Fiber-optic Daylighting Systems for Large-scale Building Interiors

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ABSTRACT

As buildings are the main source of energy use and greenhouse gas emissions, sunlight, which is one of the renewable energy sources, is provided in the interior to save electric lighting power consumption and improve indoor environments. Conventional daylighting systems have their difficulties in making a large-scale system. We propose two efficient daylighting systems to illuminate large-scale building interiors with daylight. Parabolic trough and linear Fresnel lens that are well-known solar concentrators are used to collect sunlight. Since the optical systems have two-stage concentration, a trough compound parabolic concentrator (CPC), which is a well-known nonimaging concentrator, is inserted at the upstream of the linear array of optical fibers to insert maximum light into optical fibers. To satisfy thermodynamic limits for the CPC, collimated light is created at the second-stage of concentration. Light is transmitted and distributed in the interior of each floor through optical fibers and a lens structure. Simulation results have shown that more sunlight can be harvested by the large-scale daylighting systems.

KEYWORDS: Solar concentrator, Daylighting system, Uniform illumination, Raytracing

1. INTRODUCTION

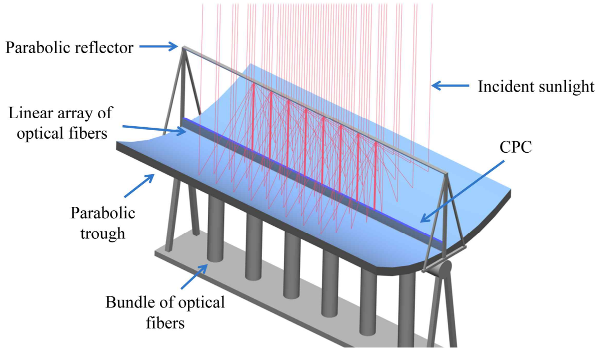
In sustainable buildings, daylighting can provide energy reductions through the use of electric light controls, and it can reduce the dependence on artificial lighting, which cannot fulfill the needs of the human body. In terms of health, artificially lit buildings fail to produce comfortable indoor environments.

A reduction in energy consumption and the production of energy through renewable energy sources can lead to a lower production of greenhouse gas emissions, which is becoming an increasingly serious global issue (U.S. EIA 2012). Buildings, especially office buildings, are the main source of power consumption and greenhouse gas emission (U.S. EIA 2012). Energy consumption due to electric lighting in buildings is approximately 40–50% of the total energy cost (Ossa *et al.* 1996). Efficient daylight buildings are estimated to reduce electric lighting energy consumption by 50–80% (U.S. Green Building Council 1995).

In the literature, large-scale, sunlight-capturing systems have been developed for photovoltaic power generation and thermal applications (Linderman *et al*. 2012). Several concepts regarding daylighting systems have been demonstrated with light pipes (Ullah and Shin 2012a) and optical fibers (Ullah and Shin 2012b, Ullah and Shin 2012c, Ullah and Shin 2013), and most of the designs have a large number of tracking reflectors and lenses, and, thus, require a large area in which to be installed. The main purpose of this study is to achieve uniform light into the optical fibers and to deliver it to large-scale building interiors. Consequently, two novel approaches are proposed for the parabolic trough and the linear Fresnel lens, and high concentration is achieved through the trough compound parabolic concentrator (CPC).

2. DESIGN OF DAYLIGHTING SYSTEMS

The idea behind the system is to capture high-intensity sunlight and then focus it over the optical fibers. A parabolic trough captured sunlight and directed the light toward a parabolic reflector, which illuminated the optical fibers with collimated illumination. Here, the main issue was to achieve a very high concentration, which was very difficult. Similarly, direct sunlight was focused through the linear Fresnel lens. The light went through a collimating lens and then the collimated light illuminated the optical fibers. It was difficult to achieve a very high concentration of light with the linear Fresnel lens. Previously, the parabolic trough and the linear Fresnel lens were not introduced in daylighting systems due to the issues described above. To solve the issue of high concentration, the trough CPC, which is a well-known, non-imaging optical element (Winston *et al*. 2005), was introduced upstream of the optical fibers. The trough CPC captured collimated light and then maximum sunlight was diverted into the optical fibers. As collimated light was produced via both approaches, both designs included the trough CPC. For the parabolic trough, collimated light entered into the trough CPC through the parabolic trough and then light entered into the optical fibers, as shown in Figure 1(a). As shown in Figure 1(b), collimated light entered into the trough CPC through the linear Fresnel lens and then light entered into the optical fibers.



(a) (b)

Figure 1. Schematic of the daylighting system with raytracing for the (a) parabolic trough and (b) linear Fresnel lens.

