Energy Conversion and Management 106 (2015) 1362–1369

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modeling study on the thermal performance of a modified cavity receiver with glass window and secondary reflector

Huawei Chang [a], Chen Duan [b], Ke Wen [a], Yuting Liu [c], Can Xiang [a], Zhongmin Wan [a,d,*], Sinian He [a], Changwei Jing [c], Shuiming Shu [a]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Wuhan Second Ship Design and Research Institute, Wuhan 430064, China
[c] China-EU Institute for Clean and Renewable Energy, Huazhong University of Science and Technology, Wuhan 430074, China
[d] College of Information and Communication Engineering, Hunan Institution of Science and Technology, Yueyang 414006, China

ARTICLE INFO

Article history:
Received 28 July 2015
Accepted 15 October 2015
Available online 11 November 2015

Keywords:
Cavity receiver
Thermal performance
Quartz glass window
Secondary reflector
Monte-Carlo ray-tracing

ABSTRACT

The development of a cavity receiver for a 1 kW beta type solar Stirling engine is presented in this work. The proposed receiver is composed of an additional quartz glass window and a secondary reflector aiming at improving the thermal performance. Monte-Carlo ray-tracing method is adopted to study the optical property and calculate radiative exchange factors of the solar collector system. The results show that the radiation flux sent to the proposed cavity receiver is 5003 W, and the optical efficiency of this receiver is 70.8%. Numerical simulation is conducted to investigate the thermal performance of this modified receiver. The proposed receiver is also compared with other three simulated receivers combining the presence and absence of the quartz glass window and the secondary reflector. The numerical simulation results show that the modified receiver with both quartz glass window and secondary trumpet reflector outperformed other designs, and its heat loss is reduced about 56% compared to the initial receiver without both quartz glass window and secondary reflector. Hence, the impact factors on the modified receiver radiation and convection heat transfer are well analyzed including temperature, the inner surface orientation and emissivity. The research indicates that the proposed cavity receiver can efficiently reduce the heat loss from cavity and is suitable for Stirling engine applications.

1. Introduction

As solar energy is clean, renewable and widely distributed, solar thermal power generation system has shown its great commercial prospects in the last decade. In solar thermal applications, highly concentrated solar radiation is reflected toward a receiver or reactor, significantly heating the absorber and the working fluid passing through the solar receiver [1]. These solar thermal systems can be applied in different applications because of the increased heat fluxes and elevated temperature in the receiver [2]. Though the dish–Stirling technology is an emerging and still not mature technology, it has the advantage of high efficiency and modularity, consisting on units varying from 7 to 25 kW [3]. In the field of low-grade energy utilization, Al-Mohamad [4] designed a Sun-tracking system to improve the photo-voltaic efficiency and the maximum thermal efficiency exceeded 40%; Guo et al. [5] studied the utilization of geothermal energy with the maximum thermal efficiency at 11.4%; He et al. [6] analyzed the recovery of low-temperature energy of LNG (Liquefied Natural Gas) with the maximum thermal efficiency at 21.6%; the maximum thermal efficiency of hybrid solar-fuel cell power systems was about 17% [7]. Thus, by overcoming the high costs and improving its efficiency, dish–Stirling could be competitive with these commercial power systems.

One of the most important factors that impact the thermal performance of the solar power system is the heat loss, including natural convection heat loss and surface radiation heat loss, which contribute for more than 10% of the energy dissipation on the concentrator aperture [8]. Further research on cavity receivers can be helpful on optimal design of the receiver. A modified cavity and semi-cavity receiver was proposed by Kaushika [9]. The results showed that the thermal performance of the proposed designs is much better than that of conventional designs. Li et al. [10] studied the natural convection heat loss characteristics of a solar cavity receiver, explained the reduction mechanism of natural convection heat loss and found some interesting natural convection heat loss characteristics. Kumar et al. [11] investigated the natural

* Corresponding author at: School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. Tel.: +86 27 87542718.
E-mail address: zhongminwan.hust@gmail.com (Z. Wan).

http://dx.doi.org/10.1016/j.enconman.2015.10.043
0196-8904/

Nomenclature

a	absorption coefficient
I	radiation intensity ($W\ m^{-2}$)
n	refractive index
P	pressure (Pa)
P_{atm}	atmospheric pressure (Pa)
$\vec{r}$	position vector
$\vec{S}$	direction vector
$\vec{S'}$	scattering direction vector
T	temperature (K)
V_{vel}	velocity ($m\ s^{-1}$)
X	body force ($N\ m^{-3}$)

