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Development of a fiber daylighting system based on a small scale linear Fresnel reflector: Theoretical elements

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HIGHLIGHTS

- The design of a fiber daylighting system based on a linear Fresnel reflector.
- A daylighting system like this has not been studied in the literature so far.
- This work focuses on the design of a new reflector cavity.
- The cavity used in a conventional linear Fresnel reflector is not suitable for it.
- The work presented in this paper shows the luminous energy produced per month.

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ABSTRACT

This paper describes the details of the design of a small scale linear Fresnel reflector (*SSLFR*) applied to a daylighting system based on optical fiber bundles (*OFBs*). This study shows the influence of the *SSLFR* design parameters (mirror width, mirror length, reflector cavity height, and number of mirrors) and the parameters of the optical fiber. A new reflector cavity is designed, consisting of two right trapeziums. Each trapezium collects the incident solar irradiance of the mirrors located at each side of the central mirror. The reflector cavity has two focal points, located in the middle of the aperture of each trapezium. A MATLAB code was developed in order to obtain the optical efficiency of the new reflector cavity and numerical simulations are presented. Two *SSLFR* configurations, C_1 and C_2, are studied. C_1 is the configuration used in large-scale *LFRs* and does not consider lateral movement of the *OFBs*, as is the case in configuration C_2. Each of these configurations is analyzed considering the optimal length and longitudinal position of the *OFB*. Numerical simulations are presented for both configurations using the MATLAB environment. Power consumption based calculations are carried out using the lumen method and the potential electric energy saving is evaluated. The illumination levels obtained are then compared using the lighting design software DIAlux, a free software widely used as a planning tool by lighting designers. The results show a considerable electric energy saving with configuration C_2, although configuration C_1 also presents good energy savings.

1. Introduction

Over the last decade, global demand for artificial light has grown at an average rate of 2.4% per annum, according to the International Energy Agency (*IAE*) [1]. Annual growth was slower in *IEA* countries (1.8%) than in the rest of the world (3.6%). Globally, 133 petalumen-hours (Plmh) of electric light were consumed in 2005, an average of 20 megalumen-hours (Mlmh) of light per person, although light consumption is very unevenly distributed [1]. This growth in artificial light demand has meant that, over the last decade, global electricity consumption for lighting applications has grown at a rate of 1.5% per annum, less than three-quarters of the light demand growth rate [1]. In view of the current socioeconomic trends and policies, global electricity consumption for lighting is projected to rise in the next 25 years to over 4250 TW h,which means an increase of 60% at an average rate of 1.9% per annum [1]. Different strategies have been proposed to reduce the energy consumption of lighting systems [2,3].

Building lighting has been the subject of special attention, as lighting represents a high percentage of the energy consumed in buildings [4,5]. It has been found that the main reason behind the increase in energy consumption is the rise in the average illuminance level. The study of the use of daylighting systems to illuminate the

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Nomenclature

A_{OFB}	total *OFB* area (m^2)
$A_{effecOFBi}$	effective area of the *OFB* (m^2)
BPF	bundle packin fraction
B	lower side of the right trapeziums (m)
b	less side of the right trapeziums (m)
CI_m	cleanliness factor of the mirror
CI_{OFB}	cleanliness factor of the *OFB*
CR	concentration ratio
DNI	Direct Normal Irradiance (W/m^2)
d	separation between two consecutive mirrors (m)
dBloss	attenuation (dB/km)
d_c	individual optical fiber core diameter (m)
d_{of}	individual optical fiber diameter (m)
f	distance between the OFB and the mirrors (m)
$G_{in,of}$	input irradiance solar (W/m^2)
$G_{out,of}$	output irradiance solar (W/m^2)
IAF	incidence angle modifier
h	depth of the air cavity (m)
K_b	luminous efficacy (Lm/W)
L	length of the individual optical fiber (km)
L_M	length of the mirrors (m)
L_{OFB}	length of the OFB (m)
L_{OFB}^l	left length of the OFB (m)
L_{OFB}^r	right length of the OFB (m)
l_{OFB}	total illuminated length of the OFB (m)
l_{OFB}^l	left illuminated length of the OFB (m)
l_{OFB}^r	right illuminated length of the OFB (m)
L_i	position of *i–th* mirror ($0 \le i \le n$) (m)
N	number of individual fibers
NA	numerical aperture of the individual optical fiber
n	number of mirrors at each side of the central mirror
n_{core}	refractive index of the core
n_{clad}	refractive index of the clad
OFB	optical fiber bundle
Q_{OFB}	total power on the OFB (W)
$T(\lambda)$	transmissivity
W_M	width of the mirrors (m)
W_{ai}	width illuminated on the aperture of the reflector cavity by the *i*-th mirror (m)
W_{OFB}	width of the OFB (m)
α_i	angle between the vertical at the focal point and the line connecting the center point of each mirror to the focal point (°)
α_S	height angle of the Sun (°)
β_{OFB}	angle between the *OFB* and the horizontal plane (°)
β_i	tilt of *i–th* mirror (°)
β_M	angle between the mirror axis and the horizontal plane (°)
γ	skew rays angle (°)
γ_S	azimuth of the sun (°)
η_{opt}	optical efficiency (%)
η_{SL}	solar luminaire efficiency (%)
θ_c	acceptance angle (°)
θ_{IA}	inclination angle for residential roofing (°)
θ_i	angle between the normal to the mirror and the angle of incidence of the sun (°)
θ_L	lateral incidence angle (°)
θ_l	longitudinal incidence angle (°)
θ_t	transversal incidence angle (°)
θ_z	zenith angle of the Sun (°)
λ	wavelength (nm)
μ	angle between the reflected ray and the normal to the NS axis (°)
ρ_m	reflectivity of the primary mirrors
ρ_{rc}	reflectivity of the reflector cavity
τ	transmissivity of the glass

