PERFORMANCE EVALUATION OF PV VENTILATED GLAZING

Tin-tai Chow[1,*], Zhongzhu Qiu[2], and Chunying Li[1]
[1]Building Energy and Environmental Technology Research Unit, Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Hong Kong SAR, China
[2]School of Energy and Environment Engineering, Shanghai University of Electric Power, Shanghai, China
[*]Corresponding author: Tel: 852-27887622; Email address: bsttchow@cityu.edu.hk

ABSTRACT

This paper reports the simulation approach and prediction of annual energy performance of PV ventilated glazing systems with daylight saving as applying to typical office environment. Our computer model was developed via the ESP-r simulation platform in association with the RADIANCE lighting software. The new attempt of using indirect interaction between the two simulation programs through daylight coefficient, together with the coupled air-flow network and energy balance technique, has been proved very useful in tackling this kind of long period analysis. The simulation results show that for the range of climate regions from tropical to temperate, the PV natural-ventilated glazing system has advantages over the absorptive natural-ventilated glazing option as well as the single-pane glazing systems.

INTRODUCTION

With the growing interest in renewable energy applications in modern cities, the investigations into the potential use of photovoltaic (PV) products in buildings become popular. A PV glazing, for example, is composed of two layers of clear glass panes and in between, a number of opaque c-Si solar cells connected in series. The electricity generation reduces the solar transmission through the window glass. Another advantage of the PV glazing is its natural light transmission since the spectrum of the transmitted light is almost identical to the incident light. The alternative use of semi-transparent solar cells in PV glazing can offer better scenery view and therefore more suitable for places where the people will stay longer. On the other hand, another approach to reduce solar transmission is the use of multi-pane window with airflow at the cavity, generally known as the ventilated window. Various combinations of glass sheets with top and bottom openings can be used. Compared with the single-paned window types, its distinct feature lies in the free or forced convection behaviour between the layers of glasses that form the cavity.

A natural-ventilated semi-transparent solar cell incorporated glazing system (D-PV) is shown in Figure 1, with a PV glass sheet as the external pane (complete with intake and discharge louvers) and a clear glass sheet as the internal pane. In order to evaluate numerically its long-term energy performance as compared to the conventional window systems, a simulation method has been developed for the task. The following introduces our approach and the findings.

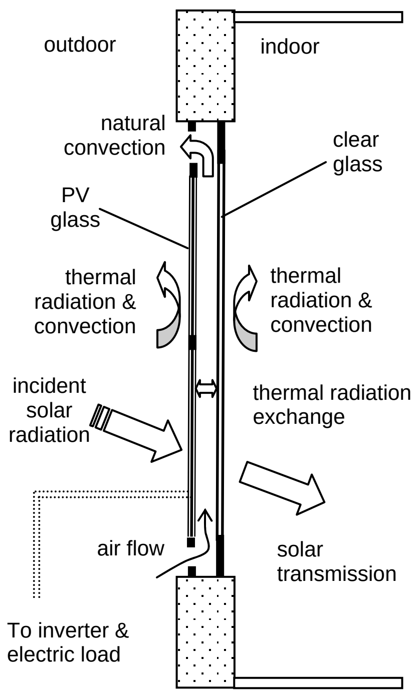


Figure 1 Cross-sectional view of natural ventilated PV glazing and energy flow paths.

SIMULATION METHOD

Simulation task

The task was to predict the electricity consumptions of the air conditioning (AC) and lighting systems for different glazing configurations in the office environment. The annual performance of the following four glazing systems with and without daylight control were analyzed:

(i) single-pane absorptive glazing (S-AB),

(ii) single-pane PV glazing (S-PV),

(iii) natural-ventilated double PV glazing (D-PV), and

(iv) natural-ventilated double absorptive glazing (D-AB).

