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Performance analysis of a concentrated solar energy for lighting-power generation combined system based on spectral beam splitting

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ABSTRACT

The novel lighting-power generation combined system (LIPGECOS) based on the approach of spectral beam splitting of the concentrated solar radiation was introduced and the components of the system consisting of paraboloidal dish, dual axes tracking system, cold mirror, fiber optic bundle and Stirling engine were explained. At the first time, a cold mirror was utilized to separate the full solar spectra into the different wavelengths experimentally. The performance analysis of LIPGECOS established at Usak University was carried out and the first experimental results were evaluated in the present study. Temperatures, rotating speed of the Stirling engine, indoor irradiance and illuminance obtained by the experiments were analyzed under different global and direct solar irradiance conditions. Thermal images of the LIPGECOS were presented to examine the thermal control of the system. The energy and exergy efficiencies of the system were determined as 0.15 and 0.09, respectively. The average luminous efficacy of LIPGECOS was calculated as 347 Lm/W. A superior luminous efficacy was obtained by LIPGECOS owing to spectral beam splitting. The average lighting efficiency was calculated as 14% ± 0.03. It is hoped that the spectral beam splitting by the cold mirror could open new research areas for concentrated solar energy technologies.

1. Introduction

The sun is the most important source of renewable and inexhaustible energy. However, terrestrial solar flux has relatively low value and the solar concentrated energy should be employed to obtain higher temperatures and to increase the supplied power. Concentrating solar energy systems could be classified into two different categories: Imaging and non-imaging systems. A high flux and high temperatures could be obtained by a paraboloidal concentrating dish which is one of the imaging solar energy systems.

Nowadays, there are many application areas of the paraboloidal concentrators, such as industrial heat supply, lighting and electrical energy. By the paraboloidal dish systems, high-temperature solar irradiance could be concentrated on the focal plane and this energy could be converted into mechanical energy by Stirling heat engines.

The primary advantage of lighting systems with solar concentrators is their potential to reduce energy consumption with respect to conventional ones. Cooling loads in buildings are reduced due to the increased luminous efficacy of fiber-optic lighting system as compared with incandescent or fluorescent lighting [1]. Daylight can provide at a level of about 110 Lm/W of solar radiation, whereas fluorescent lamps provide about 75 Lm/W of electrical input and incandescent lamps about 20 Lm/W. Thus, efficient day lighting generates only 1/2–1/5th of the heating that equivalent electrical lighting does; therefore, significantly decreasing the building cooling load [2]. The combined savings from reduced lighting and cooling loads can be substantial because electrical lighting can account for 25–40% of a commercial building's energy requirements from the energy efficiency point of view [3]. Daylight is accepted as the most suitable light for good color rendering and its spectral properties provide a perfect match with human visual response. At this point, integrated fiber-optic lighting systems based on solar energy emerged as an alternative, energy efficient and qualitative option for the spaces with insufficient illumination, specialized safety or having a large lighting load. Since the early 1980s, many theoretical and experimental studies for the purpose of power generation and lighting based on the principle of transportation of concentrated solar radiation with fiber optic

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Nomenclature

A	Area (m^2)
C	Geometrical concentration (dimensionless)
D	Diameter (m)
d	Image diameter (m)
dB	Decibel loss/attenuation of optical fiber (dB/m)
$\dot{Ex}$	Exergy rate (W)
F	View factor (dimensionless)
f	Focal length (m)
G	Solar irradiance (W/m^2)
L	Length (m)
NA	Numerical aperture (dimensionless)
n	Refractive index (dimensionless)
$\dot{Q}$	Energy rate (W)
h	Heat transfer coefficient (W/m^2K)
T	Torque (Nm)
T	Temperature (K,°C)
v	Velocity (m/s)

Greek letters

δ	Dispersion angle (°)
ε	Exergy efficiency
σ	Stefan–Boltzmann constant ($\sigma = 5.667 \times 10^{-8}$ W m^{-2} K^{-4})
η	Energy efficiency
ρ	Reflectivity
θ	Admission/acceptance angle (°)
τ	Transmittance
ϕ	Rim angle (°)
Ψ	Maximum efficiency ratio (dimensionless)

Subscripts

a	Ambient
b	Beam
dish	Dish
f	Focal
fob	Fiber optic bundle
in	Inlet
loss	Loss
m	Mirror
max	Maximum
min	Minimum
o	Optimum
out	Outlet
rim	Rim
s	Stirling
shade	Shading
w	Wind

cables have been carried out [4].

