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Design and construction of active daylighting system using two-stage non-imaging solar concentrator

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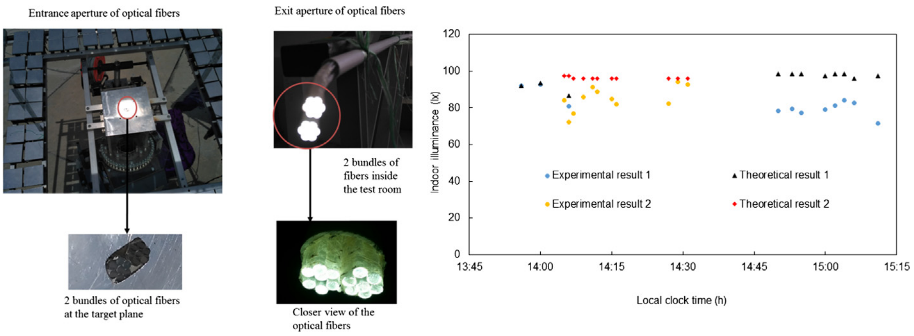
HIGHLIGHTS

- 2S-NISC has low rim angle, high tolerance to pointing error, uniform illumination.
- A reflective area of 0.2 m^2 is capable of illuminating an office area of 7.4 m^2.
- Average solar concentration ratio is 66.6 suns with standard deviation 3.0 suns.
- Power conversion efficiency of 2S-NISC prototype with the area of 0.2 m^2 is 22%.
- For interest rate 4% and fuel inflation rate 2%, payback period is 6.5 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Since lighting accounts for 20% of global electricity consumption in buildings, daylighting system is an important solution to achieve energy savings in lighting and to reduce carbon dioxide emissions. However, most of the existing fiber-optics daylighting systems are expensive, sensitive to pointing error and complicated in optical design in which multi-stage focusing devices are needed to minimize non-uniformity of focused sunlight. To overcome the aforementioned problems, we propose a novel active daylighting system using two-stage non-imaging solar concentrator (2S-NISC) inspired by our previous experience in non-imaging optics. The 2S-NISC prototype consists of 80 primary facet mirrors with a dimension of 5 cm × 5 cm each, 20 secondary facet mirrors with a dimension of 8 cm × 8 cm each, and densely packed plastic optical fibers as a daylight distribution system. Considering the input solar power of 160 W, the equivalent power conversion efficiency of 2S-NISC prototype is obtained as 22%. For economic analysis, the proposed active daylighting system using 2S-NISC with optimized collective area of 4 m^2 is estimated to cost USD 1231.20. Considering the interest rate of 4% and fuel inflation rate of 2%, the total payback period is determined as 6.5 years, which is reasonable because the active daylighting system can last for at least 15 years.

1. Introduction

In the world today, fossil fuels are the major sources of energy which when burned for power generation releases greenhouse gases consisted mostly of carbon dioxide (CO_2). The major concern in the overwhelming consumption of fossil fuels is the possibility of global climate change caused by increased levels of CO_2 and other greenhouse gases in the upper atmosphere. This issue has led to the search for environment-friendly solutions to sustain human activities even in illuminating buildings. It is a known fact that lighting system is one of the major energy consumptions in

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Nomenclature

2S-NISC	two-stage non-imaging solar concentrator
NIPC	non-imaging planar concentrator
NIDC	non-imaging dish concentrator
2-D	2-dimensional
3-D	3-dimensional
POF	plastic optical fiber
L	the distance between the primary reflector and the secondary reflector
$C_{measured}$	measured solar concentration ratio
W/m^2	Watt per square meter
lx	lux
lm	lumen
Mt	million tons
kW h	kilowatt hours
MV	megavolts
MW	megawatts
TW h	terawatt hours
DNI or **I**	direct normal irradiance
GSI	global solar irradiance
ω	half rim angle
dB/km	decibel per km
lm/W	lumen per Watt
mrad	milliradian
CPV	concentrator photovoltaic
$I_{\text{sc-1}}$	short-circuit current under concentrated solar flux (reading from CPV cell 1)
$I_{\text{sc-2}}^{\text{DNI}}$	short-circuit current under one sun contributed by DNI only (reading from CPV cell 2)
C_{avg}	average solar concentration ratio
$\Delta C_{\text{measured}}$	measurement error of solar concentration ratio (number of suns)
$\Delta I_{\text{sc-1}}$	measurement error of short circuit current 1
$\Delta I_{\text{sc-2}}$	measurement error of short circuit current 2
V_{DNI}	DNI voltage
V_{GSI}	GSI voltage
ΔV_{DNI}	measurement error of DNI voltage
ΔV_{GSI}	measurement error of GSI voltage
$\text{Illum}_{\text{theo}}$	theoretical result of indoor illuminance
A_{fiber}	cross-sectional area of plastic optical fiber
$\%\ VL$	percentage of visible light in the solar spectrum
$T_{\text{hot mirror}}$	transmissivity of hot mirror to visible light
L_{fiber}	total transmission loss via optical fiber
N_{fiber}	number of plastic optical fibers
E_{L}	the average value of direct beam luminous efficacy
A_{illum}	indoor illuminance area
R_{facet}	reflectivity of primary/secondary facet mirror

