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Study on the thermal performance of a novel cavity receiver for parabolic trough solar collectors

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HIGHLIGHTS

- A novel cavity receiver was presented for a PTC.
- It was simple and overcame the possible shortcomings of tube bundle absorber.
- A three-dimension heat transfer model was established.
- The model was validated by the test results from a built experimental setup.
- Effects of physical property parameters on the thermal performance were analyzed.

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ABSTRACT

In this research, a novel cavity receiver for the parabolic trough solar collector (PTC) is presented. A center tube and two inclined fins act as the absorber to absorb the solar energy concentrated by the parabolic trough reflector. Its manufacture is simple. Compared to the tube bundle absorber, it is more convenient to connect in series and avoids the possible non-uniform distribution of the flow in practical applications. An experimental setup was constructed to test the thermal performance of this kind of cavity receiver. The experimental collector efficiency was in the range of 34.18–48.57%. The used physical parameters and installation error in the experiment resulted in the relatively low collector efficiency. A three-dimensional heat transfer model was established and validated by the test results. Effects of thermal conductivity of the insulation materials, emittance of the glass cover and absorber, and optical parameters on the thermal performance of the cavity receiver were estimated in detail. The results quantitatively indicated the importance of improving the physical property parameters of the collector, e.g. if the optimal parameters were selected, the collector efficiency could reach 64.25%, which was comparable to the metal-glass evacuated tube receiver. It indicates that the performance improvement potential of this kind of cavity receiver is huge and the results can theoretically guide the improvement in manufacture and installation. The present study is beneficial for promoting the large-scale application of the PTC in a simple and convenient way and the development of solar thermal technologies. The experimental test of the collector with the optimized parameters of this research and detailed cost analysis will be performed in the future work.

1. Introduction

The rapid economic growth results in large consumption of fossil fuels, which causes not only the shortage of global energy supply but also the deterioration of global environment [1–3]. For solving these problems, renewable energy technologies have become a research hot spot. Solar energy is one of the most promising renewable energy sources as it is abundant and free.

Among all the solar energy technologies, the parabolic trough solar collector (PTC) is one of the most promising applications, which is widely used in space cooling, heating, power generation and so on. As one of the most important components of a PTC, the receiver affects the thermal performance of the system significantly. At present, two major types of receivers are under active investigation: metal-glass evacuated tube receiver and cavity receiver. For a metal-glass evacuated tube receiver, the annulus between the glass cover and metal absorber is

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Nomenclature

W_g	width of the cavity aperture (mm)
W_c	width of the cavity receiver (mm)
W_t	total width of the receiver (mm)
h_c	height of the cavity receiver (mm)
d_r	diameter of the center absorber tube (mm)
L_c	length of the cavity receiver (mm)
W_p	width of the reflector (mm)
W_a	gap value along the width of the reflector (mm)
L_p	length of the reflector (mm)
L_a	gap value along the length of the reflector (mm)
f_p	focal length of the reflector (mm)
q	energy of each photon (W)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
t_{in}	inlet temperature (°C)
t_{out}	outlet temperature (°C)
$\dot{m}_{oil}$	mass flow rate (kg/s)
t_a	ambient temperature (°C)
v_a	wind speed (m/s)
I_d	normal direct solar irradiance (W/m^2)
c_p	specific heat capacity (J/kg/K)
A_p	area of the reflector (m^2)
Q_{loss}	heat loss (W)

Greek symbols

λ_{s1}	thermal conductivity of insulation material 1 (W/m/K)
λ_{s2}	thermal conductivity of insulation material 2 (W/m/K)
ρ_p	reflectance of the reflector
τ_g	transmittance of the glass cover
α_c	absorptance of the absorber
γ	intercept factor
ε_c	emittance of the absorber
ε_s	emittance of the shell
ε_g	emittance of the glass cover
ε	threshold value of photon energy
η	collector efficiency (%)
η_{error}	estimated error of collector efficiency (%)

Abbreviations

PTC	parabolic trough solar collector
MCRT	Monte Carlo ray tracing
LCR	local concentration ratio

generally evacuated to reduce the convection heat loss. Nevertheless, the vacuum may be compromised due to glass breakage, seals broken, hydrogen penetration and getter decomposition [4,5]. In contrast, a cavity receiver faces less technical difficulties in production and requires less manufacture and maintenance costs [6–9], though the thermal efficiency is slightly sacrificed because of the non-vacuum design. Thus, the cavity receiver has gradually attracted attention.

