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Exploring the optimization potential of thermal and power performance for a low-energy high-rise building

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Abstract

In this study, a novel high-efficient energy-saving vacuum BIPV (building integrated photovoltaic) curtain wall, which combines photovoltaic curtain wall and vacuum glazing technologies, was developed and investigated. This vacuum BIPV curtain wall can not only perform on-site power generation, but also significantly reduce the heat transfer through the building envelope with improved thermal insulation. The thermal and power performance of the vacuum PV glazing were investigated by experiments and numerical simulations. A prototype of the vacuum BIPV curtain wall was set up for a short-term outdoor testing to consolidate its thermal and power performance under typical weather conditions of Hong Kong. A comprehensive energy model was then developed to predict the dynamic power and thermal performance of the vacuum BIPV curtain wall to evaluate its annual energy saving potential compared to other advanced window technologies used in buildings in Hong Kong. Based on the simulation model, an optimum design of the vacuum BIPV curtain wall was proposed. In addition, the annual energy-saving potential for a typical high-rise commercial building with the application of miscellaneous BIPV products was estimated using the typical meteorological data. BIPV characteristics were jointly optimized with other passive architectural design parameters and the net building energy demand can be decreased by up to 60% compared with a benchmark office building in Hong Kong. The target of near-zero energy high-rise building can therefore be further approached by this integrated design optimization process.

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Keywords: Optimization, Thermal performance, BIPV, Power generation, Vacuum

1. Introduction

As a new functional curtain wall, the solar photovoltaic (PV) glazing has attracted a great deal of attention from the construction industry in recent years due to its novel integral function of power generation, decoration and

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simultaneously serving as building envelope materials. Briefly, it combines the PV and curtain wall technology, representing a new direction of the development and application in the future building industry. Integrated with solar cells, the curtain wall can convert sunlight into electricity and become an architectural power generation system. In this sense, the technology can utilize renewable sources for energy saving and CO_2 emission reduction. Usually, PV modules can be integrated into building facades without impairing their outlook. One of BIPV applications, semi-transparent photovoltaic (STPV) windows, has gained increasing popularity as an alternative of traditional building envelope, because it can provide electricity while maintaining its daylight function. Many researchers conducted experimental and simulation studies on this new application. Lu and Law [1] investigated the overall energy performance of a single-pane semi-transparent PV window applied in commercial buildings. The thermal performance of glazing is determined to be most important for energy saving in their research. The energy conversation effect of semi-transparent PV windows was also reported in comparison to the traditional glazing.

However, current PV envelope with common double-glazing performs poorly in thermal insulation due to the high solar heat gain coefficient (SHGC) and U-Value [2]. The vacuum glazing technology, which was initially proposed by Zoller in 1913 [3], could minimize conductive and convective heat transfer through the glazing unit by introducing a vacuum chamber in it. Compared with a normal double glazing, the vacuum glazing exhibits superior heat insulation performance with an extremely low U-value (lower than 0.86 W/m^{2}K [4]). Therefore, if the vacuum glazing could be applied in PV envelopes, the indoor air-conditioning loads are anticipated to be further reduced. Furthermore, the vacuum glazing has excellent sound insulation performance, which is also significant for its application in urban built environment.

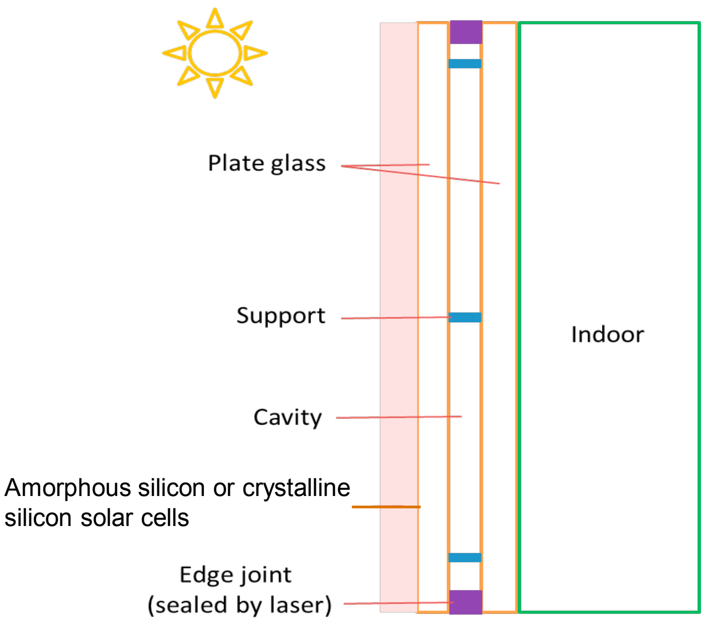

Fig.1. A schematic configuration of the proposed vacuum BIPV curtain wall panel

Based on the above review and our previous study PV curtain wall application in Hong Kong [5-7], we would like to propose a novel energy-saving vacuum PV glazing, which combines the current photovoltaic curtain wall and vacuum glazing techniques. A schematic configuration diagram of the proposed vacuum BIPV curtain wall is shown in Fig. 1. A systematic study is carried out on the overall energy performance of the developed curtain wall, and its application potential is evaluated for applications in Hong Kong. It is expected that the developed vacuum BIPV curtain wall technology will substantially reduce the heat gain and heat loss of buildings, and the research outputs will provide valuable information and theoretical basis for developing energy-saving solar PV curtain walls in the future for the local industry.

