thermal Performance of the Ventilated BIPV Wall

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ABSTRACT
This study integrated building structure, heat flow mechanism and photovoltaic system to develop the ventilated building-integrated photovoltaic wall. A full-scale ventilated BIPV wall prototype was developed and investigated using field tests to explore its heat transfer characteristics. After considering building construction practices, this prototype was transformed into a curtain wall structure that complemented the design of the overall construction. The result shows that the ventilated BIPV wall with the flow channel can dissipate BIPV heat gain efficiently and enhance the power generation. The ventilated BIPV wall has a U-value between 0.6 and 1.8 W m^{-2} K^{-1}.

Key words: Energy, photovoltaic, building integrated photovoltaic, building, energy

INTRODUCTION

BIPV are PV modules that combine the functions of building materials and building systems using architecture design methods, these PV modules can be used to generate electricity and can also replace building materials that were originally designed for use in the locations where the PV modules are installed thus, the PV modules become a part of the building envelope (Peng *et al.*, 2011). Defaix *et al.* (2012) estimated that BIPV systems in the 27 countries within the European Union (EU) had a technical potential of 951 GW_P and could provide 840 TWh of electricity which has the potential to supply approximately 22% of the total electricity consumption of the 27 countries within the EU in 2030.

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 (Mani and Pillai, 2010), wiring loss, Direct Current (DC)/Alternating Current (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. Therefore, it is imperative to include a self heat-dissipation mechanism in the design during the development of a BIPV system (Lai and Hokoi, 2014).

There is still limited existing literature on ventilated BIPV effectiveness on cooling load reduction and a lack of ventilated BIPV structures identical to this study. Zhu (2006) analyzed ventilated BIPV using a simplified analytic method by employing a cooling load component reduction ratio to evaluate BIPV effectiveness in lowering the cooling load. The results indicate that under the climatic conditions in Hong Kong, the cooling load component reduction ratio of ventilated BIPV was 32.5, 41.1 and 50.1%, respectively in Shanghai and Beijing. Yun *et al.* (2007), on the other hand, integrated the electricity generation efficiency of a ventilated BIPV panel, lighting energy-saving through the introduction of daylight and building energy-saving through the introduction of indoor ventilation and solar shading to propose a comprehensive evaluation factor, effectiveness of a PV facade (PVEF). It is concluded that the PVEF reached an optimal value when the transmittance was at 30%.

Within this context, the objective of the present study which is a follow-up to previous study (Lin *et al.*, 2011), is to investigate the thermal effect on BIPV module via field tests and explore how to use natural ventilation to decrease the thermal impact. Building structure, heat flow mechanism and photovoltaic system were integrated to develop the ventilated building-integrated photovoltaic wall. Natural ventilation and double-skin design were incorporated into the prototype to dissipate the solar heat gain and enhance building insulation performance.

VENTILATED BIPV WALL PROTOTYPE

Design development: In Taiwan, residential buildings in reinforced concrete or light steel structure can be commonly seen. The construction method of which is first to erect the C-shaped or square steel columns and then equip the outdoor and indoor wall panels on these columns. This study suggests replacing the exterior wall panels with PV panels and leaving the space between the exterior and interior walls as an airflow channel to provide a natural ventilation and heat dissipation for the ventilated BIPV wall. The channel space, having the same dimension with the column width, can also be used to install PV cables. Each row of PV panels (i.e., every external wall unit divided by two columns) has an air inlet at the base. After the outdoor airflow enters through the inlet into the mezzanine channel, formed by the PV panels and indoor decorative boards. After flowing through the entire row of PV panels, the airflow in the channel will be discharged from the outlet located on top of the PV panels as shown in Fig. 1. Therein, the detailed design of the outlet vent has gone through several pioneering CFD simulations to ensure that the outdoor airflow will not flow in through the top air vent and reduce the strength of buoyant convection. As the content of this section (detailed design of the outlet) is somewhat unrelated to this study, its introduction is omitted.

