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PERFORMANCE EVALUATION OF THE PHOTOVOLTAIC DOUBLE-SKIN FACADE

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ABSTRACT

The mathematic models for thermal, and PV solar power inserted in the ESP-r, which is the integrating building energy and environment simulation tool, were verified with the measured data. Using the verified model, the energy performance of an office building, equipped toward the south with conventional absorptive single facade or un-ventilated double PV facade or outward ventilated double PV facade installation, located at Shanghai was simulated. From the simulation result, the conclusions about annual electricity output generated by the semi-transparent solar cell attached on the south window, impacts of chimney effect on cooling load and heating load, and the optimal operation approach for outward ventilated double PV facade were presented.

INTRODUCTION

Semi-transparent PV, which is different from conventional opaque PV, permits direct solar heat gain and daylight use. Currently, semi-transparent PV panels are widely used as facades, roof or even shading devices in office and/or commercial buildings. Famous buildings include the Mataro Public Library in Spain (Lloret et al., 1995), and the De Kleine Aarde Boxtel in the Netherlands (Reijenga et al., 1997). Current research includes thermal modelling of ventilated PV facades (e.g. Infield et al., 2004 and Mei et al., 2003), and simulation of total energy consumption in office buildings equipped with semi-transparent PV panels (Miyazaki et al., 2005, Boer et al., 2001]. In the aspect of total building energy consumption, Miyazaki et al. and Boer et al. reported research findings on semi-transparent PV incorporated as facades in office buildings. The objective of this paper is to investigate the energy performance of the double photovoltaic facades compared to the conventional single absorptive glazed facades and chimney effect of the ventilated photovoltaic facades on its thermal performance.

EXPERIMENT SETUP

A natural ventilated photovoltaic window prototype, schematicly shown in figure 1, was constructed and installed at the environmental chamber located on the building roof level on the main campus of City University of Hong Kong. The chamber was maintained at 22±0.5C at all time round the clock. Fig.2 shows the window assembly fixed at the front wall of the chamber. The temperature conditions at the air cavity and glass surfaces were monitored by thermocouples connecting to a data-logging station. The measured data was used to calibrate and verify the computer program in use.

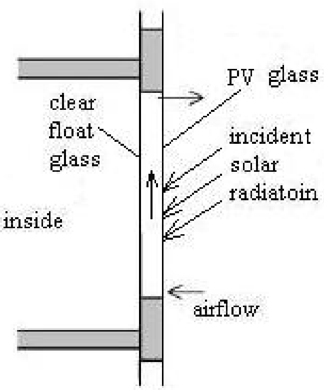

Fig. 1 The schematic diagram of double glazing

Fig. 2 The window assembly of the test chamber

MODEL VERIFICATION

Modelling Approach for Glazing System of ESP-r

Single glazing windows are easily handled by most thermal and energy building simulation programs including ESP-r. In the case of the double natural airflow window, however, it is necessary to account for the effect of the air flow in the open air gap. Since in most simulation programs the effect of air flow is not accounted for, the traditional approach of window integration in building simulation models becomes inadequate. Furthermore, the air flow in the open air gap is driven by buoyancy, which requires the simulation of the combined effect of heat and mass flow. Potentially, this can be achieved by two methods: (a) CFD simulation or (b) coupled air flow network and energy balance simulation. The first alternative probably has the potential for obtaining more accurate results. However, its implementation depends on many calibration parameters often not available from experimental monitoring. Even more important, the CFD approach requires such computational time that with common computing resources it is even impracticable to run whole building simulations for long periods, such as annual simulation. The approach of coupled air-flow network and energy balance, on the other hand, has the potential to simulate long period. This kind of approach has been successfully used in the simulation of photovoltaic facades elements and double-skin facades with an opaque wall. Such model was also implemented in whole building thermal and energy simulation software ESP-r. The model involves buoyancy-induced flow, and for example the open-air channel could be initially divided into a few different thermal zones. Each thermal zone is associated with an air-flow network node. The network nodes are linked to their neighbors by components such as air-flow cracks, ducts and/or openings. Fig. 3 shows a geometric view of the ESP-r model of the experimental setup and a representation of the air-flow network obtained for winter mode. The convection correlation for the external surfaces was set as the ‘ ‘MoWitt’ ’ correlation, which is more appropriate for low-rise buildings, as is the case of the test chamber. Another point is that all simulations should run at not longer than 5-minute time-steps to ensure that the temperature control in the simulation acts as in the real case.

