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Original article

A detailed parametric analysis of a solar dish collector

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ABSTRACT

The objective of this work is to investigate parametrically an innovative solar dish collector with a spiral-coil absorber and to determine its optimum operating conditions. This solar dish collector is a lightweight and low-cost technology which can operate mainly at medium temperature levels. A thermal model is developed in Engineering Equation Solver and it is validated with the experimental results. Different parameters as the inlet temperature, the flow rate, the absorber emittance, the optical efficiency, the wind velocity and the ambient temperature are investigated parametrically in order to investigate their impact on the collector performance. The analysis is performed in energetic and exergetic terms and the emphasis is given in the quantity and the quality of the useful product. In the last part of this work, the optimum inlet temperature and flow rate, which maximize the collector exergetic performance, are determined for various design cases. According to the results, the optimum fluid temperature is 212.3 °C and the optimum flow rate is 314.6 L/h with the thermal and exergetic efficiencies to be 49.83% and 21.42% respectively. The results of this work can be utilized for the improvement of the examined physical model in order to establish it as a reliable solar technology.

Introduction

Solar energy utilization is one of the most attractive ways in order to face many threads as the climate change, the high CO_2 emissions, the fossil fuel depletion, the increasing electricity price and the growing worldwide energy consumption [1,2]. Solar thermal collectors are the devices which capture the incident solar irradiation and they convert it into useful thermal energy with a high efficiency [3].

Concentrating solar collectors gain more and more attention because of their high thermal efficiency in medium and high-temperature levels. Parabolic trough collectors, Fresnel reflectors, solar dish collectors and solar towers are the most established representatives of concentrating solar technologies [4]. Among these technologies, solar dish collectors present the higher interest for high-temperature applications due to the high concentrations ratios which can be achieved with them [5]. Thus, a lot of research has been focused on their design in order to achieve high-temperature levels, high thermal efficiency and relatively low construction cost.

Solar dish collectors have been used in many applications as desalination [6], methanol reforming [7] and electricity production. In the applications for electricity production, solar dish collectors can be coupled with Stirling engines [8], Organic Rankine Cycles [9], water/steam Rankine cycles [10] and micro-gas turbines [11].

In literature, there is a great variety of studies which examine experimentally or numerically solar dish collectors. These studies use energetic (1st law analysis) and exergetic (2nd law analysis) in order to examine the solar dish collector as a heat exchanger and as heat engine [12]. The main goal of the literature studies is to investigate new and innovative ideas for the dish concentrator and the absorber type. Moreover, Coventry and Andraka [13] in a recent detailed study highlighted the need for improvements in solar dish technologies in order to be established as reliable and low-cost technologies.

In the first category of literature studies, the examination of different and innovative concentrators is found. Prenzak et al. [14] examined a high-temperature receiver with a two focal point concentrator. They gave emphasis to the optimum location of the receiver in order to achieve maximum optical performance. Wang et al. [15] examined a two-stage solar dish concentrator in order to develop a more compact system, compared to the conventional dishes. Yu et al. [16] investigated the use of 31 small dishes which focus on a volumetric tubular reactor for menthol reforming. Chandrashekara and Yadav [17,18] investigated a Scheffler dish concentrator with various coatings in order to determine their behavior. They gave emphasis to the energy storage for desalination proposes and the finally found that EG coating leads to higher daily yield. Hijazi et al. [19] presented ways for reducing the cost of the dish concentrators by using available sheets in every

Abbreviations: EES, Engineering Equator Solver; PMMA, Polymethyl methacrylate

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Nomenclature

A_a	Area, m^2
c_p	specific heat capacity under constant pressure, J/kg K
D	diameter, m
E	exergy flow rate, W
f_r	friction factor, –
G	global solar irradiation, W/m^2
G_b	solar beam irradiation, W/m^2
G_d	solar diffuse irradiation, W/m^2
h	convection heat transfer coefficient, W/m^2K
h_{air}	convection heat transfer coefficient between the absorber and ambient air, W/m^2K
k	thermal conductivity, W/mK
m	mass flow rate, kg/s
Nu	mean Nusselt number, –
Pr	Prandtl, –
Q	heat transfer rate, W
Re	Reynolds number, –
T	temperature, °C
u	fluid velocity, m/s
V	volumetric flow rate, L/h
V_{wind}	wind velocity, m/s