Greek symbols

λ_s	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
β	inclination of receiver (°)
ε	emissivity of the inner surface
ν	kinematic viscosity of the fluid ($m^2\ s$)
Φ	phase function
Ω'	solid angle
ρ	density of the fluid ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
σ_s	scattering coefficient
∇	Laplace operator

convective heat loss in three different types of receivers for solar dish concentrator with both numerical and experimental study. The flow pattern, orientation, geometry and correlations of characteristic parameters were studied. In the respect of coupled heat transfer research, Balaji et al. [12] found that the surface radiation played an important role in the flow and heat transfer of a receiver through the numerical simulations on surface radiation. Yuan et al. [13] evaluated heat loss predictions using the commercial computational fluid dynamics (CFD) software packages Fluent 13.0 and Solidworks Flow Simulation 2011 against experimentally measured heat loss for a heated cubical cavity receiver model and a cylindrical dish receiver model. Reddy et al. [14] conducted simulation study to investigate the laminar natural convection in the cavity receiver of solar power system; the same simulations were also conducted on the surface radiation heat transfer. With large numbers of numerical calculation, Nusselt number correlations were proposed for both kinds of heat transfer forms. Another research presented a series of experiments to investigate the thermal performance of a fuzzy focal solar dish concentrator [15]. The heat losses, including conduction, natural convection and radiation, were experimentally studied after theoretical thermal analysis. The results showed that the thermal performance can be greatly affected by the volume flow rate. Qiu et al. [16] also conducted numerical and experimental study on the volume flow rate as well as the flow pattern. It was concluded that the thermal performance can be much better with up-flows than that of down-flows.

In order to enhance the receiver performance, minimizing the heat loss may be the most effective and common way that attracted many researchers' eyes. Tu et al. [17] proposed a modified method to calculate the steady-state performance of the cavity receiver and studied the effects of radiative surface properties inside the receiver. Kribus et al. [18] designed a multistage receiver to get high operating temperature and thermal performance. Ngo et al. [19] designed a new kind solar cavity receiver with plate fins and studied the influence of fluid flow and geometric parameters on natural convection heat loss. Then they conducted a three-dimensional model for solar cavity receiver to study the natural convection and radiation heat loss. Optimization on the fin geometry was also conducted to get better thermal performance. The results are very helpful for improving the design of solar receivers [20]. Experimental study on heat loss of hemispherical cavity receiver was conducted by Tan et al. [21], and correlations of Nusselt number were also developed. Wang et al. [22] designed a solar receiver for parabolic trough collector system. The effects of glass cover were seriously investigated with numerical study; the results showed that elliptic glass cover can be more suitable for tube receiver with the thermal performance increasing by 32.3%. Shuai et al. [23] predicted the radiative characteristics of the cavity receiver in the solar power system through Monte Carlo method coupled with optical model. Then further study on the solar collecting efficiency and the temperature of the quartz glass window was conducted. The new receiver with special quartz glass window showed great thermal performance due to the exceptional characteristic of the special quartz glass window. Cui et al. [24] studied the influence of quartz glass cover on the performance of cavity receiver. The simulation results showed that the glass cover could significantly reduce heat loss via both the natural convection process and radiation process. Larrouturou et al. [25] studied the reflection and thermal emission losses in a solar cavity receiver and the influence of the cavity wall BRDFs on the absorption efficiency. Reddy et al. [26] investigated the thermal performance of a modified cavity receiver to study the impact of insulation for solar collector system, the results indicated that the receiver without insulation performed more efficiently and would be a better choice. Then through the analysis of its thermal behavior with different secondary reflectors, the trumpet one was proved to be more efficient [27]. Badescu [28] theoretically studied the optimum operation of solar receiver and analyzed energy conversion efficiency in detail, which can be treated as theoretical upper bounds. The same analysis in this field was also conducted in another work from Badescu [29].

The literature review on the simulation of cavity receivers showed that the thermal characteristics of the cavity receiver with glass window and with secondary reflector were investigated separately. Based on this consideration, this work proposes a new type of cavity receiver, means With Glass and Reflector (WGR). It has a quartz glass window and a secondary trumpet reflector to combine the advantages of both glass window and secondary reflector to reduce the heat loss more efficiently.

This proposed receiver was designed and optimized with Matlab for the potential application on the 1 kW beta type solar prototype Stirling engine designed by the authors [30,31]. The total flux sent into the proposed cavity receiver was obtained through the optical simulation with TracePro. For comparison of optimized performance and design, additional three receivers were simulated combining the presence and absence of the quartz glass window and the secondary reflector: WOGR (WithOut Glass and Reflector), WGWOR (With Glass WithOut Reflector) and WOGWR (WithOut Glass With Reflector). Finally, a brief comparison with the total heat loss of other models was carried out to demonstrate the efficiency improvements achievable with the proposed receiver.

2. Physical and mathematical model

2.1. Description of the Stirling engine and the proposed cavity receiver

The prototype Stirling engine proposed in this work is depicted in Fig. 1. Considering the structure of the heater, a heat-pipe reflux cavity receiver is suitable to be applied on it.