Previous study (Lin *et al*., 2011) showed that, the wider the airflow channel width, the lower the heat removal rate of the ventilated BIPV wall. When the outdoor wind velocity was 0.5 m sec^{-1}, the channel width affected the heat removal rate slightly and its average value was about 1073-1155 W. When the outdoor wind velocity was 1.0 m sec^{-1} and the channel width 5 cm, the heat removal rate was found to be maximum. The larger the channel width, the lower the heat removal rate, with an average value of about 1228~1628 W. When the outdoor wind velocity was 2.0 m sec^{-1} as the airflow channel width greater than 10 cm, the heat removal rate gradually unchanged with an average heat removal rate of 2439-3065 W. Considering the above results and the common size of external walls in light steel houses, the flow channel width used in this study was 10 cm.

Experimental prototypes: For this study, two tested prototypes were constructed, including an experimental prototype (the ventilated BIPV wall) and a comparison prototype (the conventional BIPV wall), in which the PV panel was directly attached on the existing external wall. The experimental prototype with a flow channel consisted of two multicrystalline silicon solar modules (SM-83KSM, Kyocera) with 83 W (+10%/-5%) of generating power each and connected in parallel. It was assumed that the power generation characteristics of the two solar modules were similar. The net flow channel width was 10 cm, the 68×15 (H) cm airflow inlet was at the lower portion and a similar size airflow outlet was at the upper portion of the experimental prototype.

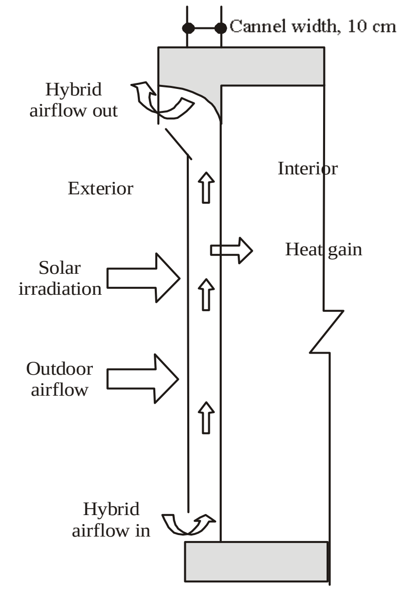


Fig. 1: ventilated BIPV wall proposed in this study

A ramp diversion composed of an aluminum plate was installed on the upper outlet of the experimental prototype which was designed based on previous study (Lin *et al*., 2011), in which a recommended guide-airflow passage was obtained through a Computational Fluid Dynamics (CFD) simulation. The side and rear materials of the prototype wall were composed of a wood board which was affixed to and surrounded by 1.5 cm of thick thermal insulation foam. The thermocouples and anemometers were placed in the flow channel.

The comparison prototype without a flow channel comprised the same two solar modules (SM-83KSM, Kyocera) with 83 W of generating power each and connected in parallel. This prototype did not have the designed heat dissipation; thus, the back of the solar modules was simply covered with 2.5 cm of thick insulation material which was also used to fill any gaps and then sealed with the wood boards. Insulation foam was affixed around the four sides as above. These two prototypes faced south and we confirmed that other facilities did not generate a shadow impact during the experiment.

The electric energy generated by PV modules was stored in batteries. Because of the limited battery capacity and the need to measure input voltage and current, a light bulb was added as the load to eliminate any effects from battery saturation in the experiment process. The charge controller used in this experiment was a charge controller (SunSaver) with a voltage of 12 V and a current of 20 A, this voltage was the series voltage for PV panels and the input current was

