Applied Energy 156 (2015) 519–527

Contents lists available at ScienceDirect

Applied Energy

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

Experimental investigation on the energy and exergy performance of a coiled tube solar receiver

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HIGHLIGHTS

- Thermal performance of a coil type solar dish receiver is discussed.
- Energy and exergy analysis is performed for the overall system.
- The role of the heat loss factor is analyzed.
- The efficiency of energy and exergy are compared.
- The effect of temperature difference on exergy factor is explored.

ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 29 May 2015
Accepted 4 July 2015

Keywords:
Solar receiver
Exergy
Energy efficiency
Heat transfer
Radiation

ABSTRACT

In this article, an experimental investigation is carried out to examine the heat transfer characteristics of a coil type solar dish receiver under actual concentrate solar radiation conditions. During the test, the concentrated solar flux is approximately 1000 kW/m^2 at aperture. The solar irradiance is almost unchanged (650 W/m^2) for continuous two hours in the afternoon, which is used to analyze the energy and exergy performance of the solar receiver. Experimental results show that, the efficiency of the solar receiver is normally above 70% with the highest efficiency of 82%, whereas at steady state, the efficiency is maintained at around 80%. A very low value of the heat loss factor (0.02 kW/K) could be achieved during the current steady state operating conditions. The highest value of the exergy rate is around 8.8 kW, whereas the maximum energy rate can reach 21.3 kW. In addition, the highest exergy efficiency is approximately 28%, and the highest energy efficiency is around 82%.

1. Introduction

Nowadays, owing to the global progressively increasing demand for primary energy and the increasing scarcity of fossil energy sources, Concentrated Solar Power (CSP) system is considered as one of the most attractive ways to solve the energy crisis in the future [1]. A CSP plant uses the concentrated power of the sun as a heat source to generate mechanical power [2]. Many developed countries like the United State and the European Commission have done a lot of work on the solarised Brayton micro-turbines. The researches on the solar air receiver are done in three forms tower, trough and dish. In the framework of the French PEGASE project (Production of Electricity by gas turbine and Solar Energy); CNRS/PROMES laboratory is developing a 4 MW pressurized air solar receiver with a surface absorber based on a compact heat exchanger technology [3]. ETH Zurich and Paul Scherrer Institute have done a field testing of a 42 m-long full-scale solar receiver prototype installed on a 9 m-aperture solar trough concentrator, the receiver efficiency ranges from 45% to 29% for a solar power input of 280 kW [4–6]. Comparing to the parabolic trough system with the concentration ratio of 100 suns and the central tower system with the concentration ratio of 1000 suns, the parabolic dish system can achieve concentration ratio of 10,000 suns. According to this, very high efficiency can be achieved in a parabolic dish solar system due to its high concentration ratio [7]. The solar concentration part which is used to provide high temperature air is very crucial for the entire solar power system. The system efficiency and the cost of power generation are highly

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http://dx.doi.org/10.1016/j.apenergy.2015.07.013
0306-2619/

Nomenclature

A_{ap}	effective aperture area of dish (m^2)
A_p	project area (m^2)
c_{av}	average specific heat capacity (J/kg K)
D_f	focus point diameter (m)
E_D	concentrated solar radiation power (kW)
E_L	heat loss (kW)
E_R	receiver power (kW)
E_S	solar radiation power on the dish (kW)
Ex_D	rate of dish exergy concentrated(kW)
Ex_f	exergy factor (–)
Ex_R	receiver exergy (kW)
Ex_s	rate of solar exergy delivery (kW)
G	solar radiation (W/m^2)
$\dot{m}$	mass flow rate (kg/s)
n_d	parabolic dish combined optical efficiency (–)
r_c	concentration ratio
T_{in}	inlet temperature of the air (K)
T_{out}	outlet temperature of the air(K)
T_{ave}	average temperature of the air(K)
U_L	heat loss coefficient (kW/m^2 K)
$\eta_{th.R}$	energy efficiency of the receiver (–)
$\eta_{ex.R}$	exergy efficiency of the receiver (–)

depended on the solar concentration part conversion efficiency from solar radiation to thermal fluid. Thus, the solar concentration part has to be well designed in order to achieve high efficiency and low pressure loss.

