Solar Energy 153 (2017) 679–690

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Theoretical and experimental analysis of an innovative dual-axis tracking linear Fresnel lenses concentrated solar thermal collector

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ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 13 April 2017
Accepted 6 June 2017
Available online 21 June 2017

Keywords:
Solar energy
Fresnel lens
Two-axis tracking system

ABSTRACT

Linear concentrating solar thermal systems offer a promising method for harvesting solar energy. In this paper, a model for a novel linear Fresnel lens collector with dual-axis tracking capability is presented. The main objective is to determine the performance curve of this technology by means of both experiment and theoretical analysis. A mathematical model including the optical model of the concentrator and the heat transfer model of the receiver pipe was developed. This tool was validated with experimental data collected using a proof of concept prototype installed in Bourne, UK. The performance curve of the collector was derived for temperatures between 40 °C and 90 °C. The results show that the global efficiency of the collector is limited to less than 20%. The energy losses have been analysed. The optical losses in the lens system accounts for 47% of the total energy dissipated. These are due to absorption, reflection and diffraction in the Fresnel lenses. Furthermore manufacturing error in the lens fabrication has to be considered. One third of the solar radiation collected is lost due to the low solar absorptance of the receiver pipe. Thermal radiation and convection accounts for 6% of the total as relatively low temperatures (up to 90 °C) are involved. In order to increase the performance of the system, it is recommended to install an evacuated receiver and to insulate the recirculation system. Considering data from manufacturers, these improvements could increase the global efficiency up to 55%. Utilising the results from this work, there is the intention of building an improved version of this prototype and to conduct further tests.

1. Introduction

1.1. Solar thermal energy potential and linear concentrated collector systems

Heat represents 76% of the global industrial energy consumption and 57% of this demand is required at temperatures below 400 °C (Rawlins and Ashcroft, 2013). Solar thermal energy can be an extremely convenient and sustainable source of heat, but only concentrated system can reach temperature levels up to 250 °C, as required in most industrial processes. In several industry sectors, such as food, textiles and chemicals the share of heat demand required at temperatures below 250 °C is around 60%. The United Nations Industrial Development Organization (UNIDO) estimated the potential of concentrated solar technologies in industry to be 500 million GJ in 2050 (Taibi et al., 2010).

Flat plate solar collectors are designed to deliver lower temperature levels (up to 150 °C) (IRENA, 2015). Concentrated solar collectors can produce temperatures up to 3000 °C in central receiver concentrated solar power (CSP) plants. Concentrated systems (linear or point focus) have higher efficiency at high temperatures because the ratio of thermal energy loss to total incident solar radiation on the receiver decreases significantly (Zhai et al., 2010). Current medium temperature collectors that can meet the industrial process heating requirement are based on concentrated technologies developed for power generation purposes. Parabolic trough collectors are based on thick (3–4 mm) glass second surface mirrors which have high cost and are difficult to integrate with existing industrial processes (Kumar et al., 2015). Therefore, there is a need for the development of innovative concentrated solar thermal collectors for applications in industrial processes.

Linear concentrating solar thermal systems offer a promising method for harvesting solar energy (Zhai et al., 2010). There are three main linear concentrator technologies: parabolic trough solar concentrators, linear reflected Fresnel concentrators and linear refracted Fresnel lens arrangements. Most published studies on linear concentrating collectors are related to parabolic trough systems with evacuated tubular absorbers, illustrating the emphasis on power generating applications (Fernández-García et al., 2010; Xie et al., 2011). PMMA Fresnel lenses have the disadvantage of transmittance loss through the lens, but also have advantages in

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http://dx.doi.org/10.1016/j.solener.2017.06.010
0038-092X/

Nomenclature

A	aperture area [m^2]
C_p	heat capacity at constant pressure [kJ/kg K]
D	diameter [m]
f	focal distance [m]
G	irradiance [W/m^2]
H	prisms height [m]
h	convective heat transfer coefficient [W/m^2 K]
i	incident angle on the back surface [°]
k	thermal conductivity [W/m K]
L	pipe length [m]
$\dot{m}$	mass flow rate [kg/s]
n	refractive index
Nu	Nusselt number
Pr	Prandtl number
$\dot{q}'$	linear heat transfer [W/m]
Re	Reynolds number
R^2	coefficient of determination
T	temperature [°C]
v	fluid velocity [m/s]
x	thermal efficiency parameter