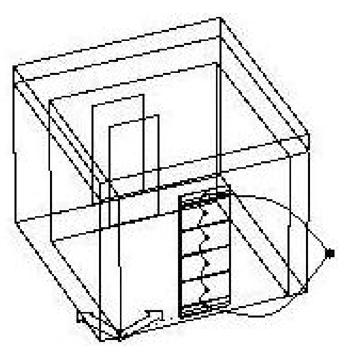

Fig. 3 Perspective view of the geometry model of the test chamber

Verification of ESP-r Model for Glazing System

The default thermal model integrating flow network module for natural ventilated PV glazing system of the ESP-r was verified. The properties of the PV glass and Clear float glass installed in the test chamber were shown in Tab. 1 and Tab.2. The Comparison of measured and simulated average temperature of external PV and clear glass for natural ventilation glazing system was shown in Fig. 4, and the Comparison of measured and simulated solar electricity was shown in Fig.5. It should be noted that the PV model for amorphous silicon solar module was used in electricity output simulation. On the whole, the simulated temperatures of the glass and the solar electricity output are in a good agreement with the measured data.

Table 1 Properties of absorptive and clear float glass

Items	unit	Absorptive	Clear float
Thick	mm	8	8
Conductivity	W/(m·C)	1.05	0.9
Emissivity		0.84	0.84
Absorptivity		0.52	0.05
Transmissivity		0.42	0.84

Table 2 Properties of the PV glazing

Items	Value
window size (H×W)	2.0m×1.0m
module size (H×W)	0.98m×0.95m (each cell) exposed area: 0.88m×0.88m
Glass type	2×0.005m float
Solar cell type	Amorphous silicon
Cell width	0.00878m
No. of solar cells: series×parallel	108×1
Max power voltage	58.6 V
Max power current	0.648 A
Open circuit voltage	91.8 V
Short circuit current	0.972 A
Rated output power	38.0 W

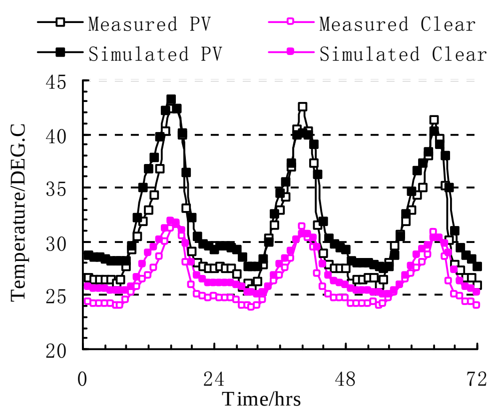

Fig. 4 Comparison between the measured and simulated average temperature of the glass

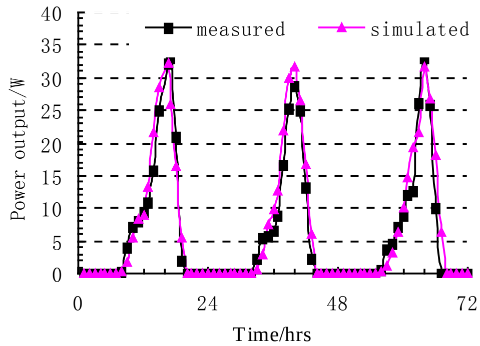

Fig. 5 Comparison of the measured and simulated power output

BUILDING DESCRIPTION UNDER SIMULATION

After the model validation, the photovoltaic double-skin façade assessment was carried out through simulation with ESP-r software, integrating thermal simulation and air low net work module. One of the advantages of the ESP-r over other building simulation tools or commercial CFD tools is that ESP-r is an integrated tool integrating building thermal simulation, air flow, even renewable power process. Particularly the air flow calculation could use the thermal simulation result on each time step, which makes it possible to carry out an annual simulation considering both thermal and air flow situation.

