Applied Thermal Engineering 144 (2018) 13–20

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Thermal and concentration performance for a wide range of available offset dish solar concentrators

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HIGHLIGHTS

- Opto-geometric and thermal model for an offset dish solar reflector is investigated.
- Available offset reflector capacities range from 0.071 kWt to 5.08 kWt.
- Geometric concentration of the offset reflector (957) is similar to other reflectors.
- Proposed reflector built with OPSD exhibits the lowest cost (0.47 €/W).

ARTICLE INFO

Keywords:
Solar concentrator
Offset dish
Geometric concentration
Thermal performance

ABSTRACT

This article incorporates an opto-geometric model to estimate the theoretical energy concentration performance of solar concentrators with Offset Parabolic Satellite Dishes (OPSDs). In addition, new methodologies and results are presented to characterize the solar energy capacities of offset reflectors of different sizes by means of computational simulations. The solar energy concentration capacity of these concentrators is evaluated for different aperture areas associated with commercially available OPSDs. The mathematical model is validated by comparing the results obtained by the simulator with the experimental results for an offset concentrator with a 0.7-m aperture diameter used to heat water in an open circuit with a serpentine receptor. Based on the numerical study, offset reflectors are available in a wide range of thermal energy concentration capacities ranging from 0.071 kWt to 5.08 kWt, with a receiver image width that varies from 0.006 m to 0.7 m. This range corresponds to collector aperture diameters of 0.45 m to 3.8 m. The offset concentrator is compared to other types of dish concentrators, and the results show that the cost of the OPSD concentrator is the lowest (0.47 €/Wt). Additionally, the geometric concentration value (958) is very similar to those of other offset concentrator geometries. Finally, due to the advantages of operation and maintenance and the high availability and low cost of offset reflectors, the potential for using these reflectors in solar energy applications should be evaluated based on the results and methodology outlined in this article.

1. Introduction

Global warming and the dependence on oil, a non-renewable resource, have promoted the search for new sources of energy, such as converting solar energy into thermal energy. By utilizing technologies such as parabolic troughs, central towers and parabolic dishes, thermal energy can be used for steam generation in industrial processes or electrical generation systems [1]. Parabolic satellite dishes are frequently used as solar concentrators or in water heating systems to reduce the costs of development [2], as shown in some recent demonstration projects [3,4,5]. This practice of incorporating satellite dishes as solar concentrators is doubly beneficial for the environment because it limits the pollution resulting from the waste of these devices and promotes the use of solar energy due to the reduced costs associated with reflector construction. This practice is widely promoted on Internet sites, such as Green Power Science [6], Cocina Solar [7], and Alternative Energy Tutorials [8], and by organizations involved in the research and development of solar concentration technologies.

The use of Offset Parabolic Satellite Dishes (OPSDs) in telecommunication, including in Internet and satellite TV systems, has

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https://doi.org/10.1016/j.applthermaleng.2018.08.028
Received 19 October 2017; Received in revised form 14 July 2018; Accepted 8 August 2018
Available online 16 August 2018
1359-4311/

Nomenclature

A	area, m^2
b	correlation coefficient
Cp	specific heat, J/kg K
D	diameter, m
DR	width of the focal image, m
F	focal length, m
GC	geometric concentration, –
h	coefficient of convection, $W/(m^2 K)$
Id	direct solar radiation, W/m^2
k	constants, –
m	mass, kg
n	number of segment reflectors, –
P	distance from the edge to the focal point, m
Q	energy flux density, W/m^2
r	radius, m
t	correlation variable, –
x	x coordinate, –
y	y coordinate, –
z	z coordinate, –

Greek symbols

α	absorbance, –
ε	subtended angle of the sun, mrad
ξ	emissivity, –
ρ	surface reflectance, –
ϕ	intercept factor, –
σ	Stefan-Boltzmann constant, $W/(m^2 K^4)$
σ^*	standard deviation of the optical error, mrad
ψ	rim angle, rad