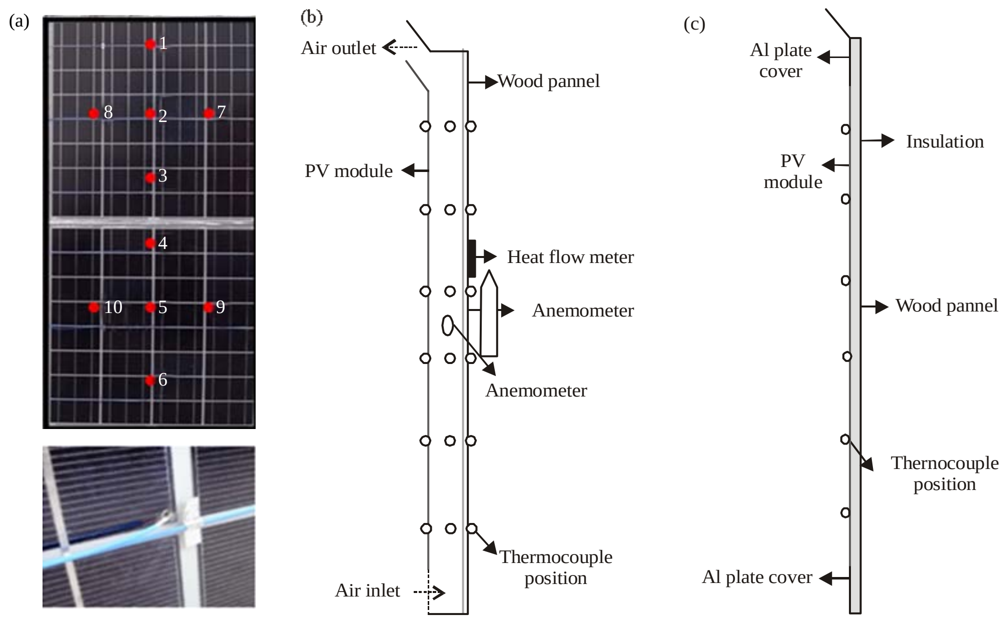


Fig. 2(a-c): Measuremnet points, (a) Front view, (b) Ventilated section profile and (c) Conventional section profile

higher than the PV panel charging current. In addition, the controller also had anti-over-voltage protection and anti-reverse charge for nighttime.

Measurement factors and equipment: The results from the experiment were subject to weather conditions; therefore, during the experiment, a weather station (S-WCA-M003, HOBO) was used to record temperature, wind speed and solar radiation (LI-250A and LI-200SA). Type K thermocouples were used and 10 temperature-sensing points were assigned which were located on the front of the ventilated BIPV wall (PV module surface), in the center of the flow channel and on the backplane (common indoor decoration materials, wood board) as shown by the red dots in Fig. 2a and 2b. Ten temperature-sensing points were placed on the front of the conventional BIPV wall (PV module surface) as shown in Fig. 2c. The thermocouple wires on the PV module surface were routed along the blank portion of the solar cells to avoid masking the solar cell and affecting electricity production. In addition, to protect the thermocouples installed on the PV module surface from direct sunlight exposure, the thermocouple sensor points were covered by an aluminum foil layer as shown in the inset in Fig. 2a.

To understand heat transfer performance, a heat flow meter (HFM-201, Kyoto electronics) was placed in the center of the back plane of the ventilated BIPV wall. TESTO 445 Multi-functional ventilation/air-conditioning detector was used to detect the air flow velocity and temperature at the channel center. Data analysis was conducted using an RS 232 transmitting line and professional analyzing software ComSoft 3 (Testo 0554 0830) on the Windows platform. For power measurement, the voltage and current from the PV module were tested before they entered the battery to ensure that the measured value for the electrical energy generated was unaffected by the battery storage level or other factors. The MX100 data (YOKOGAWA) collection device was used to measure and record this voltage, a 50 A 50 mV shunt was added to this circuit series to measure the current using the MX100.