buildings to cause a large amount of CO_2 emissions even during the daytime [1]. The total CO_2 emissions attributed to lighting were estimated to be 1900 Mt, which was about 7% of the total global CO_2 emissions from flaring of fossil fuels for power generation [2,3]. Increase of energy consumption in lighting due to the rapid growth in population will continuously generate a substantial rise in greenhouse gas emissions, which justifies the necessity to encourage energy conservation in the lighting sector.

The Energy Information Administration (EIA) estimated that the residential and commercial sectors in the United States consumed about 279 billion kWh of electricity for lighting in 2016. It was about 10% of the total electricity consumed by both of these sectors and about 7% of the total electricity consumption in the United States [4]. For agricultural sector, artificial lights are widely used in various applications such as area lighting, task (packaging and processing) lighting, and to provide illumination for livestock, animal housing, poultry as well as plant growth. In the United States, electricity consumed by agricultural operations was approximately 0.14 quadrillion BTU, which was mainly driven by lighting and ventilation-related energy expenses in the livestock and greenhouse areas [5,6]. In Europe, the interiors of medium and large buildings utilize about 40% of the total electrical energy for illumination only [7]. In South Asia, lighting consumes approximately 132 TW h, which is about 15% of the total electricity consumption [8]. In Malaysia, approximately 30% of the total energy produced is consumed by lighting in buildings in which Zakaria et al. highlighted that over 40% of the carbon emissions in Malaysia are from the existing buildings and communities [9,10]. The International Energy Agency (IEA) stated that lighting accounts for around 20% of global electricity consumption in buildings [11].

Solar energy as one of the most abundant clean energy sources on earth should be fully explored to meet the energy saving demands. It has been estimated that a building with efficient daylighting system can reduce energy consumption for lighting by 50–80% in which daylighting is generally defined as introducing natural light into a building for illumination [12]. Direct use of sunlight is a more sustainable way to illuminate the interior space of a building than the indirect use of photovoltaic module for converting solar energy to electrical energy and back to light energy as the multiple conversion processes involve significant energy losses. In principle, there are two different methods of daylight harnessing for achieving green building status via energy conservation: passive daylighting system that is stationary and active daylighting system that requires sun-tracking mechanism. There are many studies on how passive and active daylighting systems can contribute in energy saving for the building. Chow et al. examined the daylighting performance towards energy saving including economic and environmental benefits for a 13-storey atrium building in Hong Kong. The total potential energy savings per year is 43,003 kW h and the average emissions of CO_2, SO_2, NO_X and particulate could be reduced annually by 32,252 kg, 440 kg, 42.4 kg and 2.1 kg respectively [13]. Galasiu et al. demonstrated that passive daylighting systems in a building could reduce the average amount of electricity consumed by 50–60% in comparison to utilizing artificial lights from 6 AM to 6 PM under a clear sky without blinds [14]. Jenkins and Newborough predicted the annual energy savings for lighting in a range of 56–62% by accounting for the daylight contribution from windows and roof lights in a six-storey office building [15]. Zain-Ahmed et al. demonstrated that the use of daylighting strategies in Malaysian buildings could achieve 10% of energy savings [16]. Elmualin et al. presented a daylighting system using dichroic material as a light pipe to transmit visible sunlight into a room, which is capable of removing approximately half of the solar heat in daylight and thereby saving electrical energy consumption for both cooling as well as lighting [17]. Berardi proved that aerogel windows can offer a solution for energy saving by providing a better distribution of daylight while reducing the solar heat gain in buildings [18]. An integrated meta-model daylighting, heating, ventilating and air conditioning system developed by Kim et al. has shown an average of 13.7% energy savings against the conventional method throughout three months of observation in winter [19]. On the other hand, Pohl and Anselm

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