Sub–indices

amb	ambient
ap	aperture
int	intermediate point
flu	fluid
gc	geometric concentration
los	thermal loss
ref	reflector
rec	receiver
w	water

recently increased due to the advantages of the dishes. These advantages include low costs, a large effective reflector area because the receiver does not shade the reflector, and easy installation and maintenance. In addition, OPSDs have a few disadvantages related to their geometry. Specifically, they require off-axis parabolic collector surfaces that create interference with the receiver at low solar elevation angles [9]. Consequently, applications have increased regarding the use of offset solar concentrators in cooking, water heating and lighting applications, as noted on the Internet sites listed above and formal studies [10]. Specifically, the incorporation of OPSDs into lighting applications has been investigated for interior spaces using fibre optics [11]. A report by Sosa et al. described the incorporation of an OPSD into a solar coffee maker [12]. A recent report by Pavlović et al. described the simultaneous incorporation of 3 OPSDs for heating fluids [13].

As highlighted by these studies, the thermal performance of OPSDs in solar concentration systems has been extensively researched; however, previous studies did not consider opto-geometric performance. Notably, the potential for and area of energy concentration for a wide range of OPSDs must be considered in optical and geometric models and reflector thermal models. Therefore, in this study, an opto-geometric model is combined with a thermal performance model of an offset reflector to investigate the characteristics of various OPSDs and the associated reflector ability.

2. Development

2.1. Description of an offset dish solar concentrator

As noted above, the manufacturers of OPSDs mainly size the reflectors according to the transmission and/or reception of satellite communication signals for TV or the Internet and design offset reflectors with large effective areas while facilitating easy installation and maintenance. The reflector design is based on the intersection of the projection of a cross-sectional aperture area with diameter (D_{ap}) onto a parabola with focal distance F, where the receiver is located [14].

These parameters are commonly used in solar concentration systems and can be directly measured for offset reflectors, as shown in Fig. 1, or obtained from the manufacturer manual for a given OPSD used in a solar concentration system.

2.2. Mathematical model

The amount of energy that can be provided by an offset reflector (Q_{ref}) in a solar energy concentration system is given in Eq. (1), which was originally proposed by Duffie and Beckman [15]. This equation considers the amount of direct radiation (Id) that strikes the aperture area of the reflector (A_{ap}) with aperture diameter (D_{ap}), the surface reflectance (ρ) and the intercept factor (φ), as shown in Eq. (1).

$$Q_{ref} = I_d \cdot A_{ap} \cdot \rho \cdot \varphi, \tag{1}$$

To perform a homogeneous evaluation of the models corresponding to offset reflectors, the following assumptions are made:

- The surface reflectance of the reflector and the absorbance of the receiver are constant values.
- The heat transfer analysis is performed under steady state conditions in one dimension without heat loss associated with the transport and storage of fluid.

2.2.1. Optical-geometric model

The optical-geometric model is particularly useful for estimating the size of the solar image on a receiver (DR) and the geometric concentration (GC) of the reflector. As noted above, the geometric model of

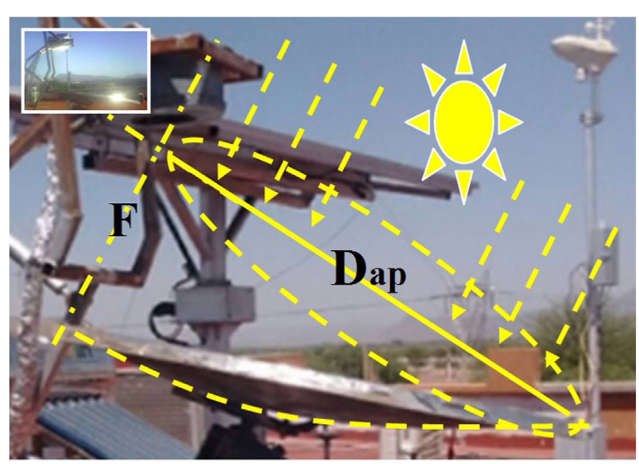

Fig. 1. Offset dish solar concentrator.