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Research Paper

Experimental study of the energy and exergy performance for a pressurized volumetric solar receiver

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HIGHLIGHTS

- Performance of a pressurized volumetric solar receiver is experimentally discussed.
- Energy and exergy analysis is performed during a two-hour period in the morning.
- The efficiency of the solar receiver is maintained at around 60% under steady state.
- The highest exergy efficiency and energy efficiency is approximately 36% and 87%.

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ABSTRACT

This article presents an experimental investigation of the heat transfer characteristics as well as energy and exergy performance for a pressurized volumetric solar receiver under variable mass flow rate conditions. During a two-hour period of continuous operation in the morning, the solar irradiance is relatively stable and maintained at approximately 600 W/m^2, which is beneficial for analyzing the energy and exergy performance of the solar receiver. Experimental results show that the mass flow rate fluctuation has insignificant effect on the solar receiver outlet temperature, whereas the mass flow rate plays an important role in the solar receiver power, energy efficiency and exergy efficiency. The efficiency of the solar receiver is normally above 55% with the highest efficiency of 87%, and under steady state operating conditions the efficiency is maintained at approximately 60%. A very low value of the heat loss factor (0.014 kW/K) could be achieved during the current steady state operating conditions. The highest exergy efficiency is approximately 36%. In addition, as the temperature difference increases, the impact of the exergy factor increases. The highest exergy factor is 0.41 during the entire test.

1. Introduction

With rapidly increasing energy prices and globalization, process industries seek opportunities to reduce production costs and improve energy efficiency. Among the energy-efficient technologies, Concentrated Solar Power (CSP) system is considered as one of the most attractive ways to solve the energy crisis in the future [1,2]. Many developed countries like the United State and the European Commission have been devoted to the solarized Brayton micro-turbines system over the past decades [3–5].

Compared to the traditional gas turbine, solarized Brayton turbines use a solar receiver to replace the combustion chamber in the traditional gas turbine [6]. 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 the power generation are highly depended on the solar concentration conversion efficiency from solar radiation to the thermal fluid. Thus, the solar concentration part has to be well designed in order to achieve high efficiency and low pressure loss. Many studies have been devoted to the design and performance of the receiver. Neber and Lee [7] designed a high temperature cavity receiver using silicon carbide. Then a scaled test section was placed at the focal point of a parabolic dish collector and reached a maximum temperature of 1248 K.

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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]
C_P	solid 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]
δE_R	uncertainty of the receiver power [–]
δEx_R	uncertainty of the receiver exergy rate [–]
G	direct 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]
T_s	surface temperature of the sun [K]
T_{amb}	ambient temperature [K]
U_L	heat loss coefficient [kW/m^2 K]
$\eta_{th\cdot R}$	energy efficiency of the receiver [–]
$\eta_{ex\cdot R}$	exergy efficiency of the receiver [–]

Lim et al. [8] designed a tubular solar receiver with a porous medium and found the optimal design point of the proposed solar receiver concept to heat up compressed air. The results of this study offer a valuable design guideline for future manufacturing processes. Wu et al. [9] developed a novel particle receiver concept for concentrating solar power (CSP) plants. Special attention was paid to the effect of rotation on convective flow in a cylindrical cavity with heated side walls for solar applications. Buck et al. [10] introduced a receiver module consisting of a secondary concentrator and a volumetric receiver unit which was closed with a domed quartz window to transmit the concentrated solar radiation. Hischier et al. [11,12] 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 methods. 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%.

It is recognized that the flow and heat transfer processes in the solar receiver are very complicated. Over the past years, many studies have been devoted to the optimization of the design using theoretical and numerical methods. Tu et al. [13] studied a saturated water/steam solar cavity receiver with different depths by adopting a combined computational model. Various trends of thermal efficiency and heat loss with depths were obtained. A suitable cavity depth was finally found for the receiver. Wang and Siddiqui [14] developed a three-dimensional model of a parabolic dish-receiver system with argon gas as the working fluid to simulate the thermal performance of a dish-type concentrated solar energy system. Wu et al. [15] presented and discussed temperature and velocity contours as well as the effects of aperture position and size on the natural convection heat loss. Their study revealed that the impact of aperture position on the natural convection heat loss is closely related to tilt angle, while the aperture size has a similar effect for different tilt angles. Hachicha et al. [16,17] proposed a numerical aerodynamic and heat transfer model based on Large Eddy Simulation (LES) modeling of parabolic trough solar collectors (PTC), and verified the numerical model on a circular cylinder in the cross flow. The circumferential distribution of the solar flux around the receiver was also studied. von Storch et al. [18] proposed a process for indirectly heated solar reforming of natural gas with air as heat transfer fluid. Different solar receivers were modeled and implemented into the reforming process.

On the other hand, many numerical research works are also conducted to simulate the detail heat transfer process. Flesch et al. [19] numerically analyzed the impact of head-on and side-on wind on large cavity receivers with inclination angles ranging from 0° (horizontal cavity) to 90° (vertical cavity) and compared with the data published in the open literature. Yu et al. [20] performed a numerical investigation on the heat transfer characteristics of the porous material used in the receiver of a CSP with different structure parameters. The effects of different boundary conditions were revealed. Tu et al. [21] proposed a modified combined method to simulate the thermal performance of a saturated water/steam solar cavity receiver. Capeillere et al. [22] numerically studied the thermomechanical behavior of a plate solar receiver with asymmetric heating. The numerical results showed that the choice of the shape and levels of the solar irradiance map is crucial. The distribution of the most relevant incident solar flux and the geometry compromise were determined. Wang et al. [23] conducted a numerical study focusing on the thermal performance of a porous medium receiver with quartz window. Their results indicated that the pressure distribution and temperature distribution for the condition of fluid inlet located at the side wall was different from that for the condition of fluid inlet located at the front surface. Roldan et al. [24] 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 fluids. A good agreement between the measured and computed thermal gradient was achieved.

Exergy analysis has been applied in various power studies. In the authors' earlier studies [25,26], a coiled tube solar receiver had been designed and tested in the real solar radiation condition. But due to the limitation of the tube material, the coiled tube solar receiver could not achieve very high temperature. Thus, a pressurized volumetric solar receiver using metal foam as thermal absorbing core is designed in this work. It appears from the previous investigation that the key point for the solarized Brayton micro-turbines is to develop solar receivers which have exemplary performance on the pressure loss and heat transfer. To the best of the authors' knowledge, there is a lack of available experimental data under real concentrated solar and variable mass flow conditions especially for the cases of extremely high heat flux and high temperature. To this end, the present research is aimed to experimentally analyze both the efficiency and heat loss of a pressurized volumetric solar receiver under real solar radiation and variable mass flow conditions in more detail.