RESULTS AND DISCUSSION

The surface temperature distribution on the ventilated BIPV PV module (measured on 2011/12/07) is shown in Fig. 3. The surface temperature variations throughout the module do not vary to a large extent, the temperature at point 1 is the maximum and the temperature at point 6 is the minimum. This temperature difference may be attributable to the air flow channel in this experimental prototype, the outdoor air flowed into the flow channel from the lower opening was heated by the PV panels and then raised to the outlet to dissipate the heat which distributed the high temperatures at the top of the PV module while the lower temperatures were at the lowest portion.

Figure 4 shows a comparison of the average PV surface temperature and power generated from the ventilated and conventional BIPV walls in the experimental day. The module surface temperatures in both of the tested prototypes rose with solar irradiation and higher outdoor temperatures. At noon, the temperature difference between the two tested prototypes increased significantly, the surface temperature of the conventional BIPV wall was 5-10° higher than the ventilated BIPV wall. When the solar radiation was low, the surface temperature of the ventilated BIPV wall was close to the conventional. The module temperature of the conventional BIPV wall was higher than that of the

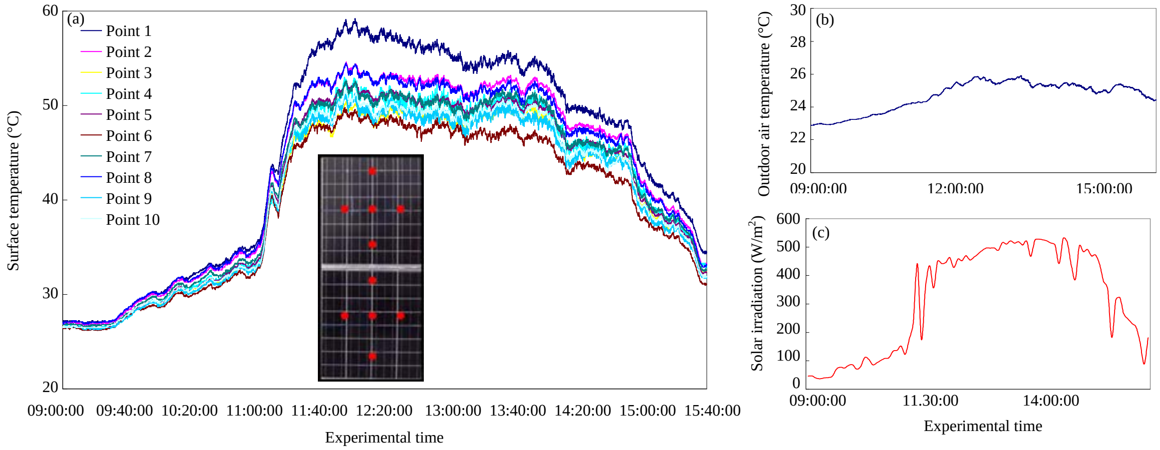


Fig. 3(a-c): (a) Surface temperature variation on the ventilated BIPV PV module, (b) Outdoor air temperature and (c) Solar irradiation

