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Numerical investigation of a novel vacuum photovoltaic curtain wall and integrated optimization of photovoltaic envelope systems

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HIGHLIGHTS

- VPV IGU can reduce up to 81.63% and 75.03% of heat gain in Hong Kong and Harbin.
- Sensitivity analysis is conducted to evaluate the influence of design parameters.
- High-efficiency design optimization is suitable and reliable for initial designs.
- VPV IGU is more suitable for application in cold areas with small glazing area.
- Systematic approach detailed can provide user guidelines for BIPV applications.

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ABSTRACT

This study presents a comprehensive investigation of the thermal and power performance of a novel vacuum photovoltaic insulated glass unit (VPV IGU) as well as an integrated design optimization of photovoltaic envelope systems. A prototype office building model with a curtain wall design is first constructed in EnergyPlus to compare the heat gain, heat loss, thermal load, lighting energy and PV generation for different curtain walls. The comparative analysis proves the excellent thermal insulating performance of VPV IGU, which can reduce up to 81.63% and 75.03% of the heat gain as well as 31.94% and 32.03% of the heat loss in Hong Kong (HK) and Harbin (HB) respectively. With the application of VPV IGU in all available facades of the prototype building, net energy savings of 37.79% and 39.82% can be achieved in diverse climatic conditions. Furthermore, screening and variance based sensitivity analyses are conducted to prioritize building integrated photovoltaic design parameters with respect to specific weather conditions. The selected important design parameters are then optimized with the non-dominated sorting genetic algorithm-II (NSGA-II), by which the optimum building design can achieve a net energy consumption reduction of 48.72% and 60.80% compared to benchmarking designs in Hong Kong and Harbin. Such an integrated design optimization can successfully improve computation efficiency with an acceptable solution accuracy, and assist the incorporation of PV envelop systems with passive architectural designs. The novel VPV IGU is determined to be more suitable for cold areas where the curtain wall design should also be avoided for energy conservation.

1. Introduction

The building sector plays a critical role in the total energy consumption of human communities. As reported in the statistical year book of 2015, energy consumption of commercial and residential sectors accounted for 64% of total energy use in Hong Kong, with 43% for the commercial and 21% for the residential use [1]. Accompanied by the aggravation of the energy crisis, energy conservation has received more attention from researchers. Although solar energy is recognized as a promising alternative energy source, it merely takes up 1.8% of utilized renewable energy in Hong Kong. As a result, there is still a great potential for developing the building integrated photovoltaic (BIPV), which can help cut down energy bills of the building sector without additional land use [2].

1.1. BIPV applications

BIPV can simultaneously serve as the building component and

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power generator, and its integration with building facades usually causes no negative impact on their appearance [3]. Semi-transparent photovoltaic (STPV) windows, as one prospective BIPV applications, can generate electricity while allowing partial daylight penetration. Given its increased popularity in building envelope designs, many researchers conducted experimental and simulation studies on this new application. Fung and Yang developed a one-dimensional transient heat transfer model to evaluate the heat gain of semi-transparent photovoltaic modules for the building-integrated application [4]. Lu and Law investigated the overall energy performance of a single-pane semi-transparent PV window for office buildings in Hong Kong [5]. The results showed that the glazing thermal performance was critical for energy saving in the building envelope. The energy saving potential of semi-transparent PV windows was also reported in comparison to the traditional glazing [6,7]. STPV can contribute to better overall building energy performance compared with single and double-pane clear glazing in Hong Kong' climatic condition [8]. Furthermore, the PV insulating glazing unit (PV IGU) was proved to have better thermal performance than the PV double skin façade (PV DSF) based on numerical simulations and experimental validations conducted in Hong Kong [9,10].

However, a shortcoming of the current PV curtain wall with common double-glazed PV modules lies in the poor thermal insulation performance due to the high solar heat gain coefficient (SHGC) and U-Value [11]. BIPV modules can still have a thermal conductivity of 1.1 W/m K, even when inert gas filled up the gap within a double-glazing unit [12]. The vacuum glazing technology, which was initially proposed by Zoller in 1913 [13], could minimize conductive and convective heat transfer through the glazing unit by introducing an internal vacuum chamber. Compared with a normal double glazing, the vacuum glazing exhibits superior heat insulation performance, which is identified by its U-values. U-value of the vacuum glazing can be as low as 0.86 W/m^2 K, indicating a much better performance than a double-glazing [14]. Therefore, if the vacuum glazing could be coupled with PV curtain walls in buildings, the heat gain and heat loss could be further reduced. In addition, the vacuum glazing has excellent sound insulation performance owing to its vacuum environment, which is considered an added value for buildings in urban areas.