2. Research methodology

2.1. Experiment test specification

Experimental tests of the thermal and power performance of the developed PV vacuum glazing involve miscellaneous equipment such as pyranometers, I-V curve tracers, spectrometers thermocouples, heat flux meters and data loggers. These devices, whose specifications are summarized by previous research [5, 6], are used for measuring environment temperature, power generation properties, solar radiation and its spectrum distribution, glazing surface temperatures as well as heat fluxes through glazing. All sensor signals are recorded once per minute with a GL840 Midi Data Logger processing signals including the voltage, temperature, humidity, pulse and logic signals.

2.2. Building performance modelling

EnergyPlus 8.3.3 and WINDOW 7.0 are coupled to investigate the energy and indoor environmental performance of an adapted prototype office building. WINDOW has a comprehensive library of glazing with miscellaneous combinations of glass and gas layers, where the optical and thermal properties of a selected glazing can be generated and converted to a format compatible with EnergyPlus. EnergyPlus can perform daylight, airflow, thermal balance and renewable power modelling [8], whose results have been validated by existing research [9-11]. A joint simulation model is then developed by combining two modelling platforms to compare the performance of different envelopes of the prototype office building. The overall building energy and indoor environment performance can then be obtained from a cooperation of sub-modules including the thermal balance, daylighting, airflow network and power generation model.

2.3. Holistic design optimization

To further achieve a holistic design optimization process for daylight, ventilation, thermal conditions and power generation, a joint modelling platform will be developed with the combination of EnergyPlus and R programming. The possibility distribution function is first determined for all design inputs and the FAST (Fourier Amplitude Transformation Analysis) based sensitivity analysis (SA) with bootstrapping is adopted to exclude non-significant design parameters form the problem space. FAST is adopted for factor prioritizing because of its adaptivity to non-linear or non-additive models. The variance of model outputs can be therefore denoted as per Eq. (1):

$$V(Y) = \sum_{i=1}^{k} V_i + \sum_{j>i}^{k} V_{ij} \cdots + V_{12\cdots k} \tag{1}$$

When conducting the modelling experiments, a machine learning method (SVM) is used to obtain a metamodel to substitute EnergyPlus simulation. SVM is a non-parametric modelling algorithm capable of the non-linear regression, whose kernel functions is obtained by minimizing the output deviations as per Eq. (2):

$$k(x, x') = \exp(-\sigma \| x - x') \|^2) \tag{2}$$

The obtained surrogate model is further fine-tuned in R to optimize the setting of the machine learning process. The ultimate favorable design solutions are derived from the combination of metamodels and genetic algorithms.

3. Results and discussion

This session presents the main findings and outcomes of the research project and indicates their potential impacts on the local energy use and construction industry. Achievements of the specified research objectives are illustrated, and limitations of the project are also mentioned for the reference of future studies.

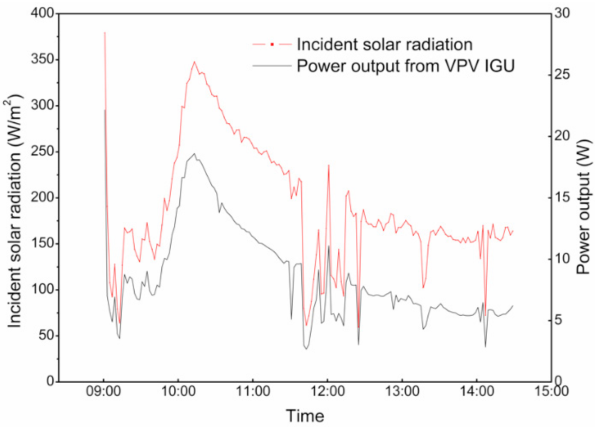

Fig. 2. Power output from the vacuum PV glazing in a sunny day (South facing)

3.1. Experimental study of the vacuum PV glazing

Outdoor experimental test is first conducted on the developed prototype vacuum PV (VPV) glazing of the standard size, whose various parameters including the ambient air temperature, incident solar irradiation, surface temperatures of the vacuum PV glazing as well as the I-V curves and the power generation were measured and recorded. The power generation and thermal performances of the prototype were also analyzed during the test. Fig. 2 presents the instantaneous power output of the vacuum PV glazing in two continuous sunny days. It can be obviously observed that power generation from the vacuum PV glazing is consistent with incident solar radiation. A comparative study in terms of internal air temperature of the chamber between the vacuum PV glazing and clear glass was conducted in June on a campus building [12].