The focal length of the parabolic reflector can be determined by

$$f = \frac{D^2}{16 \times d} \tag{1}$$

where *D* is the diameter and *d* is the depth, which is 138.9 mm, of the parabolic reflector. We used a parabolic trough with a rectangular aperture height of 1000 mm and a rectangular aperture width of 570 mm. The effective focal length (EFL) of the Fresnel lens can be calculated by

$$EFL = \frac{r}{n - 1} \tag{2}$$

where *r* is the radius and *n* is the refractive index of the material. We used a linear Fresnel lens with a length of 570 mm and width of 1000 mm. The focal length, *f*′, of the collimating lens was calculated by (Malacara 1992)

$$NA = n \cdot sin\theta_{1/2} = \frac{D'}{2f'} \tag{3}$$

where *NA* is the numerical aperture of the concentrator and *D*′ is the diameter, which is 15 mm, of the collimating lens. The CPC achieves its maximum concentration ratio through (Winston *et al*. 2005)

$$C = \frac{a}{a'} = \frac{1}{Sin\theta_i} \tag{4}$$

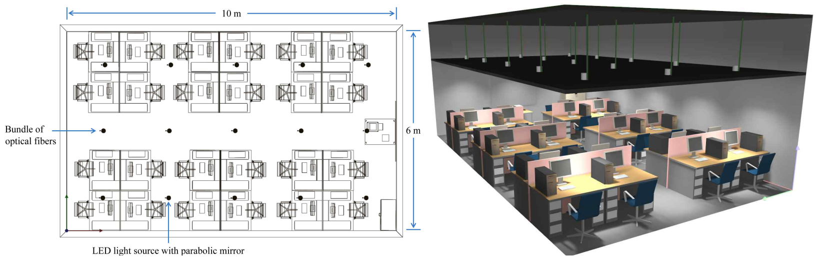
where *a* is the diameter of the entry aperture, *a*′ is the diameter of the exit aperture, and θ_i is the maximum input angle.

3. EXPERIMENTS

LightTools® and DIALux™ were used to implement and simulate the proposed daylighting systems. To achieve direct sunlight, it was presumed that both daylighting systems had sun-tracking devices to rotate the light-collecting modules toward the sun at all times of the day. For daylight, the luminous flux received on the surface was calculated to simulate the entire daylighting system by (Mahajan 1998)

$$E' = \frac{dF}{dS} \tag{5}$$

where *dS* is the (element of) surface area, *dF* is the luminous flux received on the (element) surface, and *E*′ is the illuminance on the element surface. The site of the application (office room, which has an area of 60 m^2) was located at 127° longitude and 37.5° latitude. In the U.S.A. and Asia, the floor-to-floor height of typical office buildings is from 4–4.2 m (Katz and Kohn 2002). In South Korea, the minimum floor-to-floor height is 3 m with a ceiling height of 2.4 m (Chung and Cho 2011). In this study, we used a standard 4 m floor-to-floor height and a 2.74 m ceiling height. The floor plan of the room is shown in Figure 2(a), where the placement of fiber bundles and LED light sources is indicated. Optical fiber had a diameter of 2 mm, and each fiber bundle had nineteen fibers. Our main goal was to illuminate a large area with an average illuminance of more than 500 lx, which is the minimum required value for an office building (European standard 2002). For light distribution, a combination of a biconcave lens and concavo convex lens was used. The interior view of the room under lighting simulation is shown in Figure 2(b). In the interior of the building, the illuminance was measured on the work plane, which was defined at a 2 m distance below the ceiling of the room. Illuminance distribution on the work plane is shown in Figure 2(c). The illuminance uniformity of a given space (plane) is calculated by



(a) (b) (c)

Figure 2. (a) Floor plan of the test room. (b) Indoor lighting simulation. (c) Daylight illuminance distribution on the work plane for the parabolic trough at 12 PM.

Table 2. Daylight average illuminance at different times of the day.

Time	Solar altitude (°)	Outdoor illuminance (lx)	Input flux (lm)	Indoor illuminance (lx) for parabolic trough	Indoor illuminance (lx) for linear Fresnel lens
6 AM	8	20000	11400	164	153
7 AM	19	40000	22800	328	307
8 AM	31	60000	34200	491	461
9 AM	43	80000	45600	655	614
10 AM	54	100000	57000	819	770
11 AM	65	105000	59850	860	807
12 PM	74	110000	62700	900	847

$$Unifomity = \frac{E_{min}}{E_{avg}} \tag{6}$$

where E_{min} is the minimum level (value) of illuminance and E_{avg} is the average level (value) of illuminance. We achieved illuminance uniformity of 0.3 on the work plane for the parabolic trough and linear Fresnel lens. Illuminance uniformity of 0.7 was attained on the floor for the parabolic trough and linear Fresnel lens.

4. CONCLUSIONS

In this paper, we proposed two efficient approaches for a large-scale, optical fiber-based daylighting system. The light was focused through the parabolic trough and the linear Fresnel lens and then light was guided through the collimating device and the trough CPC. After that, POFs were used for light transmission, and a combination of a biconcave lens and a concavo convex lens was designed for uniform light distribution in the interior.

We solved the high-concentration problem by using a collimating device and a CPC upstream of the optical fibers. We achieved the same intensity of light in each fiber to deliver uniform light in different areas of the building. The proposed system has been highly accepted due to the simplicity of its design, the ease in manageability, the applicability of rapid manufacturing, and because it is widely expandable to produce large-scale systems. The results have shown that the efficiency of the system is better than that of traditional lighting systems. It was found that the parabolic trough gave more illuminance than that of the linear Fresnel lens. In the future, a hybrid system combining sunlight and LED light with electric lighting controls will be integrated to save electric lighting power consumption by maintaining an average illuminance of 500 lx at all times.

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