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Effective solar-thermal collector with uniform concentration

Rabi Ibrahim Rabady *, Abeer Andrawes

Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan

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Abstract

Solar concentrators are essential to reach high temperatures in solar-thermal applications. The high temperature is required to achieve effective heat transfer between different sections in solar-thermal systems that are utilized to produce electricity from the produced steam. The commonly used parabolic trough and cylindrical reflectors do not provide a uniform concentration on the receiving tube; therefore, in this paper a reflector profile design that uniformly concentrate the sunlight onto the receiver was attempted and was accomplished by solving a second order differential equation numerically. Unlike the parabolic reflector, the proposed reflector was found to exhibit more uniform concentration profile; therefore it is expected to enhance the conversion efficiency and the overall solar-thermal system performance.

Keywords: Solar energy; Uniform concentration; Reflector profile; Solar-thermal

1. Introduction

The common approach for large scale solar farms to produce electricity with affordable cost is to concentrate the solar power using special reflectors in order to heat a working fluid at high temperatures, usually around 400 °C, which thereafter transfers its sensible heat to water in order to produce the pressurized steam that is necessary to rotate the turbines of the electrical generators. Usually, the receiving tube that contains the circulating fluid is positioned at the focus of parabolic troughs that are arrayed in the solar farm field to capture and transfer the heat energy to the steam generation station.

Many researchers have treated the aspects of sunlight to heat conversion using a receiving pipe that contains a circulating fluid with a parabolic reflector in order to reach higher performance (Bakos et al., 2001; Thomas and Guven, 1993; Coventry, 2005; Islam et al., 2012; Jeter, 1986). Nevertheless, few have addressed the issue of realizing a uniform feeding of the concentrated sunlight onto the receiver. For instance, the work of Akbarzadeh and Wadowski (1996) has treated this problem for flat receiver with narrower prospective by considering the uneven sunlight concentration that is due to the uneven spatial angular reflection from the curved reflector only; whereas, the sunlight reflection angular dependencies at the air-reflector interface was not accounted for. Nevertheless, a recent work for the author treated the problem on broader prospective for a flat photovoltaic receiver by accounting for all effects that cause the non uniform infiltration of the concentrated sunlight into the flat receiver (Rabady, 2014). In this work the problem is treated with same objective of achieving uniform sunlight concentration, but for the solar-thermal application with different ray tracing configuration that is suitable for the geometry of the receiving

* Corresponding author.
E-mail addresses: rabirabady@yahoo.com, rrabady@just.edu.jo (R.I. Rabady).

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tube and not a flat photovoltaic cell. As a matter of fact, the uniform sunlight concentration for thermal-solar applications is favored because of different reasons. For instance, the uneven heating of the receiving tube outer surface may cause internal thermal stress, especially, at the welding points and because of the imperfect homogeneous composition of the receiving tube, which may degrade its' performance and lifespan. Moreover, the uneven heating of the fluid inside the receiver may increase the internal turbulent motion of the fluid, which could work against the pumping of the circulating fluid, therefore, reduces the overall system efficiency. Additionally, the uneven temperature distribution around the receiving tube that comes from the uneven illumination by the concentrated sunlight results with more average infrared emission off the hot tube because of the nonlinear relation of the infrared emitted power and the surface temperature ($E_{\mathrm{emitted}} \propto T^4$), therefore, leads to more power leak off the system that would reduce the system's overall efficiency.

It is well known that the commonly used parabolic and cylindrical reflectors do not provide an even sunlight illumination onto the receiving tube. Therefore, this paper attempts to find the reflector profile which handles the uneven concentration problem onto the receiving tube. The problem will be treated from a broad prospective by accounting for both the curvature-associated-uneven-spatial-reflection that leads to uneven concentration on the one hand and the angular dependency of the sunlight reflectivity at the air-reflector interface on the other hand.