Latest investigations on solar lighting via fiber optics are very remarkable. Firat and Beyene investigated seven configurations of Photovoltaic (PV) energy conversion systems involved use of filters, concentrator lens, fiber transport, and direct use of PV in their theoretical study. They found that transmission of concentrated light onto PV cell proved to be the most efficient, but also the most expensive. They also showed that transmission of filtered light onto PV cell using a plastic optical fiber (POF) bundle was the most affordable [5]. H.J. Hun et al. introduced the applicability and functional effectiveness of a daylighting system which consists of dish concentrator(s), a dual-axis solar tracker and light guides including optical fiber cables. They developed simulation models using a number of different software where Photopia provided the relevant photometric data (candela power distribution curves, CDCs) by producing a virtual luminaire of the daylighting system. It was found that the model based on Relux could produce more realistic results, closer to the measured data [6]. H.J. Hun et al. also performed a computational analysis on the enhancement of daylight penetration into an unevenly lit lecture room with north-facing windows with the help of Photopia and Radiance. They considered two different daylighting systems, a light tube and a fiber-optic solar dish concentrator, as means to lead light rays into an interior space with insufficient illumination from daylight. Their results revealed that the functional benefits of each system when harvesting daylight for indoor illumination and more daylight can be harvested by the solar tracking dish concentrator system for solar altitudes of less than 50° [7]. Wong and Yang proposed the remote source solar lighting system which is composed of a simple heliostat and side-emitting fiber optic. They carried out simulation on the light transmission performance in the system by the ZEMAX-EE. They showed that the proposed remote source solar lighting system can be applied as an alternative lighting system to illuminate the enclosed lift lobby at daytime in clear sky condition [8]. Wong and Yang also designed and experimentally tested a remote source solar lighting system using side-emitting fiber optic as illuminators to reduce the emission of greenhouse gases for providing illumination to these lift lobbies as a promising system. They proved that the remote source solar lighting system could displace an average of 3 h of electric lighting in a day and reduce 6.7×10^6 kg of carbon dioxide emission in a year [9]. In their other study, Wong and Yang investigated the factors of solar altitude, solar azimuth angle and solar irradiance, analyzed the shadowing effects caused by neighboring buildings and the supporting framework in details, defined design parameters of the natural daylight system, and finally developed design guidelines and a model design as a reference for building designers in designing a remote source solar lighting system [10].

Fiber optic cables based on plastical materials could not resist to high temperature for concentrated solar energy applications. Regarding silica based fiber cables, they are not preferred for solar lighting applications due to lack of flexibility. On the other hand, concentrated solar radiation could be transmitted to any space by acrylic based fiber optic cables at low operating temperatures as 70 °C. In this context, it is very significant to the temperature control for FOB in solar lighting systems. In addition, PMMA based fibers can only transfer the visible light of the solar spectra. For this reason, a great loss is emerged for the other part of the spectra including UV and IR regions. This energy loss causes excessive heat on the FOB. Concentrated solar irradiance damages and melts the FOB made of PMMA at the entrance. In the present study, the proposed system can eliminate this excessive heating problem and prevent the FOB owing to "spectral beam splitting approach".

As well-known, solar spectra has a wide range wavelength band including from 200 nm to 2500 nm. The spectral beam splitting could be defined as separating the solar full spectra into different wavelengths by an optical device. This idea provides many advantages such as reduction of heat losses in solar energy applications and utilizes all spectra in an efficient way. Certain portions of the spectrum could be employed for Concentrating Photovoltaics (CPV)