Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 108 (2014) 331–339

SOLAR ENERGY

www.elsevier.com/locate/solener

Daylighting system via fibers based on two-stage sun-tracking model

Jifeng Song [a,*], Yong Zhu [b], Zhou Jin [b], Yongping Yang [b]

[a] *Renewable Energy School, North China Electric Power University, Beijing 102206, China*
[b] *School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China*

Received 28 December 2013; received in revised form 28 June 2014; accepted 23 July 2014
Available online 8 August 2014

Communicated by: Associate Editor Jean-Louis Scartezzini

Abstract

A daylighting system consisting of optical fibers and a sun-tracking model has been developed. The system has a concentrating level of 2500 suns and a tracking precision of better than 0.1° to ensure that the amount of overlap of the focal spot and the entrance face is greater than 80%. The device includes two feedback circles, coarse and fine adjustments, using an angle encoder and a special photodiode array, respectively. The coarse adjustment process relies on predictable a priori information of the sun's trajectory, and discrete features of the output signals from the photodiode array are used by the control program for the fine adjustment. The system then operates in a predictive control mode and exhibits good tracking performance. The optical transmission efficiency is maintained between 37% and 40%, which is close to the theoretical maximum value of 42%. The fluctuation range of illuminance on the working face is less than 20%, which meets visual demands. Five lenses (100 mm in diameter) and five 10-m, 2-mm-diameter plastic optical fibers can provide an illumination of 26.7 lx for an underpass (4.6 m × 4.2 m) 10 m away. Of a direct normal irradiance of 514 W/m^2, about 70% of the light illuminates the floor.

Keywords: Daylighting; Sun tracking; Concentrated light; Fiber

1. Introduction

Illumination of underpasses or dark rooms can be achieved using optical-fiber-based daylighting systems that use dual-axis solar tracker technology and lenses to concentrate and transmit sunlight. Such systems also prevent the transmission of ultraviolet and infrared rays as well as energetic particles. The optical isolation characteristics of these systems are advantageous for essential safety lighting in places such as underwater sites, oil depots, and ammunition depots (Kandilli and Ulgen, 2009). Furthermore, making full use of sunlight for natural lighting purposes will have health and energy-saving benefits: urban densification has seen an increase in the dependence on artificial light sources, and a lengthy decrease in the amount of exposure to sunlight may lead to an increase in the incidence of endocrine disorders and sick building syndrome due to the poor quality of the indoor environment. Artificial light sources also account for a large proportion of electric power consumption, and daylighting systems will reduce not only this cost but also that of air-conditioning systems owing to fewer infrared rays. It is also essential that the color display behavior and photopic vision effects of daylighting systems are close to those of human vision to provide comfortable working environments (Schlegel et al., 2004; Tzempelikos et al., 2007).

The small diameters of optical fibers mean that light can be concentrated by a level of 2500 suns in daylighting

---

* Corresponding author.
E-mail address: songjifeng@ncepu.edu.cn (J. Song).

http://dx.doi.org/10.1016/j.solener.2014.07.021
0038-092X/

systems, and as such, sun-tracking errors of less than 0.1° are required. Even a tiny error in the focusing process at the entrance face of fiber may result in a substantial fluctuation in the total output light flux and lighting quality. The requirements on the accuracy and stability of such a tracking system are strict (Tekelioglu and Wood, 2009) and differ from those for solar trackers of photovoltaic power stations (Teolan, 2008).

High-accuracy dual-axis solar trackers are based on a solar position formula and photosensitive sensors. In such trackers, a global positioning system (GPS) is employed to acquire date, time, longitude, latitude, and elevation information to determine the azimuth and altitude angles of the sun. These angles are then compared with the feedback signals of the high-accuracy sensor to adjust the position. The hybrid daylighting system developed at the Oak Ridge National Laboratory, USA, that uses a parabolic mirror (Schlegel et al., 2004; Feuermann and Gordon, 1999; Earl et al., 2003) is an example of such a system. This system is highly reliable because its performance is not influenced by the local climate. Considering the gravity-induced deformations of plane mirrors and the support, optical fiber bundles are a suitable sunlight transmission medium. However, in practice, the accuracy of a solar tracking system is affected by several factors including the initial setting accuracy, foundation settlement, and long-term gravity deformation (Arbab et al., 2009). In addition, a high-accuracy angle sensor is required, which increases costs. However, photosensitive sensor sun positioning systems are advantageous because there is no error accumulation and no dependence on the initial setting.

Image-based sun positioning sensors can operate at a high accuracy even under cloudy conditions, and the average accuracy is better than 0.04°. However, the associated image processing software and hardware are expensive. Furthermore, the maximum direct normal irradiance (DNI) at sea level is only about 1 kW/m^2, and so the cost of high-accuracy tracking technology is prohibitive for household-oriented daylighting systems (Lee et al., 2013). It is important to also note that traditional photosensitive position sensors have a narrow field of view, and sunlight capture at sunrise and recapture in cloudy weather may be difficult. To guarantee synchronized outdoor and indoor natural lighting, a daylighting system the sun position needs to be determined accurately and rapidly, which would necessitate a sun positioning system with a wide field of view.

Daylighting systems should be as stable as possible and have a low sun-tracking error to ensure comfortable lighting. Here, we propose a system that exploits predictable a priori information of the sun's trajectory to ensure a stable tracking mechanism. The overall utilization rate of the daylighting system is calculated for a set of sunlight transmission experiments, and the tracking smoothness of the system is verified.

2. System configuration and strategy

2.1. Double-axis sun-tracking and concentrating system

The daylighting system is composed of a dual-axis sun-tracking subsystem and an optical fiber transmission system. The dual-axis sun-tracking subsystem (Fig. 1) includes a mechanical support, reduction gear pair, drive motor, angle sensor, photosensitive positioner, and control circuit. The structure of the azimuth gear drive is shown in Fig. 2.

The configuration of the lens and the polymethylmethacrylate optical fibers of the transmission system is shown in Fig. 3. Light is focused to a spot (2 mm in diameter) that overlaps the entrance face of the fiber (also 2 mm in diameter), and concentrated sunlight is transmitted over a long distance owing to total internal reflection. Light cannot be stored, and so any positional offset of the focused spot will result in a decrease in the output light flux and a change in the output spectrum distribution, which will degrade the lighting quality. The optical parameters of the transmission system are listed in Table 1, and the transmission efficiency of the system was previously calculated experimentally to be 34%. The attenuation ratio of the optical fibers and the light transmittance of the lens will both affect the transmission efficiency. The total reflection angle is ±30°, and experiments have shown that larger incident angles result in greater attenuation.

Table 2 lists the parameters of the sun-tracking system.

As shown in Fig. 4, if there is an angular offset between the photodiode and the focal spot of 0.1° (about a 0.3-mm distance), then the area of the shaded region is

$$\begin{aligned}\eta_{lost} &= \frac{S_{Missed}}{S_{Spot}} = \frac{\pi r^2 - 2r^2 \arccos\frac{e}{2r} + e\sqrt{r^2 - \frac{e^2}{4}}}{\pi r^2} \\ &= \frac{\left(\pi r^2 - 2r^2 \arccos\frac{f\tan\theta}{2r}\right) + f\tan\theta\sqrt{r^2 - \frac{(f\tan\theta)^2}{4}}}{\pi r^2} \qquad (1)\end{aligned}$$

where η_{lost} is the loss ratio, r is the radius of the focused spot (optical fiber), f is the focal length of the lens, e is

Fig. 1. Double-axis sun tracking & concentrating system.