In 1976, Boyd et al. [10] presented a kind of cavity receiver consisting of an annular cylindrical tube. It was designed without special surface coatings and vacuum enclosures. The theoretical analysis of its thermal performance at moderate and high-temperature applications was carried out. Barra and Franceschi [11] analyzed the thermal performance of a circular cavity with a V-shape glass cover. Eight copper pipes were placed inside the cavity acted as the absorber to absorb the solar energy reflected by the parabolic trough reflector. Reynold et al. [12] studied the heat loss characteristics of a trapezoidal cavity, with a flat plate absorber on the upper surface. The flow visualization technique was adopted in their test. Singh et al. [13] also estimated the heat loss of the trapezoidal cavity receivers. It was found that the selective surface coating and double glass cover could reduce heat loss coefficient by 20–30% and 10–15%, compared to the ordinary black coating and single glass cover respectively. Zhai et al. [14] investigated the optical and thermal performance of four cavity receivers with different shapes, i.e. circle, semicircle, square and triangle. It indicated that the optical efficiency of the triangular cavity could reach 99% and its solar conversion efficiency could be beyond 67%. Li et al. [15] evaluated the thermal performance of a triangular cavity receiver, operating with a double effect lithium bromide chiller. The instantaneous efficiency of the receiver was about 44% when the direct solar irradiance was about 500 W/m^2. Bader et al. [16] proposed four cavity receiver configurations: smooth or V-corrugated absorber tube and single or double-glazed aperture window. The collector efficiency was 60–65% and 37–42% at a working fluid temperature of 125 °C and 500 °C respectively when the direct normal solar irradiance was 847 W/m^2 and solar incidence angle was 13.9°. Gao et al. [17] presented three types of cavity receivers: the secondary reflecting cavity, Two-Plus M-type cavity, and Three-Plus M-type cavity. The geometrical-optical method was employed to analyze the absorptivity, and the results indicated that absorptivity of these cavities approached to blackbody. Daabo et al. [18] and Qiu et al. [19] adopted another more common method of Monte-Carlo algorithm to study the optical performance of cavity receivers. It was easy to understand and suitable for computer calculation. Wang et al. [20] utilized the non-dominated sorting genetic algorithm to perform the multi-objective optimization of the aiming strategy for the solar power tower with a cavity receiver, in order to homogenize the solar flux distribution on the inner surfaces within the cavity receiver, as non-uniform solar flux distribution could cause some crucial problems, e.g. the local hot spot, the thermal stress, and the thermal deformation. Zhang et al. [21] studied the thermal performance of the molten salt cavity receivers with different structures. The results showed the thermal efficiency of a too-low or too-high height of the receiver was low, and an appropriate height should be chosen. Saeed Mostafavi Tehrani and Taylor [22] proposed a thermal model for evaluating the design/off-design performance of molten salt cavity receivers in both steady state and transient conditions, which provided a theoretical guide for realistic operational modes and control strategies.

Although a lot of research has been carried out on the optical and thermal performance of cavity receivers up to now, there are still some problems in the utilization of this kind of receivers in PTCs. The shapes of the absorber in some studies are irregular and difficult to manufacture, such as the annular cylindrical absorber. Some existing cavity receivers employ more than one tube to act as the absorber. The flow might be distributed non-uniformly in each tube if the flow resistances are different, which can result in overheat of the tube with small flow. In addition, the previous investigations mainly focus on designing the geometrical shapes of the cavity to improve the optical and thermal performance. The effects of physical property parameters on the energy transfer process of the cavity receivers for PTCs are required to be evaluated more comprehensively, which is the key point to reduce the heat loss and improve the collector efficiency.

In this study, a novel cavity receiver is proposed, in which a center tube and two inclined fins act as the absorber. Its manufacture is simple. Compared to the tube bundle absorber, it is more convenient to connect in series and avoids the possible non-uniform distribution of the flow in practical applications. An experimental setup is constructed to test the thermal performance and verify the technical feasibility of the novel cavity receiver. The test results are used to validate the established three-dimensional numerical heat transfer model. The effects of main