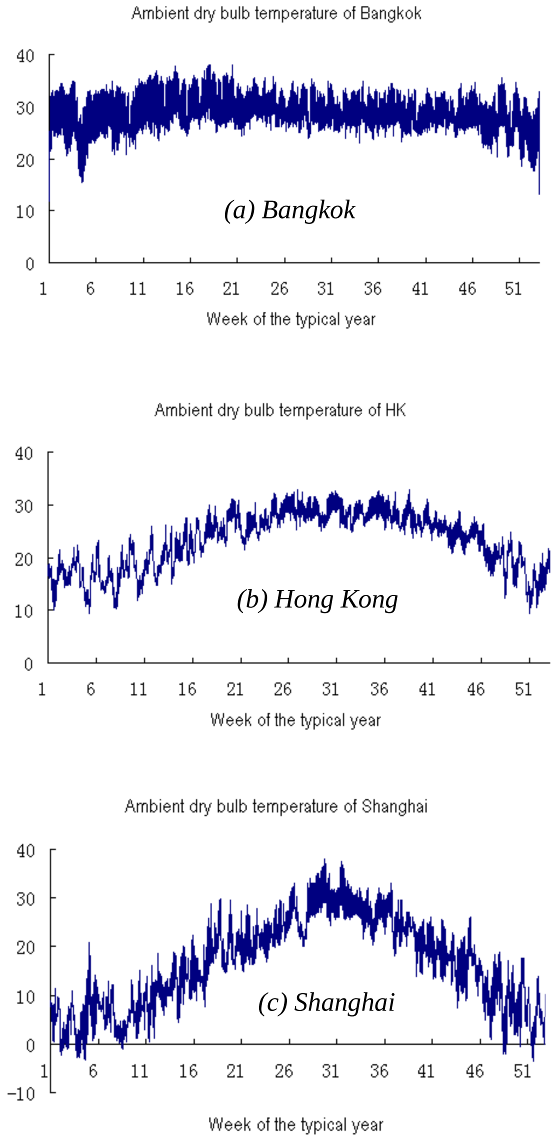


Figure 2 Variation of TMY ambient temperature (^oC) in Bangkok, Hong Kong and Shanghai.

Their integrative energy performance at three different modern Asian cities, i.e. Bangkok, Hong Kong and Shanghai were evaluated in turn. Bangkok (at 13^{o}N latitude) represents the tropical climate, Hong Kong (at 22^{o}N latitude) the subtropical climate, and Shanghai (at 31^{o}N latitude) the temperate climate regions. Their Typical Meteorological Year (TMY) weather files from the EnergyPlus website were adopted, and the simulations were performed over the 8760-hour period. Figure 2 shows the annual variations of ambient temperature of these three cities. In Bangkok, the temperature variation is relatively stable and the yearly average temperature is 28.5^{o}C. This is different from Hong Kong and Shanghai, where show distinct summer and winter periods. Amongst the three, Shanghai is the only city having ambient temperature occasionally lower than the ice point. The yearly average temperatures for Hong Kong and Shanghai are 23.1^{o}C and 16.3^{o}C respectively.

Simulation tools

In a ventilated glazing model, it is required to predict the airflow in the air cavity. This can be achieved by either one of the following two methods: (i) CFD simulation, or (ii) coupled air flow network and energy balance simulation. The CFD approach is impracticable to run whole-building simulations for an extended period of 8760 hourly steps. The coupled air-flow network and energy balance technique was therefore employed. Three simulation programs were used in this study, namely WINDOW, ESP-r and RADIANCE. A brief description of their applications is given below.

(i) WINDOW

Developed at the Lawrence Berkeley National Laboratory (LBNL), WINDOW (2003) can be used for determining the thermal and solar optical properties of window systems. It is composed of a series of libraries that almost cover the whole range of glazing properties. In particular, the Glass Library holds the thermal and optical properties of glazing materials, in that the total solar, visible and thermal infrared optical properties of a glazing system, as well as the thickness and thermal conductivity, are displayed. The glazing properties in the present work were obtained from this library.

(ii) ESP-r

ESP-r (ESRU 2002) is capable of simulating the building thermophysical processes within thermal zones, surface heat transfer regimes within rooms and with outside surfaces, 3D conduction within and between surfaces, and long/short wave radiation exchange between surfaces in rooms and with the outside environment. Apart from the above mentioned, the treatment of airflows between thermal zones based on nodal network airflow modelling is allowable (Clarke 2001). In the present study, the ventilated glazing system was divided into six thermal zones, as shown in Figure 3, in order to examine the airflow condition. The upper and lower openings were set as specific airflow openings, and the six thermal zones were set as constant-volume-flow components. In ESP-r, the airflow network method is to solve for the steady fluid flows within a network of connected pressure points (nodes) when subjected to successive sets of boundary conditions. In other words, the problem reduces to the calculation of mass flows through each connection when the nodes represent internal (unknown) and external (known) pressure conditions. Thermal zones are taken as internal nodes and the openings set as boundary/excitation nodes, which are dictated by the input thermal properties and weather file. Solution for any unknown internal node is obtained by an iterative approach in which the unknown nodal pressures are repeatedly adjusted considering wind and buoyant effects, until the nodal mass imbalances are within the tolerance limit.