The office building geometry, which is shown in Figure 6, consists of ten floors, the ground floor is 7.2 meters high, and the others are 3.6 meters high. The building locates at Shanghai, which is of hot summer and cold winter climate area. The photovoltaic double-skin façade was designed toward the south and consists of external PV glass, air gap, and internal clear glass. The air gap width was designed as 600mm, and the air gap is naturally ventilated which results from buoyant flow. The window wall ratio(WWR) on east, north, west is 50%, 40%, 50% respectively, and WWR of the internal skin of the south envelope is 60%, while the external photovoltaic skin of the south envelope was fully glazed. Any other properties of the office building, such as the opaque envelop construction, lighting density, equipment density, occupancy and schedules were specified as guidelines(Electrical & Mechanical Services Department. (2007)).

The conventional building glazing is single absorptive glazing in Shanghai, while the PV facade was often designed as double skin, so the following three glazed facades will be simulated,

(i) S-AB, single absorptive glazing;
(ii) D-PV-V, photovoltaic natural ventilated double-skin glazing
(iii) D-PV-C, photovoltaic closed double-skin glazing

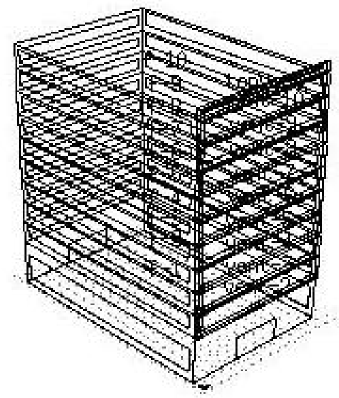

Fig. 6 The perspective view of an office building with double skin facade

SIMULATION RESULT AND DISCUSSION

The weather data of Shanghai of China, which was downloaded on the Energyplus website and converted into the binary format for ESP-r use, was adopted in simulation.

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The simulation result in typical week

The typical summer week ranges from Jul. 11 to Jul.17 and the typical winter week from Jan. 9 to Jan. 15 according to the ESP-r program. The ambient temperature in typical summer and winter week of Shanghai were shown in figure 7 and figure 8. And the solar direct and diffuse radiations were also shown in figure 9 and figure 10.

The hourly cavity air temperature in typical week was shown in figure 11 and figure 12. The figure 11 showed that the hourly cavity air temperature of D-PV-V is lower than that of D-PV-C in typical summer week, which means that heat gain through D-PV-V is less than that through D-PV-C in summer. Nevertheless the hourly cavity air temperature of D-PV-V is much lower than that of D-PV-C in typical winter week, which means that heat gain through D-PV-V is much less than that through D-PV-C in winter.