3.2. Simulation study of the vacuum PV glazing

The developed simulation model was applied to a 20-floor prototype office building. Typical floors of the building are divided into 5 conditioned zones, with a total floor area of 540 m^2. The reference case – Model 1 keeps the curtain wall as the commonly used double-pane clear glazing, while the design cases include Model 2 and Model 3. Model 2 changes all curtain walls to the developed vacuum PV glazing. The opaque part of all building facades is assumed to be covered with traditional crystalline BIPV with a power conversion efficiency of 15% to maximize the power generation potential of the building envelope. Model 3 shares similar settings with Model 2, except that the window transparency is tuned to 20% with a crystalline silicon (c-Si). The U-value and SHGC of a-Si vacuum PV glazing are obtained from previous experiments and those of double-pane clear glazing are calculated by the simulation software WINDOW. Thermal and power generation properties of c-Si vacuum PV glazing are obtained from existing literatures. The comparison of building energy between Model 1, Model 2 and Model 3 is summarized in Table 1.

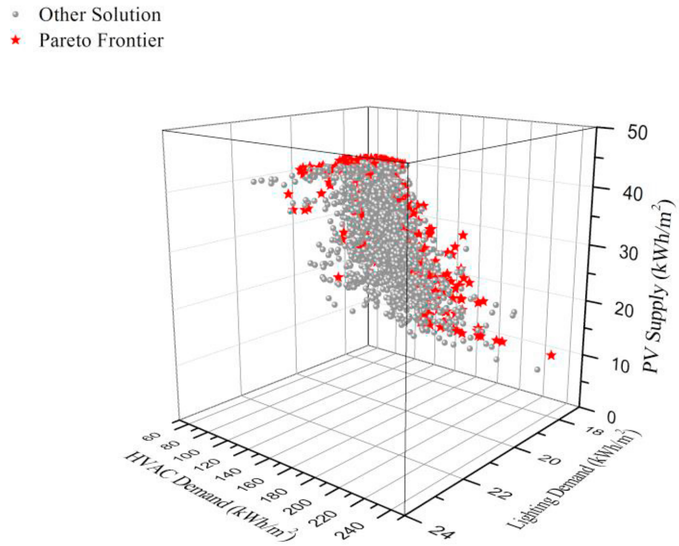

Fig. 3. The 3D plot of Pareto optimal solutions

3.3. Further design optimization of the prototype office building

The PV glazing is further jointly optimized with traditional architectural design factors including the Visible Light Transmittance (VT), Window U-value (WU), Overhang projection ratio (OPF), Building Orientation (BO), Infiltration Air Change per Hour (IACH), Wall Thermal Resistance (WTR), Wall Specific Heat (WSH), Window to Wall Ratio (WWR) and Light to Solar Gain ratio (LSG). Based on the integrated optimization process, the Pareto optimal solutions were highlighted in Fig. 3, where a clear trade-off between the total HVAC demand, lighting demand and PV supply can be observed when all design parameters are varied simultaneously. The final optimum solution achieved a minimized net building energy consumption of 110.33 kWh/m^2, which leads to around 60% energy saving compared with the benchmark case specified in Section 3.2 (i.e. Model 1).

Table 1: Comparison building energy consumption/generation for three models

	Lighting (kWh/m^2)	Equipment (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	PV (kWh/m^2)	Total (kWh/m^2)	Saving (%)
Model 1	35.27	44.87	197.80	0.24	-	278.18	-
Model 2	35.27	44.87	127.46	0.16	22.96	184.80	33.57%
Model 3	35.27	44.87	107.13	0.47	39.59	148.15	46.51%

4. Conclusions

This research mainly developed an innovative product incorporating the advantages of BIPV and vacuum glazing. An outdoor field measurement was conducted with the designed prototype to evaluate the energy performance of the vacuum BIPV glazing. The prototype achieved excellent solar shading and thermal insulation with a large air temperature difference between the internal and external ambiance. A comprehensive simulation model coupling EnergyPlus and R was developed to compare the overall energy performance (i.e. thermal and power generation properties) of the product with other commonly available windows. To explore the maximum energy saving potential for a high-rise commercial building, the product was assumed to be applied to all facades of the developed building model. Based on simulation results, an optimized vacuum PV curtain wall design was achieved to maximize its overall energy performance in terms of the power generation and air-conditioning load reduction with a total energy saving up to 60%. The developed technology can also be used to fulfil energy use criteria in local/global green building assessment schemes, by which the target of near-zero energy building can be further approached. In future work, a brief design guideline is to be developed to promote the application of the new envelope system in the local construction industry.

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