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A comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds

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HIGHLIGHTS

- A new double skin façade using photovoltaic blinds was proposed and studied.
- Experiment and simulation method were used for comparative study.
- Influence of different system ventilation modes and blind parameters were analyzed.
- Thermal performance of proposed façade and standard double skin façade was compared.

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ABSTRACT

The glazing façade is embraced by architects, but this configuration may result in huge energy consumption. This research proposed a new double skin façade using photovoltaic (PV) blinds as a shading device (named PVB-DSF), which could realize multi-function of power generation, solar penetration reduction and flexible daylighting control. The purpose of this comparative study is to demonstrate the superb thermal performance of PVB-DSF. Experimental rig was built at hot-summer and cold-winter zone of China. The first stage comparative study was conducted to evaluate system thermal performance under the effects of ventilation modes, PV-blind angle and PV-blind spacing. The second stage study was conducted to compare thermal performance between PVB-DSF and standard DSF. A validated numerical model was used to describe standard DSF. The results suggested the operation of natural ventilation mode and indicated the evident influence of PV-blind spacing on system performance. The comparison study further demonstrated that PVB-DSF can save about 12.16% and 25.57% of energy in summer compared with conventional DSF with and without shading blinds. The insulation performance of PVB-DSF is shown by its daily average heat transfer coefficient which was as low as 2.247.

1. Introduction

Building envelope plays a vital role in protecting the indoor environment and controlling indoor and outdoor space interactions [1], but also is a major reason for huge building energy consumption in terms of space cooling and heating [2]. External wall and glass façades (or windows) are two kinds of building envelope. Extensive researches indicated that conventional window or glazing façade is responsible for about 40% of the total building energy consumption [3–7]. It is the modern architectural aesthetics rather than the superior system performance that facilitates the popularity of conventional glazing facade. Actually, the ever increasing building energy consumption is partially the results of massive installation of glazing facade without energy saving considerations.

Currently, double glass window or double skin façade (DSF) is widely applied to commercial and public buildings around world due to its better thermal performance. DSF refers to a building façade covering one or more levels with multiple glazed skins, separated by an air gap, with the common attribute of controllable shading system and airflow within the cavity between the skins of the façade [8,9]. Some DSF structure has combined with overhangs which proved to be energy efficient [10].

A number of experiments, numerical simulations or case studies were implemented to understand the energy saving potential of standard DSF. Different research conclusions about energy saving potential of DSF may be different in various climate zones applications, and those reported results of energy saving potential are ranging from negative to 50%. A comparative study by Chan et al. [11] showed that DSF using reflective glazing as the outer pane can cut up to 26% of building cooling energy annually. However, the payback time is as long as 81 years. In another study on

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the thermal performance of DSF based on the ESP-r simulation, the results indicated that DSF can save 20% of heating energy demand compared with single-skin façade [12]. The field experimental study by Xu and Ojima showed that 10–15% and 20–30% of energy could be saved by DSF in summer and winter respectively [13]. From extensive literatures reading and learning, it is implied that DSF may not be the best option for building energy conservation in every region [14] considering climatic features and other factors.

Apart from the advantages of DSF, two big challenges confronted by conventional DSF were summarized by Ghaffarianhoseini in a review study [1]. One of them is the initial cost concerning system design, construction as well as high cleaning, operating, inspection and maintenance costs in comparison to the conventional façades [1]. Another challenge is the high risk of unacceptable performance including the overheating problem in summer [15,16] and other economic factors [12]. For the past decade, advanced materials and new structures were applied to fix the mentioned problems of glazing façade and most of the structures are almost evolved and inherited from the prototype of conventional double glass façade. There are about 8 types of materials used in the newly developed glazing façade, which are insulating and phase change material (PCM) material, reflecting material, electrochromic material, thermochromic material, photovoltaic material, water film based material and other materials [17]. When those materials are used in glazing façade, they can largely reduce solar heat gain and heat loss in summer and winter respectively. Among those materials, c can not only improve system thermal performance, but also transform parts of solar energy into direct electricity. Different PV cells may have their specific property and some limitations currently, but this technology is deemed as one promising solution for the energy problem, especially in the building sector.

In order to enhance glazing system performance with little damage to the transparency of PV glazing facade, the PV materials and glazing structure should be fairly designed and optimized. There are 4 kinds of PV materials used to model semi-transparent PV glazing system. They are Crystallic silicon (c-Si), Amorphous silicon (a-Si), Dye sensitized solar cells (DSSC), and Organic photovoltaics (O-PVs). The later three kinds of materials are semi-transparent in nature. Therefore, a-Si, DSSC and O-PVs can be directly used as the external skin of PV-DSF structure to realize multi-function of daylighting, heat gain reduction and power generation. However, c-Si as an opaque PV cell, if it is to be used to manufacture semi-transparent PV glazing, has to be uniformly installed on the surface of external glass while leaving some room for sun light penetration through the uncovered regions [18,19].

