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Indoor daylight distribution in a room with integrated dynamic solar concentrating facade

Li Zhu [a], Zebiao Shao [a], Yong Sun [a,*], Veronica Soebarto [b], Feng Gao [a], George Zillante [b], Jian Zuo [b]

[a] School of Architecture, Tianjin University, Tianjin, 300072, China
[b] School of Architecture & Built Environment, The University of Adelaide, SA, 5000, Australia

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ABSTRACT

Concentrating solar technology for building façade has attracted a growing level of attention due to its complex structure and dynamic optical properties. In the study presented in this paper, a new concentrating module using Fresnel lens as a concentrator has been designed to be integrated into a building curtain wall while a new connection control structure has been designed using joint bearings as the center fulcrum. The overall optical efficiency of the modules under the vertical incidence of solar radiation and maximum allowable deviation (1° deviation) is 78.68% and 76.86%, respectively. When the deviation exceeds the maximum allowable value, the amount of radiation obtained on the receiver decreases rapidly.

The indoor daylight distribution with the integrated concentrating array is examined in this study under typical sunny and cloudy conditions of winter solstice, summer solstice and spring equinox in Tianjin, China. The results show that, during sunny days, the amount of solar radiation received on the floor surface behind the modules will decrease when the concentrating array is in a working state. However, the amount of solar radiation is still higher than in the area without direct sunlight. When the concentrating array is in a non-working state, the amount of radiation received by the floor surface is greater than that of working state, but less than that of without the integrated concentrating array. With the increase of solar altitude, the overall transmittance of the integrated concentrating array will decline. In cloudy conditions, the integrated concentrating array has less impact on the indoor daylight.

1. Introduction

As the interface between indoor and outdoor spaces, building skin or envelope plays an important role in the building energy consumption, either positively or negatively. Studies have shown that the building envelop accounts for up to half of the building energy consumption related to cooling and heating [1]. In the context of sustainable design, building skin is developing towards the directions of ecological, environmentally adaptable and dynamically adjustable [2,3].

With the rapid depletion of natural resources, the utilization of renewable energies such as solar energy resources has attracted a growing level of attention. Building integrated photovoltaics is one of most effective approaches to generate power from solar energy [4]. Sprenger et al. [5] simulated the electricity production from the building-integrated photovoltaic system. Their study found that the consequences of the integration as a thermally insulating component of the building envelope and the electrical properties of the PV system are well understood. Lamnatou et al. [6] suggested that building-integrated solar thermal systems based on a vacuum-tube technology are beneficial to both building and environment. Solar cooling systems have also gained an increasing level of attention due to its potential to reduce the building energy consumption [7]. Akter et al. [8] conducted a case study to comprehensively evaluate the performance of residential buildings with solar photovoltaic and battery energy storage systems. Their results show that there are significant economic benefits associated with building integrated solar energy systems.

Concentrating solar technology is an advanced approach to utilize the solar energy. Life cycle assessment of concentrating solar systems shows that this technology performs well in terms of environmental protection due to its efficient energy output capacity [9]. The aesthetic appearance, structure and energy production characteristics of building integrated concentrating photovoltaic (BICPV) are different from those of flat solar PV systems. Various levels of magnification (high, medium and low) of concentration sys-

* Corresponding author.
E-mail address: yong.sun@tju.edu.cn (Y. Sun).

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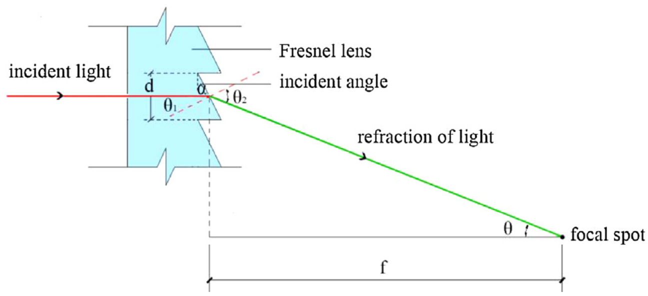

Fig. 1. Illustrating of concentrating light for Fresnel lens.

tems can be integrated into the buildings for different facade forms [10]. Fresnel linear concentrators are the most commonly used in BICPVs. Chemisana [11–13] conducted a series of studies on Fresnel linear concentrators. His studies revealed that the application of linear Fresnel lenses in combination with secondary concentrators provides an effective approach to integrate concentrating photovoltaic into buildings. The analysis of the optical system offers useful insights for the application of Fresnel linear concentrator.

Reflective concentrating components can also be used as a shading system. In the research conducted by González-Pardoet al., a novel configuration of vertical heliostat field for integration with building façades is proposed and optically assessed [14]. Connelly et al. [15] designed a reflective concentrating PV smart window system for buildings. This novel system can be treated as an electricity-generating smart window or façade which automatically respond to climatic conditions.