Greek letters

α	material absorptivity
β	slope angle [°]
β'	refraction angle [°]
ε	material emissivity
η	thermal efficiency
π	pi
σ	Stefan-Boltzmann constant [W/m^2 K^4]

Subscripts

abs	absorber
amb	ambient
ave	average
cond	conductive
conv	convective
DNI	Direct Normal Irradiance
in	inlet section
lens	lenses
loss	losses
out	outlet section
rad	radiative
trans	transmitted

comparison with small-scale reflecting concentrators, which tend to mitigate this radiation disadvantage. These include (Kumar et al., 2015):

- Ultra high temperatures can be generated with Fresnel CSP technology, which is suitable for various thermal energy applications.
- A compact and maintenance free concentrator.
- Fresnel-CSP based Direct Steam Generation (DSG) systems do not need a heat transfer fluid or heat exchanger.
- A high thermal efficiency, compact plant size, low cost, and a shorter payback period.
- 30% of industrial energy consumption required as process heat is in the low to medium temperature range i.e. 80–250 °C, and PMMA Fresnel lens technology is ideally suited to this range.

1.2. Linear Fresnel lenses

The flat linear Fresnel lens is considered to be a suitable concentrator for both photo-thermal and photovoltaic conversion of solar radiation (Al-Jumaily and Al-Kaysi, 1998; Boyd et al., 1976; Franc et al., 1986). A Fresnel lens is an optical component which can be used as a lightweight alternative to conventional continuous surface optics. Fresnel lenses also possess the advantage of higher flexibility in optical design when compared to conventional mirror concentrators (Leutz and Suzuki, 2001). The refractive capacity of standard lenses depends mainly on the curvature of the surface. Removing as much of the optical material as possible while still maintaining the curvature will create the same effect. This is obtained by means of a series of parallel grooves with different angles. The solar radiation passing through each groove is refracted at a slightly different angle and converges on the focal line of the lens (Fig. 1) (Davis and Kuhnlenz, 2007).

1.3. Linear Fresnel lenses for thermal applications

Research into Fresnel lenses is mainly focused on point focus concentrating photovoltaic systems and there are limited studies available about Fresnel linear concentrating solar collectors for hybrid photovoltaic and thermal systems.

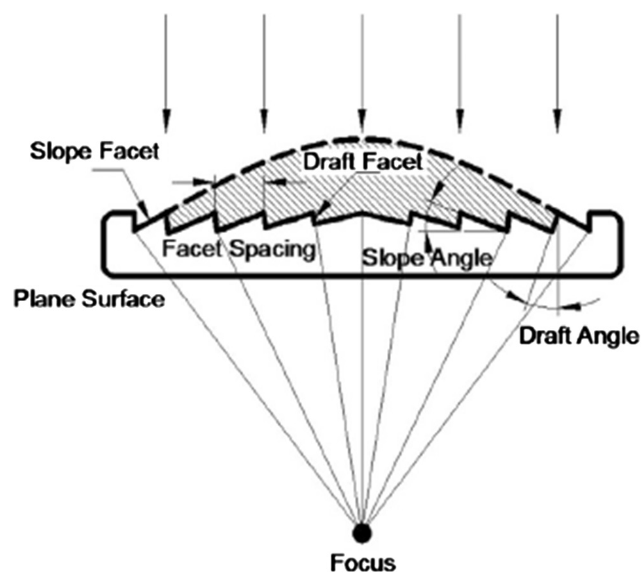

Fig. 1. Principle of Fresnel lens.

A first theoretical performance analysis of a linear Fresnel concentrating collector with cylindrical blackbody absorber was carried out in 1976. The study demonstrated that the concept output temperatures were between 130 °C and 370 °C (Boyd et al., 1976). Franc et al. (1986) studied and tested a stationary linear Fresnel lens system with movable absorber. The experiments showed a yearly gain of 360 kW h/m^2 under climatic condition in Central Europe. AL-Jumaily and Al-Kaysi (1998) studied a solar collector which consisted of two flat linear Fresnel lenses made of glass. The system was designed to track the sun in two directions. The peak measured efficiency was 58% in Iraq. The two lens system reached an outlet temperature of 37 °C.