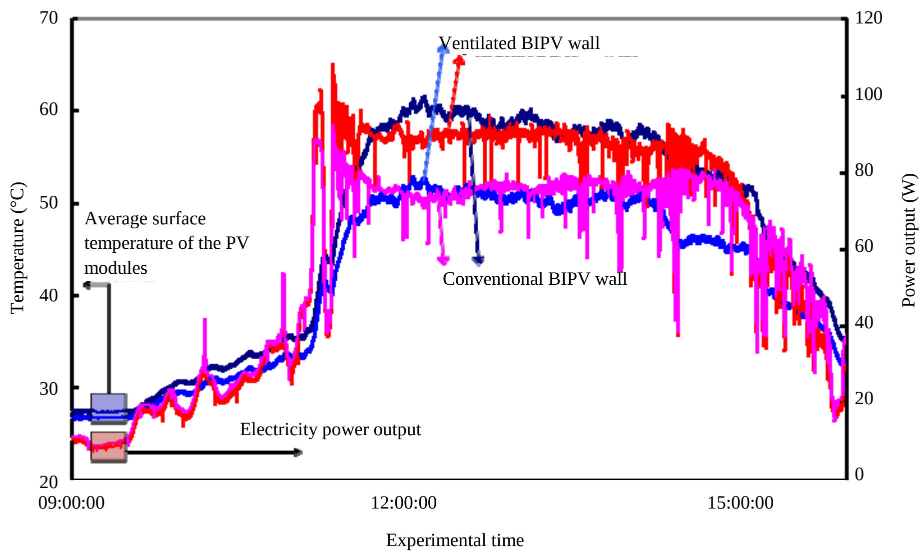
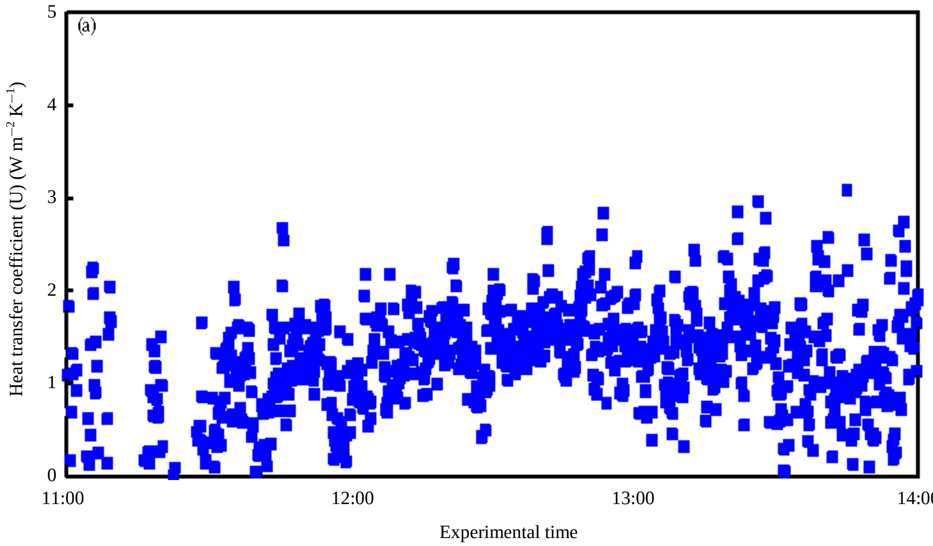


Fig. 4: Comparison of the average PV surface temperature and power generation from the ventilated and conventional BIPV walls

ventilated throughout the experiment. Because of the change in power generation over time, the power generation for the two tested prototypes increased as solar radiation intensity increased.

The power outputs for both tested prototypes during low radiation conditions were not high but they were similar, however, at noon, instantaneous power generation from the ventilated BIPV was approximately 10 W higher than that from the conventional BIPV wall. Thus, it was demonstrated that module temperature affects power generation and also confirmed that the heat transfer mode via ventilation can dissipate BIPV heat efficiently and enhance the power generation. The daily power-generation of the ventilated BIPV wall was 0.426 (kW-h) and the daily general conventional power generation was 0.388 (kW-h) thus, the daily generation of the ventilated BIPV wall was 9.8% (0.038/0.388) higher than that of the conventional BIPV wall.

The main purpose for the experiments was to understand heat transfer performance of the ventilated BIPV wall developed in this study, therefore, the experiment data from noon were used to analyze the overall heat transfer coefficient (U). The reasons for selecting the noon time period were that first, it is hottest at noon and the possibly maximum level of heat penetration at that time. Second, during this period, the