2. Theory

Based on the previous discussion, the problem here is to find the reflector surface profile $y(x)$ such that a uniform flux of the incident sunlight is reflected and concentrated uniformly onto the receiving tube; which has a finite radius r and is positioned at point (0,H) above the reflector as depicted in Fig. 1a. The reflector curvature is responsible for the incidence of the uniform sunlight rays at various angles along the reflector surface; which, not only leads to a spatially uneven angular distribution of reflected sunlight rays toward the receiver, but also with different reflected power because of the Fresnel reflection angular dependency. Again, referring to Fig. 1a, the spatially different reflection angles effect is accounted by tracing two sunlight rays that strike the reflector at $(x, y(x))$ and $(x + dx,\ y(x + dx))$. The incremental length on the reflector surface between the two sunlight rays is denoted $\boldsymbol{dL}$; and because of the up-concaved surface those two rays converge to meet at distance $\boldsymbol{L}$ which is defined here as the effective converging length as shown in Fig. 1b. However, the two rays will be intercepted by the receiving tube and, therefore, an incremental arc length $\boldsymbol{dr}$ of the outer surface of the receiving tube shall be illuminated by the incremental pre-concentrated sunlight beam width $\boldsymbol{dx}$ as shown in Fig. 1c.

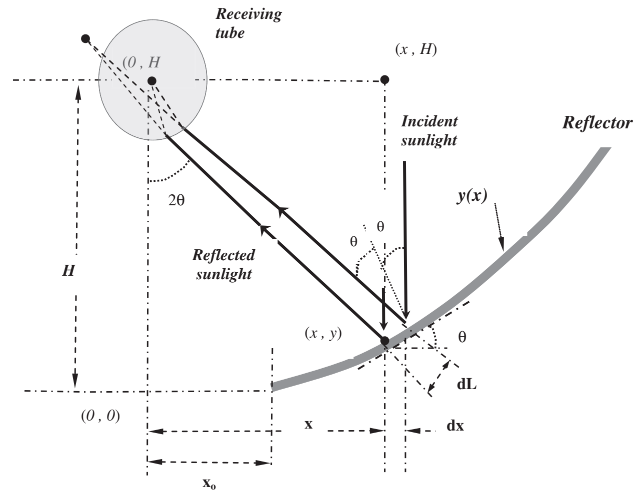

Fig. 1a. Ray tracing of sunlight concentration onto cylindrical receiver.

In order to achieve uniform concentration ratio $\boldsymbol{C}$ with the account for the reflectivity angular dependency of the reflector, the following condition need be satisfied:

$$C = \frac{dx}{R(\theta)dr} \tag{1}$$

where $\boldsymbol{\theta}$ is the sunlight incidence angle at point (x, y) on the reflector surface; $\boldsymbol{R(\theta)}$ is the Fresnel reflectivity angular dependency.

Starting with a differential length $\boldsymbol{dL}$ at the reflector surface, it can be expressed in two different ways:

$$dL = \sqrt{dy^2 + dx^2} = dx\sqrt{y'^2 + 1} \tag{2}$$

And,

$$dL = \frac{ds_1}{\cos\theta} = \left(\frac{L}{L - Z}\right) ds_2 \sqrt{y'^2 + 1} \tag{3}$$

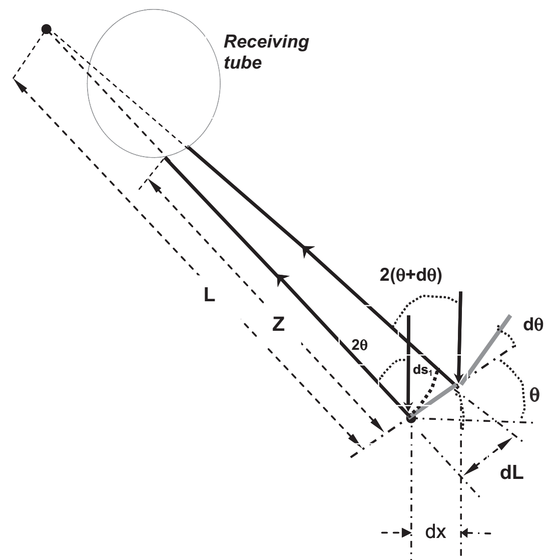

Fig. 1b. Ray tracing of the sunlight convergence upon reflection off the reflector.