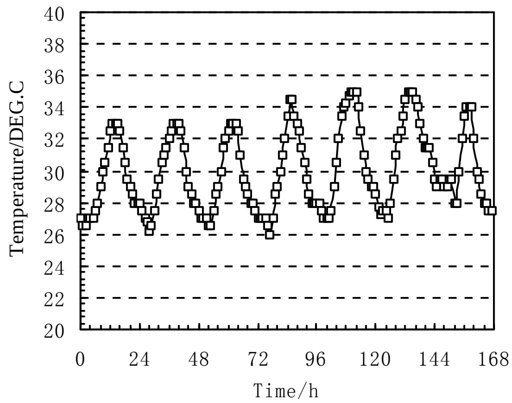

Fig. 7 The ambient temperature in typical summer week

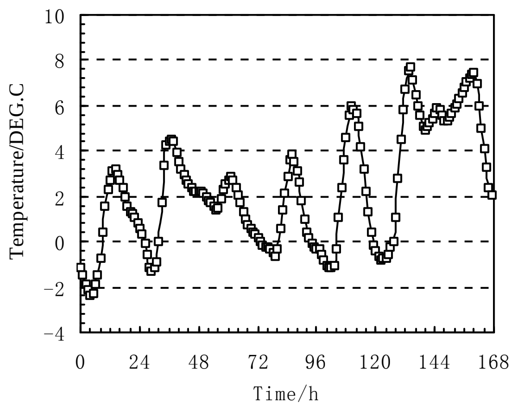

Fig. 8 The ambient temperature in typical winter week

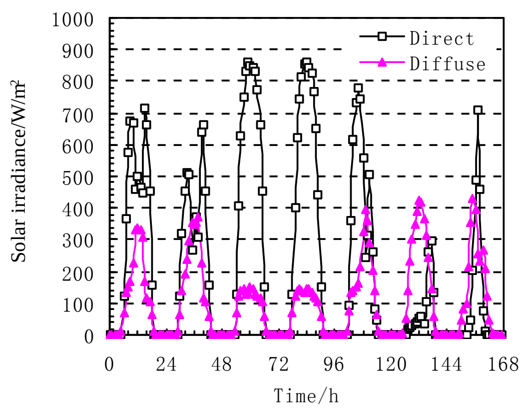

Fig. 9 The solar irradiance in typical summer week

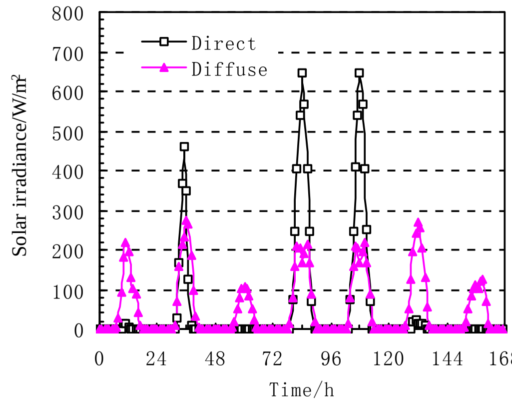

Fig. 10 The solar irradiance in typical winter week

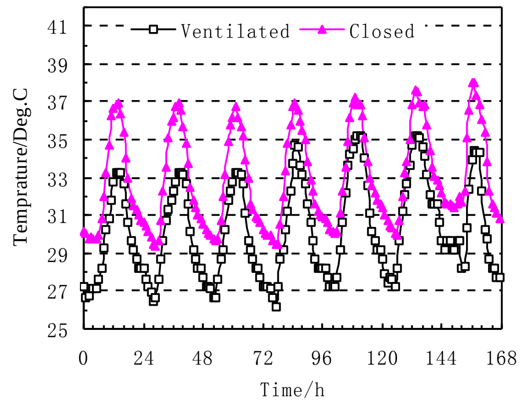

Fig. 11 The cavity air temperature in typical summer week

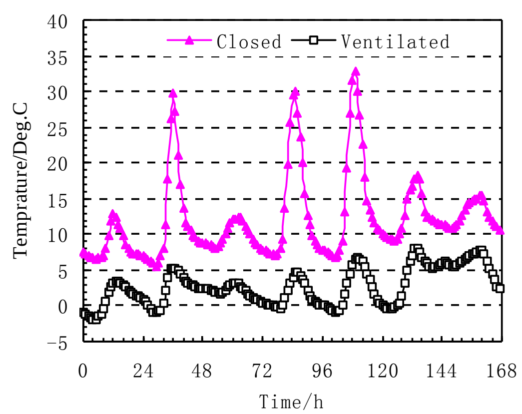

Fig. 12 The cavity air temperature in typical winter week

The hourly temperature of the inner glass for D-PV-V and D-PV-C or the absorptive glass for S-AB in typical week was shown in figure 13 and figure 14. The figure 13 showed that The hourly temperature of the inner glass of D-PV-V is slightly lower than that of the inner glass of D-PV-C and that of the absorptive glass of S-AB in typical summer week, which means that heat gain through D-PV-V is less than that through D-PV-C and S-PV in summer, and also the space equipped with D-PV-V has better indoor thermal comfort than the others. But the figure 14 showed that The hourly temperature of the inner glass of D-PV-C is obviously high than that of the inner glass of D-PV-C and that of the absorptive glass of S-AB in typical winter week, which means that heat gain through D-PV-C is more than that through D-PV-C and S-PV in winter, and also the space equipped with D-PV-C has better indoor thermal comfort than the others in winter.