interiors of buildings is not new [6]. Many subsequent researchers have shown that it is possible to transfer sunlight into residential buildings, in order to complement artificial lighting [7–9]. The lighting electricity savings associated with the installation of daylighting systems in buildings is estimated to be around 50–80% [10].

In addition, many authors have studied the health benefits associated with the use of daylighting [11,12], as the amount of illuminance and light quality are regarded as factors defining a healthy environment.

Daylighting systems are composed of five main elements [13]: sunlight sources, sunlight collection systems, sunlight transmission systems, lighting control systems, and solar luminaires. Sunlight collectors capture direct sunlight outside the building, sunlight distribution systems transmit sunlight to the interiors of the building, and solar luminaires distribute sunlight inside the building.

There are three main types of sunlight collectors used for daylighting: parabolic dishes, parabolic troughs, and Fresnel lenses. A parabolic dish system consists of mirrors arranged in the supporting structure to reflect and concentrate the solar radiation to the focus of the parabolic dish [14]. The parabolic dish is directed towards the sun automatically using a solar tracking mechanism, and the optical fiber is fixed permanently at the focus to collect reflected light [15,16]. In a parabolic trough system, a parabolic reflector plate is pointed at the sun with a tracking control system [17], and the optical fiber is permanently fixed at the focus of the parabolic concentrator to collect reflected light [18]. Fresnel lens refract incident sunlight to single focal pointbehind the opposite side of the lens [19], where an optical fiber or a bundle of several small fibers is mounted [20]. A comparative analysis on daylighting for parabolic dishes and Fresnel lenses has been presented by Kim et al. [21].

Light transmission systems use several devices for transmitting sunlight to the interiors of buildings: large-core optical fibers, optical fiber bundles (*OFBs*), and hollow-core reflective lightpipes. The transmission of sunlight via optical fiber is a flexible solution for daylighting systems and has a number of advantages, such as the exclusion of the ultraviolet infrared parts. An individual optical fiber is a transparent, flexible fiber with a diameter of the order of microns, consisting of a core and a clad. Core diameters range from 7 µm to 1 mm. The fiber can be made of glass or plastic. The plastic type provide more flexible solutions than the glass type, though the attenuation is greater.

The main objective of this work is to study the details of the design of a small scale linear Fresnel reflector (*SSLFR*) applied to a daylighting system based on optical fiber bundles (*OFBs*). The study makes two novel contributions.

The first being the design of a daylighting system based on *OFBs* using an *SSLFR*. To the best or our knowledge, a daylighting system with these characteristics has not yet been studied in the literature. A number of studies have been published using parabolic dishes, parabolic troughs, and Fresnel lenses refract as sunlight collectors, whereas this paper evaluates the performance of an *SSLFR* as the sunlight collector of a daylighting system. Second, the study focuses on the design of a new reflector cavity, as the cavity used in a conventional *SSLFR* is not suitable for this application. The reflector cavity proposed consists of two right trapeziums. This reflector cavity has two focal points, located in the middle of the aperture of each trapezium. The research work presented in this paper shows the luminous energy produced per month by the proposed daylighting system. In addition, an estimation of the electric energy saving and the illumination levels in a typical