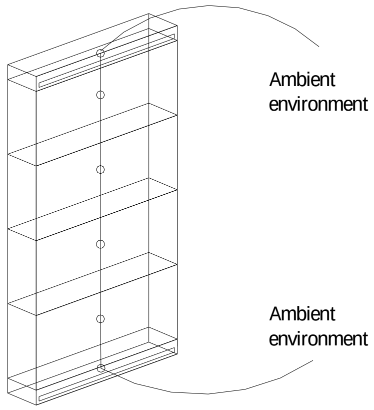


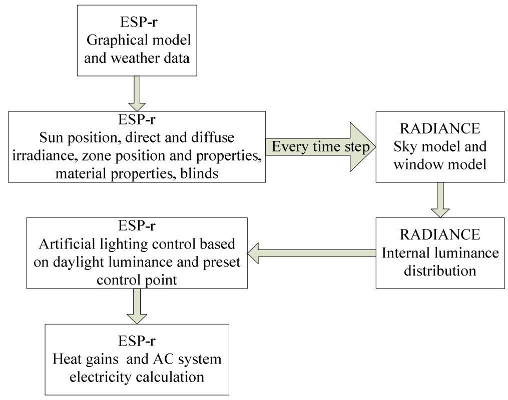
Figure 3 Simulation airflow network of D-PV window.

(iii) RADIANCE

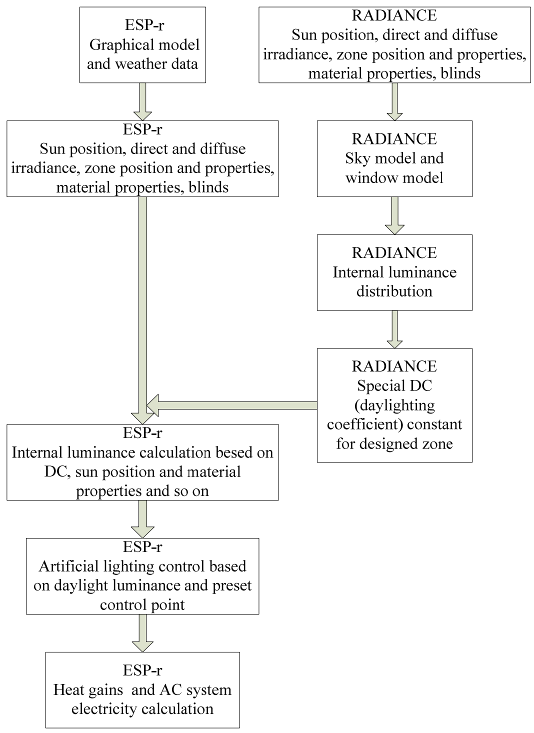
The lighting simulation engine of RADIANCE (1994) uses a hybrid approach of Monte Carlo and deterministic ray tracing to achieve a reasonably accurate solution within affordable time. The computation starts at a measurement point (usually a viewpoint) and traces rays of light backwards to the sources (i.e. emitters). The calculation procedures can be divided into three main parts: the direct component, the specular indirect component, and the diffuse indirect component. In addition, a secondary light source calculation may be performed for windows, skylights or other illumination "portholes". This is important when the focus is on indoor luminance condition with daylight transmitting through windows.

Interactive use of ESP-r and RADIANCE

In order to realize the daylight control function, and at the same time, to take the lighting load reduction to the space thermal load into account, ESP-r and RADIANCE were used interactively, in that RADIANCE calculated the luminance distribution while ESP-r exercised the artificial lighting electricity consumption control according to the indoor luminance distribution. There can be two methods for the integration: (i) direct, and (ii) indirect. The processes of these two methods are illustrated in Figure 4.