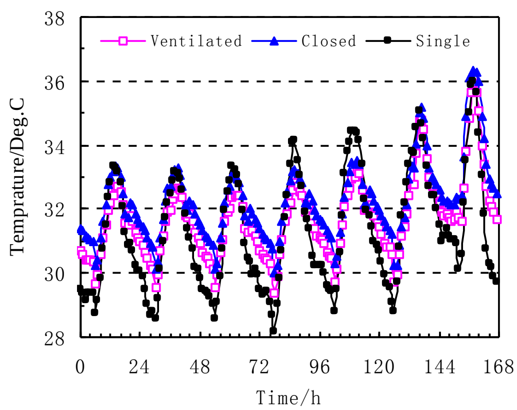

Fig. 13 The inner glass temperature in typical summer week

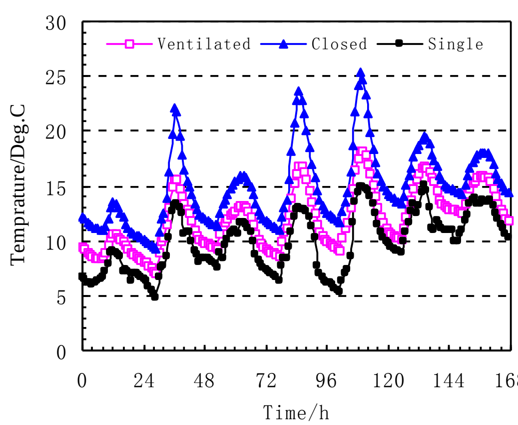

Fig. 14 The inner glass temperature in typical winter week

For D-PV-V, The air velocity in cavity in typical summer and winter week was shown in figure 15 and figure 16 respectively. From the figure 15 we could know that air velocity in cavity ranged from 0.08m/s to 0.44m/s approximately in typical summer week, while air velocity in cavity in typical winter week is much high, and ranged from 0.36m/s to 0.7 m/s approximately. It is obvious that the chimney effect of the D-PV-V in winter is more intense than in summer, and the reason is that the temperature difference between ambient and air in cavity is bigger in winter than in summer. In a word the green house effect for the double glazed facade is stronger in winter than in summer.

The annual simulation result

The simulated monthly thermal load and solar electricity output was shown in table 3, On the condition that the solar electricity out put was taken as the minus electricity consumption and assume that the unit electricity input could get 3 times of heating or cooling output, Annual electricity consumption sum, consisting of cool and heat supply, was worked out as shown in table 3. If S-AB was regarded as the baseline case, which means annual electricity % saving is zero for S-AB, annual electricity % saving of D-PV-V and D-PV-C compared to S-AB is 13.0% and 10.0% respectively.