Greek symbols

ΔP	pressure drop, Pa
ε	emittance, –
η	efficiency, –
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant [$=5.67\cdot10^{-8}$ $W/m^2 K^4$]

Subscripts and superscripts

abs	absorbed
am	ambient
conv	convection
ex	exergetic
fm	mean fluid
in	inlet
m	mean
loss	losses
opt	optical
out	outlet
r	receiver
rad	radiation
ri	inner receiver
ro	outer receiver
s	solar
st	stagnation
sun	sun
th	thermal
u	useful

case. As it is obvious from the previous studies, a lot of ideas have been examined and the researchers try to improve the existing dish reflectors in order to create low cost, efficient and compact systems.

The next part of studies is focused on the study of the receivers. Many configurations and techniques have been examined and tested in order to find the system performance in every case. Firstly it should be important to present studies associated with the impact of wind velocity on the system. Reddy et al. [5] examined the impact of convection heat losses, due to wind speed, in an open modified cavity receiver of solar parabolic dish collector. They indicated that for velocities less than 5 m/s, the convection losses are relatively low because of the absence of force convection phenomena. Moreover, they stated that the direction of the wind plays an important role in the convective thermal losses. Uzair et al. [20] examined the impact of the dish concentrator on the convection losses of the receiver. They found that the existence of the reflector leads to 40% lower convection losses and thus this phenomenon has to be taken into account in the related studies.

Various receiver shapes have been studied experimentally and numerically in the literature. The most usual shape is the cylindrical cavity receiver which is more examined in many studies. Loni et al. [21,22] examined a solar dish collector with cylindrical cavity receiver which feeds an Organic Rankine Cycle. They optimized the cavity shape and they proved that there is optimum cavity diameter which combines high optical efficiency and low thermal losses. Moreover, they stated that the coil tube diameter must be relatively low in order to enhance the thermal efficiency. The existence of an optimum inner cavity diameter is stated also by Zou et al. [23] which examined a similar concentrating collector in a solar energy cascade utilization system. Moreover, it is important to state that the cylindrical cavity receivers have been examined experimentally with the studies of Mawire et al. [24] and of Azzouzi et al. [25] to be the most representative.

There are also various other receiver configurations in the literature. Loni et al. [9] examined a square prismatic tubular cavity receiver in a solar dish concentrator for feeding an Organic Rankine Cycle. Zhu et al. [26] investigated a pressurized volumetric solar receiver for various mass flow rates. According to their results, the exergetic efficiency of this system can reach up to 36%, a relatively high value for this technology. Xu et al. [27] designed and examined a novel tapered tube bundle receiver for operation in high-temperature levels (over 1000 K). The basic goal of their design is to achieve uniform heat flux over the absorber in order to reduce the thermal losses. Daabo et al. [28,29] performed a comparative optical study between cylindrical, conical and spherical receivers in solar dish collectors. According to their results, the conical shape is more beneficial compared to the other cases.

A different configuration with a spiral absorber has been examined by Pavlovic et al. [30–32]. This solar dish collector is a lightweight system which includes a corrugated spiral absorber inside the housing. In Ref. [30], the collector is examined optically and thermally with Solidworks Flow Simulation and the distance between absorber and dish was optimized. In Refs. [31,32], the collector is examined experimentally for operation with water. Simultaneously, the authors developed a numerical thermal model in order to examine the solar dish collector in various operating conditions and various working fluids (thermal oil, water and air).

The objective of this study is to examine deeper the presented collector in Refs. [30–32]. More specifically, the solar dish collector with spiral absorber is examined deeper by presenting the impact of many parameters on its performance. The collector is examined in energetic/thermal and exergetic terms in order to perform a multi-lateral study. The validated thermal model of Refs. [31,32] is used and the examined parameters are the following: optical efficiency, receiver emittance, inlet temperature, flow rate, ambient temperature, solar beam irradiation intensity and wind velocity. The examined working fluid is Therminol VP1 which operates with a safety up to 400 °C. The selection of this working fluid allows the examination of the system for medium and high-temperature levels which are the most important temperature regions for usual applications with solar dishes (e.g. electricity production). Moreover, in this study, the optimum operating conditions (inlet temperature and flow rate) are defined in order to achieve maximum exergetic efficiency. The optimization is performed for various combinations of the environmental conditions (ambient