Extensive studies on the solar concentration systems for various applications have been done in recent years including both the concentrator and the receiver. Lovegrove et al. [8] introduced the design development and construction steps of a 500 m^2 paraboloidal dish solar concentrator in Australian National University. Li and Dubowsky [9] proposed a new concept for designing and fabricating large parabolic dish mirrors. The energy efficiency of the designed dish mirrors was estimated for validating the concept using Finite Element Analysis and experimental data. Wu et al. [10] proposed a parabolic dish/AMTEC solar thermal power system. A heat-pipe receiver was used to receive the concentrated solar radiation from the parabolic dish collector. Their experimental results indicated that the proposed system was a viable solar thermal power system. Li et al. [11] utilized the Monte-Carlo ray-tracing method to predict the radiation flux distributions of the concentrator–receiver system. The radiation flux profiles of a faceted real concentrator and an ideal paraboloidal concentrator for different aperture positions and receiver shapes were analyzed, respectively. Joo et al. [12] considered six different mirror arrangements and four different receivers to numerically investigate the performance comparisons of the dish type solar concentrators. For the calculation of the radioactive heat loss in the receiver, the net radiation method and the Monte-Carlo method were used.

Compared to the traditional gas turbine, solarised Brayton turbines use solar receiver to replace the combustion chamber in the traditional gas turbine [13]. Many studies have been devoted to the designs and performance of the receiver. Lim et al. [14] proposed a tubular solar receiver made from stainless steel with a porous medium inside to heat up the compressed air. The effects of the design factors on the system performance were numerically investigated and the optimal design point was selected. Wang and Siddiqui [15] presented the temperature distributions of the receiver wall and the working gas based on a designed three-dimensional model of parabolic dish-receiver system. The impact of the aperture size, inlet/outlet configuration of the solar receiver was investigated. Antonio et al. [16] presented an analysis for a medium size central receiver power plant and found that the net annual energy could be increased around 35%, from Seville-to-Carnarvon. Buck et al. [17] introduced a receiver module consisting of a secondary concentrator and a volumetric receiver unit which heated the compressed air of the gas turbine before it entered the combustor. The receiver unit was closed with a domed quartz window to transmit the concentrated solar radiation. Then the secondary concentrator was redesigned and rebuilt with improved efficiency. Kumar and Reddy [18] performed a numerical investigation to study the natural convective heat loss from three different types of receivers, i.e. cavity receiver, semi-cavity receiver and modified cavity receiver for a solar dish concentrator. The natural convective heat loss was assessed by varying the inclination of receiver, and then an optimum area ratio was given for modified cavity receiver. Hischier et al. [19,20] proposed a novel design of a high-temperature pressurized solar air receiver for power generation via combined Brayton–Rankine cycles. It consists of an annular reticulate porous ceramic bounded by two concentric cylinders. The heat transfer mechanism was analyzed by the finite volume technique and by using the Rosseland diffusion, P1, and Monte-Carlo radiation method. It was found that, for a solar concentration ratio of 3000 suns, the outlet air temperature can reach 1000 °C at 10 bars, yielding a thermal efficiency of 78%. Hachicha et al. [21,22] proposed a numerical aerodynamic and heat transfer model based on Large Eddy Simulations (LES) modelling of parabolic trough solar collectors (PTC), and verified the numerical model on a circular cylinder in a cross-flow. The circumferential distribution of the solar flux around the receiver is also studied. Wang et al. [23] investigated the effect of inserting metal foams in receiver tube of parabolic trough collector on heat transfer. The optimum thermo-hydraulic performance was obtained. Yu et al. [24] performed a numerical investigation on the heat transfer characteristics of the porous material that used in the receiver of a CSP with different structure parameters. The effects of different boundary conditions were revealed. The results demonstrated that the filed synergy principle (FSP) and the entransy dissipation extremum principle (EDEP) are inherently consistent. Roldan et al. [25] carried out a combined numerical and experimental investigation of the temperature profile in the wall of absorber tubes of parabolic-trough solar collectors using water and steam as the heat-transfer fluid. A good agreement between the measured and computed thermal gradient was achieved. This can be helpful to study the thermal behavior of new absorber-tube prototypes for direct steam generation in parabolic troughs.

Nowadays, energy and exergy analysis methods (First and Second Law) are normally used to evaluate the thermal performance of the solar receiver system. The energy and exergy efficiency can be used as the most crucial thermal performance criterion. Kaushik and Gupta [26] conducted an energy and exergy efficiency comparison of a community-size and a domestic-size paraboloidal solar cooker performance. The performance of the community solar cooker was found to be comparable to that of the domestic cooker. Ashmore and Simeon [27] investigated the thermal performance of a cylindrical cavity receiver for the purposes of teaching. The thermal performance was evaluated using energy and exergy analyses. Their experimental results showed that the maximum energy and exergy efficiencies were found to be around 45% and 10%, respectively. Generally, it can be concluded that the exergy analysis method would be an effective aid to analyze the rationality of the energy utilization, energy loss