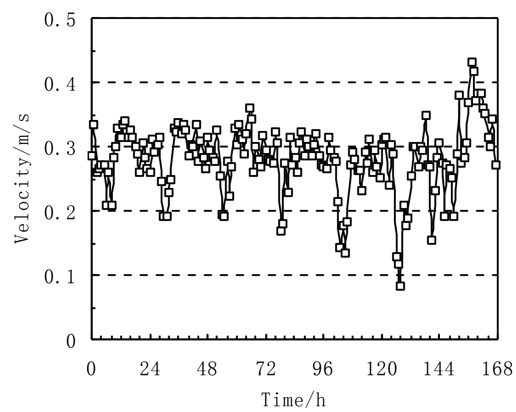

Fig. 15 The air velocity in cavity in typical summer week

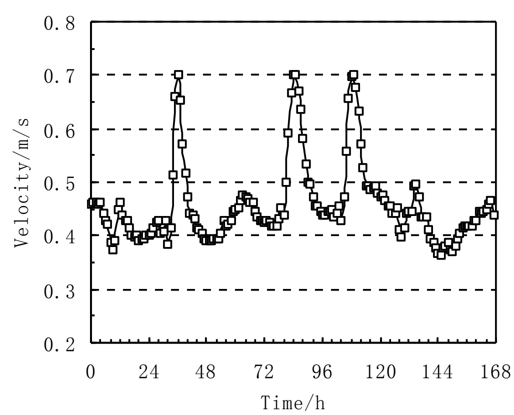

Fig. 16 The air velocity in cavity in typical summer week

The electricity generated by the semi-transparent solar cell is about 7% of the total electricity consumption to meet cooling and heating demand of the building occupancy.

Whether ventilated or not impacts on both the cooling skin facade. As shown in table 3, the outward ventilation of the photovoltaic double skin facade reduced the electricity consumption for cooling supply from 417146kWh to 403185kWh, about 3.3%. In contrast, the outward ventilation of the photovoltaic double skin facade increased the electricity consumption for heating supply from 22340 to 25551kWh, about 12.6%. We could know load and the heating load of the photovoltaic double from the above ventilation resulted in less impact in summer than in winter. And it is easy to conclude that the more electricity consumption for heating supply should be saved if the building was located at a place whose climate is colder than Shanghai.

Table 3 The energy performance of three building glazing

	S-AB		D-PV-V			D-PV-C		
	Thermal load		Thermal load		Solar Power	Thermal load		Solar Power
	Cooling	Heating	Cooling	Heating		Cooling	Heating	
Jan	26814	8124	20474	8658	3029	25713	7701	3024
Feb	32460	5614	27024	6059	2568	31770	5349	2563
Mar	52034	3655	48757	3742	2070	53108	3261	2066
Apr	91006	495	87046	516	2047	90047	456	2043
May	125300	18	121372	19	1281	123875	18	1279
Jun	156352	0	151039	0	972	153088	0	970
Jul	194310	0	186476	0	1213	187881	0	1211
Aug	213976	0	202801	0	1981	205028	0	1976
Sep	153808	0	145630	0	1914	147798	0	1911
Oct	117988	66	106886	78	3671	110746	71	3661
Nov	81520	1180	71707	1524	3653	76132	1249	3646
Dec	51485	4115	40341	4954	4292	46253	4236	4285
Annual load	1297051	23266	1209554	25551	28691	1251439	22340	28636
Annual electricity Consumption	432350	7755	403185	8517	-28691	417146	7447	-28691
Annual electricity consumption sum	440106		383011			395902		
Annual electricity % saving	0		13.0			10.0		

The optimal operation approach of D-PV-V is to keep the air inlet and outlet open in summer while to keep them closed in winter.

CONCLUSION

The following conclusion was drawn from the experiment and modelling,

(i) Of three types of facade, conventional absorptive single façade, un-ventilated double PV facade and outward ventilated double PV facade installation, outward ventilated double PV façade is the most energy efficient.

(ii) The annual electricity generation by the semi-transparent solar cell is about 7% of the total electricity consumption to meet cooling and heating demand of the building occupancy.

(iii) The outward ventilation, which represents chimney effect, of the ventilated photovoltaic double skin facade could cut down cooling load in summer, in contrast, increased the heating load in winter.

(iv) The chimney effect of the photovoltaic double skin facade in winter is more intense than in summer since air velocity in cavity ranged from 0.08m/s to 0.44m/s approximately in typical summer week, while air velocity in cavity in typical winter week is much high, and ranged from 0.36m/s to 0.7 m/s approximately. So ventilation imposing less impact on electricity consumption in summer than in winter. And it is easy to pridict that the more electricity consumption for heating supply should be saved if the building was located at a place whose climate is colder than Shanghai.

(v) The optimal operation approach of the ventilated photovoltaic double skin facade is to keep the air inlet and outlet open in summer while to keep them closed in winter.

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