(a) Direct method



(b) Indirect method

Figure 4 Interaction of ESP-r and RADIANCE.

(i) Direct method

In the direct interaction approach, ESP-r acts as the simulation controller and integrator. At each simulation time step (when the lighting control is active and daylight is available) the ESP-r ‘parent’ process initiates a ‘child’ lighting simulation RADIANCE process in the foreground. This causes the parent process to stop and wait until the child process finishes (Janak 1997). With this method, each time step will accomplish with a lengthy computation period. When studying the daylight condition for a year-long period, the extremely heavy computation load makes the simulation an almost impossible task.

(ii) Indirect method

The conception of daylight coefficients (DC), which has brought into consideration the changes in the luminance of the sky elements, offers an effective way of computing indoor daylight luminance under various sky conditions and solar positions (Tregenza and Waters 1983). The DC approach is able to give more accurate results than the traditional daylight factor (DF) method, especially for internal spaces (Reinhart and Herkel 2000). This, together with the coupled air-flow network and energy balance, has the potential to simulate lengthy period, as in our case. So in our study, the indirect coupling method was adopted.

ANNUAL ENERGY EVALUATION

Building description

The length and width of the typical office flat in a multi-storey building were both 40.8m, with a floor-to-floor height of 3.6m. The 1665 m^2 floor area was divided into five zones, i.e. South, East, North, West and Central. A perspective view of the flat is given in Figure 5. Adiabatic ceiling and floor slabs were assumed. The key building parameters are listed below.

(i) Building envelope

Absorptance of wall = 0.7
Window-to-wall ratio = 0.6
U-value of opaque external wall = 2.43 W/m^2 °C
U-value of internal partitions = 4.02 W/m^2 °C

(ii) Space load conditions

Space air temperature settings: 24°C (summer)
21°C (winter)
Equipment load = 10 W/m^2
Lighting load = 20 W/m^2 (maximum)
Occupant density = 13 m^2/person
Infiltration rate = 0.2 ACH

Daylight control

Daylight control was applied at the perimeter zones (within 4-meter distance from the external wall). These zones represented 48% of the total usable area. The daylight control was assumed operating for 24-hour a day. As shown in Figure 6, the sensors were located at a 4m distance to the external wall and on the working plane level. Whenever the luminance level was above 882 lux at the sensor, the artificial lighting would be 100% switched off. If the luminance was between 630 and 882 lux, 90% lights would be switched off. In case the luminance was below 630 lux, then the percentage of lights switched off would vary linearly and inversely with the luminance level, until it reached 100% on at 0 lux.

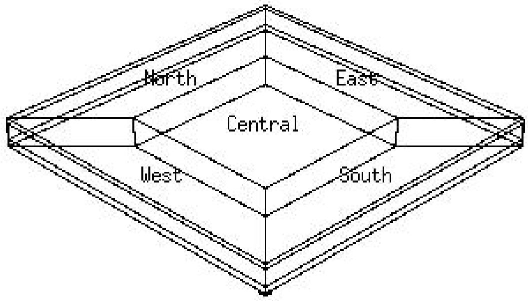


Figure 5 Perspective view of the office model.

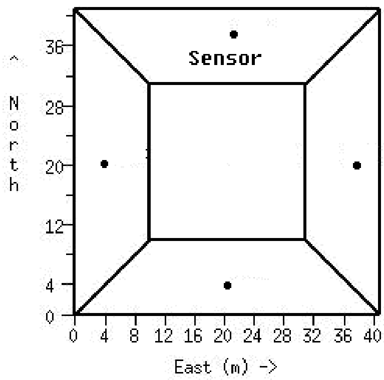


Figure 6 Locations of the luminance sensors.