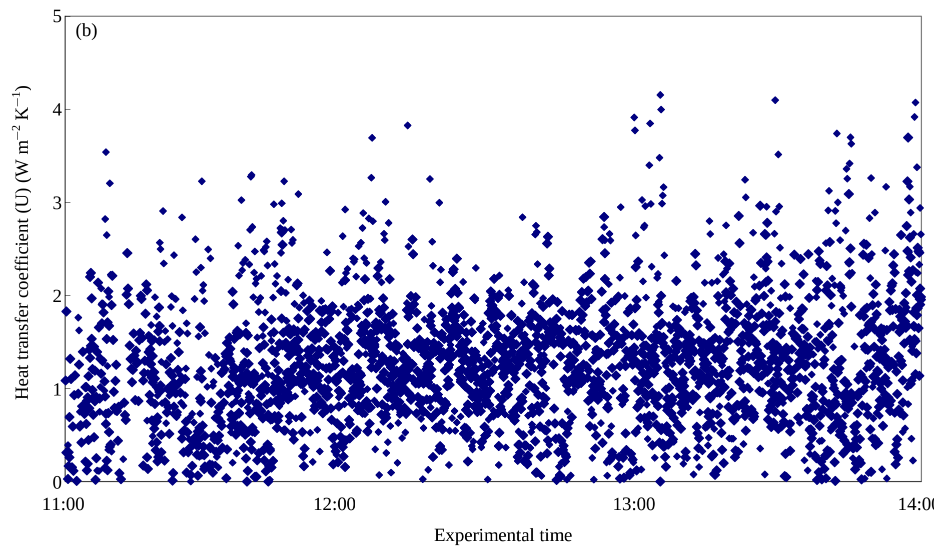


Fig. 5(a-b): U values measured on (a) 7 December, 2011 and (b) During experimental period

solar irradiation change is more stable and so is heat transfer. Thus, the time period used to study the overall heat transfer coefficient was 11:00 am to 2:00 pm.

The overall heat transfer coefficient U (W m^{-2} K^{-1}) was calculated from the heat flux (q_{in}) measured by the heat flow meter using the equation below:

$$U = \frac{1}{\frac{1}{h_o} + R + \frac{1}{h_i}} \quad (1)$$

$$R = \frac{\Delta T}{q_{in}} \quad (2)$$

where, R is total thermal resistance, ΔT is temperature difference (K) on both boundary sides of the BIPV wall and q_{in} is heat flux (W m^{-2}) into the interior. In the calculation, h_o and h_i are heat convection coefficients for the outdoor and indoor walls, respectively. In accordance with the normative values of the Taiwan Building Code, h_o = 23 (W m^{-2} K^{-1}) and h_i = 5 (W m^{-2} K^{-1}).

Figure 5a shows that the overall heat transfer coefficient of this ventilated BIPV wall is not a fixed value instead, it is impacted by the outdoor environment and its value is between 0.01 and 2.8 (Wm^{-2} K^{-1}) with a 1.28 (W m^{-2} K^{-1}) average. After compiling all the results (Fig. 5b) from these experiments (including three days in the summer and three days in the winter), we obtained that the ventilated BIPV wall, incorporating the double skin structure and natural ventilation has a U-value between 0.6 and 1.8 W m^{-2} K^{-1} with a 1.28 average and a 0.55 standard deviation. Compared with the reinforced concrete wall (U-value of 3.5 W m^{-2} K^{-1} in Taiwan), the thermal performance of the ventilated BIPV designed in this study is superior.

CONCLUSION

In this study, BIPV was used as the primary focus for development regarding the integration of building construction, heat flow techniques and photovoltaic systems to design an autonomous environment-controlled BIPV curtain wall. Natural ventilation and a double-skin structure was used to dissipate heat from the photovoltaic panel and enhance building insulation performance. A full-scale ventilated BIPV prototype was developed and investigated using field tests to explore its heat transfer characteristics.

The result shows that, at noon, the surface temperature of the conventional BIPV wall was 5-10° higher than the ventilated BIPV wall with the flow channel which can dissipate BIPV heat efficiently and enhance the power generation. The ventilated BIPV wall has a U-value between 0.6 and 1.8 W m^{-2} K^{-1} and is superior than that of the reinforced concrete wall (U-value of 3.5 W m^{-2} K^{-1} in Taiwan).

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