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Replication Studies Paper

Analysis of a novel design of uniformly illumination for Fresnel lens-based optical fiber daylighting system

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ABSTRACT

Recently, advanced daylighting has become an important part of sustainable architecture design to increase visual comfort and illuminate deep interior spaces. Daylighting systems based on solar concentrators and fiber optical transmission have attracted a lot of research attention. In this paper, the authors propose a daylight collection and transmission design to transmit the concentrated light more uniformly into the optical fibers employing two optical elements: an eight-fold Fresnel lens as the primary optical element (POE) and an octagonal spherical fiber connector as the secondary optical element (SOE). In addition, a bi-layer prismatic optical panel acting as a diffuser is proposed in order to distribute light more uniformly in the interior space. The proposed designs of those optical elements are verified by ray-tracing simulation for achieving the required illumination level. The simulation results have shown that the combination of the proposed POE and SOE transmits light more uniformly into the bundle of optical fibers, and meanwhile the light diffuser provides relatively even illuminance distribution on a working plane. This shows a considerable advancement to the optical fiber daylighting designs. A case study shows the transmission efficiency of the proposed design is about 10% better than other common designs.

1. Introduction

Solar energy is considered the most important clean and renewable energy source. In the past two or three decades, much effort has been devoted to achieve high efficiency of solar energy utilization. Daylighting is a light transmission and redirecting technique to provide natural light into a building. Contrasted with photovoltaic (PV) or photothermic (PT) solar-powered lighting applications, daylighting uses sunlight and skylight directly without energy transformation from light to electricity, or light to thermal and then to electricity, to supply lamps. From this point of view, daylighting is considered as a highly efficient light source. A well-devised daylighting system collects, directs, and diffuses sunlight into interior spaces of a building with appropriate visual and thermal comfort, thus reduces electric lighting and saves energy. Besides saving energy, daylighting system can also improve interior visual environment and therefore leads to healthy benefit and higher productivity. It is estimated that electric lighting accounts for more than 30% power consumption in commercial buildings [1], while in USA, commercial sectors had the energy consumption of 11% in 2013 [2]. Furthermore, the electric lighting energy consumption had increased by 20% from 2000 to 2013 [3], and a steady increase is foreseeable in the near future. Therefore, daylighting design means a lot in sustainable architecture design and will play an important role in saving electric lighting energy, reducing carbon dioxide emissions in buildings, and improving visual comfort and occupants health (e.g., feelings, emotions, produces vitamin D, reduces the impact of illnesses, and improves patient recovery rapidly).

Skylights and windows are often naturally taken as daylight apertures for buildings, while the appropriate choices of sizing, orientation, glazing, and light redirecting are essential [4]. Due to

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these complexes of choices, daylighting design can turns to involve a multi-objective optimization. It may be feasible for new buildings but can hardly apply for retrofit projects. Fortunately, with the ability of redirecting and guiding light through tubular apparatus or optical fibers, daylighting design can go beyond fenestration to be an interdisciplinary design between optical systems, light controlling techniques, and architecture.

A simple daylighting system often consists of sunlight collector, transmission system, and illuminator. Sunlight collector gathers sunlight from outside of the building and act as input aperture of daylighting system. With a dedicated optical element, the collected sunlight enters a transmission system and is transmitted to the interior space of a building. The transmitted sunlight is guided to different illuminators and their corresponding diffusers to achieve desirable illumination on a working plane.

Due to its high transmission efficiency, optical fibers are suitable for transmission of light over a long distance into the core of a large building. An optical fiber needs to be coupled with a solar concentrator, which tracks the sun to receive the maximum amount of sunlight, but the transmission efficiency can be largely affected by the design of an optical coupler that can re-direct or re-distribute the incoming concentrated light. One of the common issues can be the large non-uniformity of light at the entrance of a large optical fiber or a bundle of optical fibers [5], which may severely affect the efficiency of the system. To solve this problem, different strategies have been implemented using lenses, reflectors, and other optical components at the entrance of optical fibers [6,7]. However, most of the designs could not achieve uniform illumination onto the bundle of optical fibers [7]. In this study, a novel optical design is proposed to solve this issue.