Based on the above discussion and our previous study of the PV curtain wall application in Hong Kong [10,15], a novel energy-saving vacuum PV glazing was proposed. The vacuum photovoltaic insulated glass unit mainly consists of an outer PV laminated glass and an inner vacuum glass as shown in Fig. 1. The thermal and power performance has been investigated under both outdoor weather conditions and indoor standard test ambiance, while its application potential on vertical facades of typical high-rise commercial buildings requires further exploration, which will be presented in this research work.

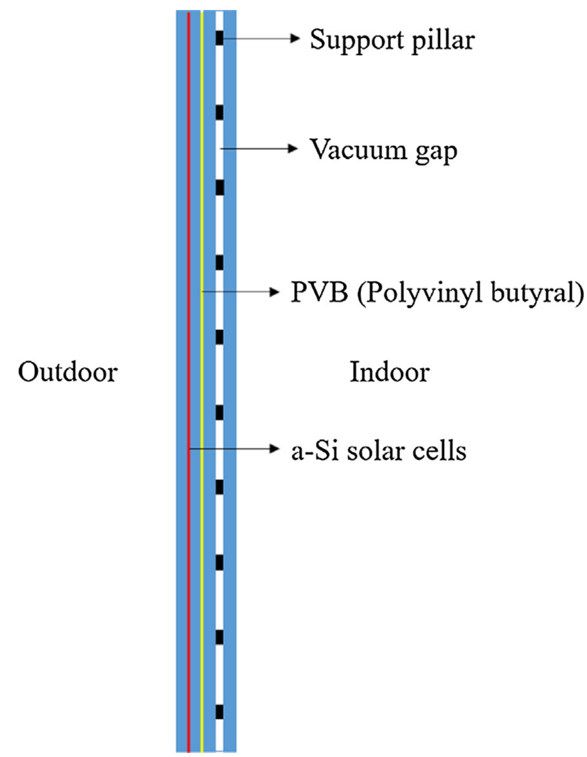

Fig. 1. The structure of VPV IGU.

1.2. Building design optimization

High-rise commercial buildings in Hong Kong usually adopts curtain wall as the external building envelope. To maximize the overall energy efficiency of PV curtain wall systems, extensive sensitivity analyses (SA) and optimizations are necessary for facilitating the resource allocation and decision-making to design low-energy buildings. Global sensitivity analysis with screening-based and variance-based methods are proved to be suitable for non-linear and non-additive building models with complicated envelope designs [16]. Morris is a classic screening-based SA approach, where the relative importance of design factors can be qualified with a small sampling dimension [17,18]. Silva et al. conducted an initial sensitivity analysis with Morris for a multi-criteria decision-making process to improve building energy and thermal performances [19]. The non-linear effect and relative importance of design factors were successfully identified for the factor prioritizing and fixing. The Fourier Amplitude Sensitivity Test (FAST) method, on the other hand, can quantify the influence of each design factor on the model output [20,21]. Mechri et al. conducted the analysis of variance (ANOVA) for the energy performance of an office building regarding the building compactness, orientation, envelope thermal properties and local shadings [22]. The methodology was proved useful for architects to evaluate the exact impact of each design strategy. ANOVA with FAST was applied to quantify the influence of design parameters over the available solar radiation on building facades. The building location, orientation and shading feature were determined to be the top three factors responsible for the major uncertainty of solar fractions.

The identified key design factors can then be subject to an integrated optimization of the overall building energy performance by simultaneous considering the lighting, cooling, heating and PV energy. Ascione et al. conducted a two-stage cost-optimal analysis of energy retrofit measures with the combination of EnergyPlus and MATLAB [23]. The energy retrofit measures mainly focus on the thermal properties of external building envelope and energy recovery systems. The developed multi-stage optimization approach was also applied in the design of a net-zero energy building in the Mediterranean climate, where the property of building geometry and phase changing materials were also investigated [24]. Multi-objective optimizations involving the lighting, cooling and heating loads were conducted based on both the swarm intelligence and genetic algorithm [25,26]. These studies also investigated the influence of window thermal and geometric properties under different climatic conditions. Apart from building energy and economic indices, indoor environmental performances including the thermal comfort, visual comfort and air quality were also investigated by a multi-objective optimization with the combination of GenOpt and EnergyPlus [27]. Multi-dimensional Pareto optima were obtained to offer design alternatives for decision-makers to reach the final design solution. Adaptive variation of optimization settings was also conducted to derive the most suitable configuration of genetic algorithms [28]. In addition, surrogate models of traditional simulation tools were incorporated into the optimization process to significantly improve the computation efficiency. Extensive modelling experiments can then be completed within a short time period for a swift decision-making in an early design stage [29].