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A study on dynamic heating in solar dish concentrators

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ABSTRACT

In recent years there has been a growing interest in renewable energy sources due to the increasing prices and the possible exhaustion of the current commercial energy reserves. The use of sunlight as an energy source offers a huge number of long-term benefits in widely varied and flexible applications. In the present work, the behavior of the temporal temperature in a specimen placed on the focal point of a parabolic dish solar concentrator was predicted, and a dimension quantity (Ω) was proposed. This parameter (Ω) correlates the diameter of the solar collector (D) with the solid mass to be heated (M) and the rate of solar irradiance (G). The behavior of the Equilibrium Temperature as a function of Ω was also investigated. Simulations were carried out by manipulating D, M and G, and they were arranged according to a full factorial design. The simulation results obtained showed that temperatures up to 1,600 °C can be achieved in relatively short periods of time, and they also indicated that the solar concentrator studied in this work can be an alternative to provide thermal energy for high temperature applications.

1. Introduction

The Sun is an important thermal energy source, whose irradiance is approximately 63 MW/m^2. However, the radiation shape factor between the Sun and the Earth drastically reduces the energy flow that reaches the planet to 1 kW/m^2 [1]. Nevertheless, this reduction in the heat flow may be counterbalanced by using concentrating solar systems [2].

The parabolic dish collector is one of the most efficient systems to produce high temperature heat. A solar parabolic dish collector consists of three components, viz., a concentrator, a cavity receiver/absorber and a support structure with tracking arrangements. The performance of the solar dish collector depends on the accuracy and reliability of these components. The two-axis tracking mechanism keeps the dish aperture always normal to the incoming solar radiation, which results in higher efficiency due to the increased radiation and utility of the energy produced.

The proper sizing of the components of a solar system is a complex problem, which includes both predictable (performance characteristics of the collector and other pieces) and unpredictable (weather data) components. Thus, the simulation tool is a great resource to anticipate the behavior of components in complex and varied situations.

During the last decade, several studies using simulation tools to predict the performance and behavior of solar concentrator systems have been performed [3–6]. Studies involving design and optimization of thermal performance in solar parabolic dish collectors have also been reported in the literature [7,8].

The design and optimization of solar apparatus were subject of research by several methods, including experimental measurements and complex calculations by different techniques. For the calculation of energy flux distribution on the receiver, three methods have been most reported in the literature: the cone optics method, ray tracing method and semifinite integration formulation [9–11]. The cone optics method assumes that the incident ray to a point at the mirror and the reflected ray from that point at mirror to the receiver is also a cone. The flux from any point at the receiver is obtained by integration of solar ray from the mirror [9]. The ray tracing method is a microscopic method that is based on trace large number of rays. This method provides a large amount of numerical information, however it obscures functional relationships and can consume a lot of computational effort [11]. In the third method, the radiation flux at the receiver surface is calculated firstly, then the total intercepted energy is obtained through integration. Many functions have been proposed to predict the flux at the receiver, however, these functions are very complicated to integrate analytically, so that numerical methods are often preferred [11].