Semi-transparent PV-DSF structures by c-Si and a-Si cells received more attentions from researchers gradually [20–22] and they even have been applied in some demonstration projects. Researchers from Hong Kong conducted experimental test and energy simulation on a new type of see-through (a-Si) semi-transparent PV module as double glazed window [23] which is similar to the system studied by Peng et al. [24,25]. It was concluded from the study that this new PV window can curtail heat gain by 47.8% and 38.9% compared with single clear glazing windows and double-pane windows under Hong Kong climate condition. Moreover, this structure can achieve equivalent thermal performance as low-E window. Besides, Myong and Jeon [26] demonstrated the another effective and efficient bifacial TBC a-Si:H PV cells. As for the application of semi-transparent PV in cold season, Taffesse et al. [27] derived a periodic modeling method for energy simulation of semitransparent photovoltaic thermal Trombe wall system. The proposed computation method was used to optimize the parameters of this PV envelope. In Skandalos's work [28], the optical, thermal and electrical simulations were conducted using TRNSYS software to analyze and optimize a-Si and c-Si PV window. Results showed that maximum saving for cooling energy occurs during September, while maximum increment in heating energy was found in December. Two configurations of semi-transparent PVT system were presented by Shyam and Tiwari [29], analysis indicated that for 30 years life time and 4% interest rate, the unit cost of electricity was \$0.016 for overall thermal saving and \$0.109 for exergy saving respectively.

Although PV glazing façade has exhibited its energy saving potential in cutting cooling and heating load of buildings [30], daylighting control in daily operation seems unattainable. On one hand, whether it is a-Si or c-Si PV-DSF, daylight transmission through PV cells is unchangeable. This is the reason that some studies are trying to improve indoor visual comfort level by optimizing the daylight and solar transmission through PV module [30,31]. On the other hand, we noticed that conventional DSF usually can shield part of direct solar radiation by placing louvers in the air cavity. However, the conventional shading device can be easily heated up to 60 °C in hot summer [32] and then become a heat radiation source. Phase change material (PCM) were adopted to buffer the heat transfer process [33]. Shen and Li [34,35] designed a pipe-embedded DSF system using natural cooling sources like a cooling tower or underground soil. The pipe-embedded DSF is proven to be at least 20% more energy efficient than conventional DSF according to their CFD simulations, but this system performance is obtained based on the supply of cool water.

This study presents a new DSF structure with built-in PV binds working as a shading device, power generator as well as the thermal performance enhancer. The purpose of this study is going to demonstrate superb thermal performance of PVB-DSF by checking the influence of operation modes, PV-blinds parameters and comparing with standard DSF system under various energy indexes. Because glazing façade suffered a more serious problem of heat gain in summer conditions rather than heat loss in winter conditions, this research is focused on comparative study of PVB-DSF system in cooling season. Some researchers previously have realized the possibility of combing PV cells and venetian blinds to shade solar irradiance while converting parts of radiation into electricity [36,37]. But there are two major limitations within their works: (1) the PV cells are directly attached onto the surface of blinds [38] which is not good for heat dissipation of PV modules; (2) although system optical [38] and electricity generation [38,39] analysis were provided, system thermal performance and full sized experimental investigations about DSF integrated PV-blinds are still not reported. Based on those two considerations, this research proposed a new DSF integrated with PV-blinds (named as PVB-DSF) and explored the system thermal performance by both experiment and simulation. The basic contribution of present study is to provide better solution for lowering heat gain of glazing façade while using PV cells for power generation. The system thermal performance is going to be demonstrated and discussed in detail.

2. Description of PVB-DSF system

In essence, the proposed new glazing façade adopted venetian blinds made from photovoltaic as shading device sandwiched by external and internal glass pane. Because this structure integrates PV-blinds with DSF, it is called as PVB-DSF in short within this research. Fig. 1 depicts a sketch of PVB-DSF installed on a south-facing wall. In order to deliver a clear presentation of this system, both lateral section view and top view from section A-A are provided respectively by Fig. 1(a) and (b). Dimension information about the PVB-DSF is listed in Table 1. The so called PV-blinds are made of a-Si PV cell in the shape of the narrow and long slats,