As the concentrator changes the transmission of the sun's rays, it is necessary to examine the optical characteristics of concentrating modules. Baig et al. [16] conducted an optical analysis of a 3D dielectric based building integrated concentrating photovoltaic system in order to investigate the impact of temperature profile on the overall performance of buildings [16]. Chemisana and Rossell [17] performed a number of ray tracing numerical simulations so that the configuration can be determined to achieve optimum efficiency.

A vast majority of existing studies focus on the energy output characteristics of the concentrating components. In addition to electricity generation, the concentrating solar system can provide heating and cooling for buildings. In the study conducted by Morciano et al., a system is designed where concentrated solar power system with dual axis solar tracker is coupled with a sensible heat storage by a plate heat exchanger [18]. Their findings show that the conversion efficiency of the system could be as high as 65%. Tsoutsou et al. investigated the integration of Fresnel lenses with solar thermal building façades and found that 43% heating energy can be saved [19]. Drosou et al. researched solar cooling system using concentrating collectors through a case of office building in Greece [20]. Their results demonstrate that the solar cooling systems have the potential to become more competitive than the conventional air conditioning technologies. Lamnatou et al. conducted a life cycle analysis of a building integrated solar thermal collector in terms of embodied energy and embodied carbon emissions [20]. Their study revealed that such system is beneficial to the environment. The study conducted by Menoufi et al. also showed that the BICPVs have better environmental performance compared to the conventional BIPVs [21].

If integrated into a building, the concentrators will replace parts of the building envelope and act as shading systems. The integration of solar modules into a building will have impact on the indoor environment of the building. Solar components have implications on the indoor daylight by absorbing and utilizing sunlight. At present, however, there is lack of research on the influence of concentrating building skin on indoor daylighting. In contrast, some studies have been conducted to examine the impact of other forms of integrated solar modules on the indoor daylighting. It is crucial to balance energy production and visual comfort. Mandalakiet al. pointed out that the quality of daylight became better when the thickness of the PV integrated to buildings is changed [22]. Daylight distribution varies according to solar facades. Transparent or semi-transparent solar building skin allows more natural light into the room. Tourasse and Dumortier's study [23] showed that the installation of a semitransparent PV system with a transparency of 20–30% would present a good balance between reducing energy consumption and increasing power generation. This design can obtain a large number of annual useful daylight hours (ranging between 300 and 2500 lx). This is comparable to a flat façade, while the occurrence of glare is reduced significantly. Leite Didoné and Wagner researched semi-transparent PV windows through a case study of office buildings in Brazil. Their results showed that semi-transparent PV windows help to reduce the final energy consumption by as much as 43% [24]. Similarly, Chow suggested that PV ventilated glazing technology provides energy saving opportunities in warm climate through the reduction in air-conditioning load, the daylight utilization, and the green electric power generation [25].

The extensive literature review shows that various forms of concentrators have been applied for the building integrated PV system. However, very few studies have examined the ways of dynamic integration of concentrating PVs with a building to track sun's position. In addition, the impacts of BICPVs on the indoor environment are largely overlooked.

This study aims to address three issues, namely concentrating module design, dynamic structure design for the integrated concentrating skin, and indoor daylighting characteristics of the new skin system. In this paper, the Transmissive Fresnel concentrating module is selected as the unit. A new type of linkage control device for the modules is designed. Joint bearings are used in the structure to connect the modules into an array. Consequently, the concentrating array is integrated into the window of the room model. The optical performance of concentrating module will be studied at different sunlight incident conditions, namely no-deviation incident, maximum allowable deviation incident, non-working incident. Different weather of the typical dates (i.e. Summer Solstice, Winter Solstice and Spring Equinox or Autumnal Equinox) are selected to study the daylight distribution in the room.

2. Design of BICPV

2.1. Modular design

A modular design of the concentrating solar technology is required for BICPVs. Compared to the units used in the field power station, those integrated into buildings are much smaller [26]. We designed a new type of concentrating module so that a better integration with the building façade can be achieved.

The concentrator used for this type module is a square Fresnel lens. The size of the Fresnel lens is 150 mm × 150 mm and the thickness is 3.1 mm. The lens consists of a highly transparent glass panel of ultra-white float glass with 91% light transmissivity and a grooved silicone material. Solar radiation incidents from the smooth surface of the lens to solar cell. The material for the other side is highly transparent silicone with a series of circular grooves of which the distance between two adjacent rings is 0.5 mm. The light concentrating characteristics are determined by the angle of the circular grooves of Fresnel lens. It is assumed that the refractive index of the selected Fresnel lens is n, according to Snell's Law:

$$n = \frac{sin\theta_1}{sin\theta_2} \tag{1}$$