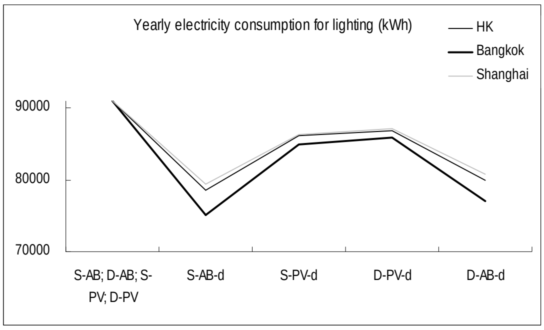


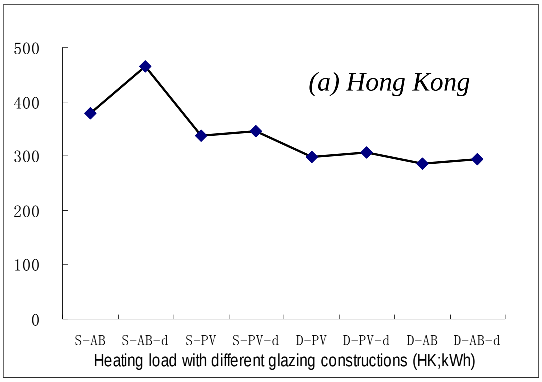
Figure 7 Annual electricity consumption (kWh) for lighting.

SIMULATION RESULTS

Electricity consumption on lighting

Without daylight control, electricity consumptions on artificial lighting were the same in all four window cases (S-AB, D-AB, S-PV and D-PV) for different cities, because of the same design illumination and operation schedule (see Figure 7). For the cases with daylight control (marked with suffix ‘d’), the energy saving potentials were all different - the highest was found in Bangkok and the lowest in Shanghai. This reflects that the lower the latitude, the more solar irradiance can be used as natural light source and more electricity on artificial lighting can be saved. Within the same city, the cases of S-AB-d and D-

AB-d were found able to utilize more sunlight than the cases of S-PV-d and D-PV-d. The percentages of light-energy saving through daylight control in the absorptive glazing configurations are thus higher than the PV glazing configurations. Also, the single glazing configurations can save more light-energy than double glazing configurations. This is owing to their higher transmissivity characteristics.



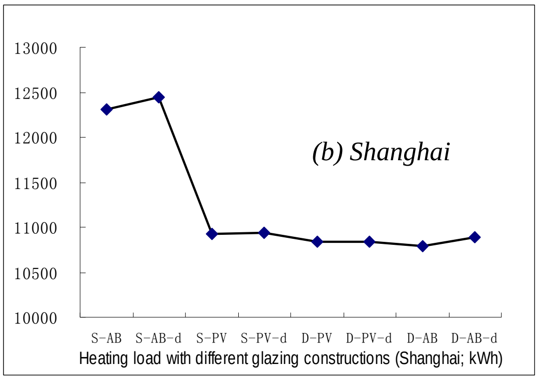


Figure 8 Annual space heating load (kWh) for Hong Kong and Shanghai.

Electricity consumption on space heating

In the subtropical Hong Kong, space heating was required in some winter morning hours, due to the lower air temperature overnight. As for Shanghai, the air temperature of the whole January was below 10°C, and the heating demand was therefore high. The space heating load of Bangkok was found zero throughout the typical year. Comparatively, the heating period of Shanghai was found longer than Hong Kong. There were heating loads in five months for Hong Kong: from November to March next year. The office in Shanghai required for space heating one month earlier, i.e. from October onwards. From Figure 8, it can be seen that the D-AB configuration was able to provide best heat preservation and consumed the least heating energy for both Hong Kong and Shanghai.

Space cooling load

In summer, the ambient temperature is the highest in August for all three cities. As a result their cooling load patterns are similar. In winter, the cooling load of Bangkok was found to be almost the same as in summer. The cooling load of Hong Kong in winter was about half of that in summer, while in Shanghai, this percentage was found only around 10% to 20%. One merit of using daylight control is the save in cooling energy through the cut in lighting load. From Figure 9, it can be seen that for the three cities, the effect of glazing configuration on cooling load saving is similar. The cooling loads for all PV glazing configurations were substantially reduced, no matter there was daylight control or not. The base case S-AB has the highest annual cooling load demand, the D-PV glazing requires the least, whereas those of the D-AB and S-PV glazing configurations are between these extremes.