Various designs have been presented to redirect sunlight for indoor illumination [5–12] where illuminance uniformity is one of the main factors to increase efficiency of the system [8]. For the prismatic daylighting system, efficiency was improved using collimating lens and light emitter [6,7]. A liquid filled prismatic façade system was analysed for daylighting and thermal energy harvesting [8]. In another study, daylight using tubular light pipe and artificial light was used in underground parking where 60.4% of electric energy was saved [10]. A critical comparison for optical fiber-based daylighting systems was conducted in [12]. It was shown that the parabolic reflector and flat reflectors, parabolic and hyperbola reflectors, offset parabolic reflector, and parabolic reflector with lens did not produce uniform illumination on the fiber bundle. Five light collection systems were discussed using parabolic reflector and Fresnel lens. As different secondary optics was used in each design, each system had different efficiency in terms of uniform illumination over the bundle of optical fibers. It was concluded that parabolic reflector as a concentrator gives high illuminance than Fresnel lens. Similar with the concentrator photovoltaics (CPV) system, several daylighting systems with solar collector and optical fiber transmission system have been proposed [12,13]. A critical comparison for optical fiber-based daylighting systems was conducted in [14]. It was shown that each collector had different efficiency in terms of illumination distribution over the bundle of optical fibers.

In this paper, we propose a novel optical fiber daylighting system with an eight-fold Fresnel lens as the primary optical element (POE) and an octagonal spherical fiber connector as the secondary optical element (SOE). This design helps to increase optical efficiency in terms of transmitting the maximum amount of light into the optical fibers more uniformly, reducing overheating problem, and decreasing aberration effect. In addition, we also propose a bi-layer prismatic structure diffuser for each illuminator, which can distribute the light more uniformly in the interior of a building. The details of our design and simulation results are given in the following sections.

2. System description

2.1. Light collector configuration – eight-fold Fresnel lens POE and octagonal spherical SOE

Different designs of POE and SOE have been demonstrated in the literature to concentrate sunlight for both CPV and daylighting systems [15]. In these collector configurations, the basic idea is to capture and concentrate sunlight through the POE, and then distribute it through the SOE into optical fibers. Generally, the optical efficiency is a primary consideration, but the resulted non-uniformity may cause an important influence on performance of a daylighting system.

In both the CPV and daylighting systems, non-uniformity is one of the major issues to reduce efficiency of the system. For example, using simple light collector and secondary optics as POE and SOE, respectively, incident light rays will not be distributed uniformly over the fiber bundle, and most of the light rays are lost, as indicated in Fig. 1(a). Both ideal and real cases have incident ray angles of 0°. If the incident angle is changed due to non-perfect tracking or misalignment in optical elements, the system will get very low efficiency. Here, an optical design to achieve uniform illuminance over the bundle of optical fibers is proposed. From Fig. 1(b), it can be seen that all rays are transmitted into the optical fibers with the combination of a specifically designed lens and fiber connector. The detailed description of its principle is reported in our previous study [16] and further explained in the following paragraph. Fresnel lens is a light concentrating collector, which is widely used in various optical applications (i.e., solar energy, lighting, and illumination) [15]. In the proposed light collector, POE is a Fresnel lens that contains eight folds, where each fold is a part of a Fresnel lens, with different respective focal points, as shown in Fig. 2, and SOE has eight spherical parts that are designed with respect to each focal point of the primary lens. One of the reasons to develop the proposed design is to increase the acceptance angle (the part of the sky the concentrator is looking at) of the daylighting system.

$$C_{max} = \frac{n^2}{Sin^2\left(\Theta_{max}\right)} \quad (1)$$

where C_{max} is the maximum geometrical concentration, n is the refractive index of the medium, and θ_{max} is the half angle of acceptance. Previously, researchers have not given importance to increase the acceptance angle of the daylighting system to maintain efficiency of the system when there is a misalignment in the hardware components and imperfect optics. The proposed collector has the acceptance angle, α, of $\pm 1.5°$. Both POE and SOE may be made of polymethylmethacrylate (PMMA) with a refractive index of 1.494, to reduce the cost and achieve good efficiency of the optical system. With the proposed configurations of POE and SOE, the diverging angle of concentrated light can be reduced, as shown in Fig. 3, which increases uniformity and reduces aberration. The effective focal length, EFL, of the Fresnel lens can be calculated by

$$EFL = \frac{r}{n-1} \quad (2)$$

where r is the radius of Fresnel lens and n is the refractive index of the lens material. It is exemplified that an eight-fold Fresnel lens had the diameter and focal length of 300 mm. Fifty five optical fibers are bundled to have an overall diameter of 14 mm. In Fig. 3(a), it is evident from the raytracing results that a larger portion of the light rays are lost when a dome-shaped SOE is used. In contrary, using the proposed octagonal spherical SOE, all rays are transmitted into the bundle of optical fibers, as shown in Fig. 3(b). In Fig. 3(c), incident