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Nomenclature

A	superficial area of the specimen, m^2
A_T	top area of the dish, m^2
A_{TU}	useful top area of the dish, m^2
C	rate of convection heat losses, J/s
C_R	concentration ratio
c_p	specific heat of the fluid, J/(kg °C)
c_{ps}	specific heat of the solid, J/(kg °C)
d	characteristic dimension of the specimen (diameter), m
d_S	diameter of the sphere of the same volume of the specimen, m
D	top diameter of the dish, m
E	rate of heat losses by emission, J/s
F	focal length (distance between the focal point and the bottom of the dish), m
$F_{C\rightarrow V}$	shape factor between the specimen and its immediate vicinity
g	gravitational acceleration, m/s^2
G	incident radiation on the top of the dish, W/m^2
h	heat transfer convective coefficient, $W/(m^2\ °C)$
I	rate of radiation reflected of the dish towards the focal point, J/s
k	thermal conductivity of the fluid, W/(m °C)
k_s	thermal conductivity of the solid, W/(m °C)
ℓ	thickness of the black painted specimen, m
M	mass of the specimen, kg
N	line numbers of the Design Matrix
Nu	Nusselt Number
Pr	Prandtl Number
R	rate of radiation reflected off the specimen, J/s
R^2	variance
Ra	Rayleigh Number
V	volume of the specimen, m^3
t	time, s
t_H	heating time, min
T	temperature of the specimen, °C
T_E	maximum temperature to be reached by the specimen, °C
T_s	temperature of the solid in a specific time, °C
T_∞	ambient temperature, °C
X_1	coded form for variable D
X_2	coded form for variable M
X_3	coded form for variable G
Y	response measured or calculated after executing the Design Matrix, °C or min, for T_E or t_H, respectively
α	thermal diffusivity, m^2/s
β_0	independent term (average) that refers to the variable response Y, °C or min, for T_E or t_H, respectively
β	thermal expansion coefficient, K^{-1}
γ	intercept factor
Δt	time step used in the integration of the energy balance, s
ε	surface emissivity of the specimen
λ	ratio between the mass to be heated and the top area of the dish, kg/m^2
μ	dynamic viscosity of the fluid, kg/(m s)
Ω	dimension quantity (−)
ν	kinematic viscosity, m^2/s
ρ	density of the fluid, kg/m^3
ρ_S	density of the specimen, kg/m^3
ρ_P	surface reflectivity of the dish
ρ_C	surface reflectivity of the specimen
σ	Stefan–Boltzmann Constant, $5.670 \times 10^{-8}\ W/(m^2\ K^4)$
σ_E	optical error, mrad
Φ_{rim}	rim angle of the dish, degree

Thus, the semifinite integration formulation has concise physical concept, but has complicated formulation and also need many computation resources [9]. Considering this technique, Huang et al. [9] first calculate the optical efficiency of each point at parabolic solar trough reflector, and then integrate them to obtain the optical efficiency of the whole concentrated solar trough system. Li et al. [11] used the same technique, but taking account of the effects of incidence angle, the optical error and heat loss for different designs.

Shuai et al. [12] applied the Monte-Carlo ray-tracing method to predict radiation performance of dish solar concentrator. The uniformity performance of the wall flux was compared with five traditional geometries [12]. He et al. [13] established a coupled method based on Monte Carlo Ray Trace (MCRT) and Finite Volume Method (FVM) to simulate the photo-thermal process of parabolic trough solar thermal power generation. The Monte Carlo Ray Trace code was used to gain the heterogeneous heat flux distribution on absorber tube, and the software FLUENT was used to solve the fluid and heat transfer problem by Finite Volume Method. A complex grid checking method had to be carried out to guarantee the consistency between the two methods and the validations to the coupled simulation model [13]. A numerical method also based on Monte Carlo Ray-Trace was used by He et al. [14] for improving design/simulation tools and answering to specific questions related with heat and mass transfer inside a pressurized volumetric receiver (PVR). Experimental and simulation studies of heat losses from trapezoidal cavity receiver used in linear Fresnel reflector system have been performed in several works [15–17].

The impact of some geometrical parameters on thermal performance of a dish-type concentrated solar energy system was studied by Wang and Siddiqu [17]. In this study [18], a three-dimensional model was used to design and simulate the thermal performance of the dish-receiver. Important contributions related to the high-temperature process applications (like pyrolysis) have been obtained in several works [19–21] using solar volumetric-receivers.

These papers [9–21] are very interesting contributions, however most of them use complex methods, like CFD simulations. It is also worth mentioning that few investigations have been found related to the behavior of temporal temperature in the receiver, as well as to the design of solar apparatus with the aim to reach a specific temperature range for a particular application. Thus in the present work, we have used a simple and novel method, instead of complex techniques, to predict the temperature reached by a specimen when placed on the focal point of a parabolic dish solar concentrator and the time necessary for this to happen. The effects of the diameter of the solar collector (D), the mass of the specimen (M) and the rate of the solar irradiance (G), as well as their influence on the Equilibrium Temperature (T_E) and the Heating Time (t_H) were also quantified. Those factors were arranged in a full factorial design of experiments. Additionally, a dimension quantity (Ω) was proposed in order to optimize the approaches to building dish concentrators for a specific temperature range.