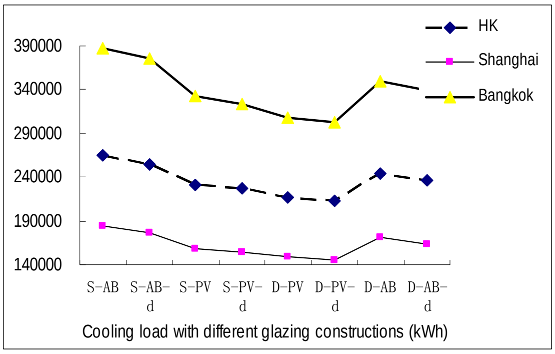


Figure 9 Annual space cooling load (kWh).

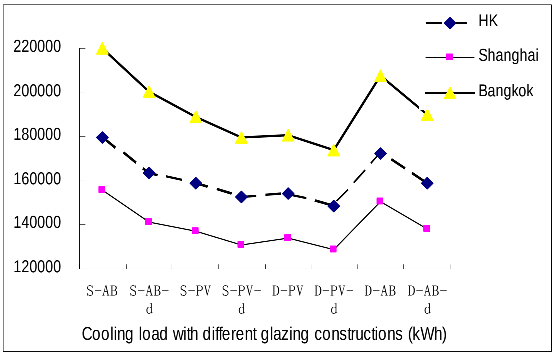


Figure 10 Annual electricity consumption (kWh) for AC and lighting systems.

PV electricity output

The annual electricity generation performance for S-PV glazing is summarized in Table 1. The results were based on the algorithm developed from the JOULE project PV-HYBRID-PAS (Clarke et al. 1998) funded by the European Commission. It can be seen that the PV-glazing has the best electricity output in Bangkok. Hong Kong and Shanghai have the similar reduced levels of output at around 70%. The D-PV cases had very similar performance to the S-PV cases with the difference in outputs less than 1%.

Table.1
Annual electricity production (kWh) of S-PV glazing configuration for different zones and cities

	South	East	North	West	Total	Percentage (%)
Bangkok	3,894	3,061	1,732	4,389	13,080	100
Hong Kong	2,977	1,981	1,034	3,186	9,178	70
Shanghai	3,464	2,067	9,10	2,988	9,428	72

Table 2
Yearly AC system and lighting electricity consumption (kWh) with different glazing configurations

	S-AB	S-AB-d	S-PV	S-PV-d	D-PV	D-PV-d	D-AB	D-AB-d
Bangkok	220,200	200,500	188,700	179,700	180,700	174,100	207,600	190,100
Percentage (%)	100.0	91.0	85.7	81.6	82.0	79.1	94.3	86.3
Hong Kong	179,400	163,600	159,100	152,700	154,300	148,900	172,400	158,700
Percentage (%)	100.0	91.2	88.7	85.1	86.0	83.0	96.1	88.4
Shanghai	155,500	141,300	137,000	131,100	133,800	128,800	150,600	138,000
Percentage (%)	100.0	90.8	88.1	84.3	86.0	82.8	96.8	88.8

Electricity consumption of AC and lighting systems

Table 2 summarizes the overall annual electricity consumptions of the above glazing systems. The results were based on the AC system COP (coefficient of performance) of 3.0 for cooling and 4.0 for heating. The PV electricity generation was assumed fully consumed in the office building. The electricity consumption of AC and lighting systems in Bangkok was found relatively stable throughout the year. For Hong Kong and Shanghai, the electricity consumption in summer (especially in August) was found to be almost twice of those in winter. For all the three cities, the office flat had the least overall electricity consumption when the D-PV-d glazing (natural ventilated double PV glazing with daylight control) system was used. Compared with the base case (S-AB glazing), the energy saving potentials were found 21.9%, 17.0% and 17.2% for Bangkok, Hong Kong and Shanghai respectively.

CONCLUSION

Using daylight control and novel glazing configurations such as PV ventilated glazing systems can improve significantly the electricity consumption in office buildings. These effects have been investigated through numerical simulation with ESP-r software at three cities: Bangkok, Hong Kong and Shanghai. The simulation approach and the results have been discussed. The mixed use of indirect interaction between ESP-r and RADIANCE via daylight coefficient, together with the coupled air-flow network and energy balance technique, was proved to be very useful in tackling this kind of annual analysis. The simulation results indicate that for the range of climate regions from tropical to temperate, the natural-ventilated double PV glazing system has the highest energy saving potential and thus this is worthy for further analysis.

ACKNOWLEDGEMENT

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