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An analysis of the heat loss and overheating protection of a cavity receiver with a novel movable cover for parabolic trough solar collectors

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ABSTRACT

In this research, the effects of the novel movable cover on reducing heat loss and overheating protection of a cavity receiver for parabolic trough solar collectors were studied. The heat loss tests were carried out at different inlet temperatures and mass flow rates. A three-dimensional heat transfer model was developed and validated by the test data. Effects of ambient temperature, wind speed, inlet temperature, rotation angle of the collector and on-off state of the movable cover on heat loss were investigated. The heat loss of turning off the movable cover was less than that of turning on it. The heat loss reduction rate varied from 6.36% to 13.55%. Three tests of collecting solar energy all the time (control group), overheating protection with the methods of rotating the reflector and turning off the movable cover were conducted under similar weather conditions. The results showed that both the overheating protection methods were effective. However, the method of turning off the movable cover avoided rotating the reflector and re-tracking the sun later. The presented novel movable cover improved the thermal performance of cavity receivers remarkably in a simple way.

1. Introduction

A parabolic trough solar collector (PTC) utilizes the concentrated solar energy to heat the working fluid in the receiver. It can be used for space heating, desalination, power generation and so on. Generally, a PTC consists of a parabolic trough reflector, a receiver, the support brackets and other components. The receiver plays a crucial role in the photothermal conversion process. It significantly affects the thermal performance of the whole PTC system. At present, there are two main types of receivers in use: metal-glass evacuated tube and cavity receiver.

Many researchers have studied the thermal performance of a metal-glass evacuated tube experimentally and theoretically, e.g. Refs. [1–8]. The annulus between the metal absorber tube and glass cover is usually evacuated to eliminate the convective heat loss, thus this kind of receiver is efficient. However, the vacuum condition in the annulus may be damaged because of the glass breakage, seals broken, hydrogen penetration and getter decomposition [2,3,9–11] in an actual operational system. This will damage the selective absorption coating on the absorber tube and increase the heat loss remarkably. Compared to cavity receivers, the metal-glass evacuated tube is more efficient, but it faces more technical difficulties in production, vacuum maintenance after long-term running, and requires more manufacture and maintenance costs [12–15]. Therefore, the cavity receivers attract more attention gradually.

In 1976, Boyd et al. [16] proposed a cavity receiver based on the annular cylindrical tube, with the advantages of needing no special surface coatings and vacuum enclosures, which demonstrated the validity of this kind of receiver at a moderate and high temperature. Barra et al. [17] studied the thermal performance of a circular cavity with eight copper pipes theoretically and experimentally, functioning to produce industrial process heat in an Italian brewery. Reynolds et al. [18] described the flow visualization technique to capture the flow patterns within a trapezoidal cavity. It was beneficial for validating the numerical model in detail. Zhai et al. [19] carried out the optical and thermal analysis of the circular, semicircular, square and triangular cavity and concluded that the

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Nomenclature

c_p	specific heat capacity (J/kg/K)
d_r	diameter of the center absorber tube (mm)
f_p	focal length of the reflector (mm)
h_c	height of the cavity receiver (mm)
I_d	normal direct solar irradiance (W/m^2)
k_{eff}	effective conductivity (W/m/K)
L_a	gap value along the length of the reflector (mm)
L_c	length of the cavity receiver (mm)
L_p	length of the reflector (mm)
$\dot{m}_{oi}$	mass flow rate (kg/s)
Nu	Nusselt number
P	static pressure (Pa)
Pr	Prandtl number
Q_{loss}	heat loss (W)
Q_{error}	estimated error (W)
Re	Reynolds number
S	source
t_a	ambient temperature (°C)
$t_{highest}$	assumed highest inlet temperature limit (°C)
t_{in}	inlet temperature (°C)
t_{out}	outlet temperature (°C)
t_{start}	assumed overheating protection starting temperature (°C)
v_a	wind speed (m/s)
W_a	gap value along the width of the reflector (mm)
W_c	width of the cavity receiver (mm)
W_g	width of the cavity aperture (mm)
W_p	width of the reflector (mm)
W_s	insulation width of the movable cover (mm)

Greek symbols

β	heat loss reduction rate (%)
ε_c	emittance of the absorber
ε_g	emittance of the glass cover
ε_s	emittance of the shell
λ_{s1}	thermal conductivity of insulation material 1 (W/m/K)
λ_{s2}	thermal conductivity of insulation material 2 (W/m/K)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m3)
ρ_p	reflectance of the reflector

Abbreviations

CSEAT	collecting solar energy all the time
H_off	horizontal, the movable cover is turned off
H_on	horizontal, the movable cover is turned on
OPMRR	overheating protection with the method of rotating the reflector
OPMTOMC	overheating protection with the method of turning off the movable cover
PTC	parabolic trough solar collector
V_off	subvertical, the movable cover is turned off
V_on	subvertical, the movable cover is turned on

triangular trough receiver was the best. Singh et al. [20] investigated the heat loss coefficients of the trapezoidal cavity with the rectangular and round pipe. It was found that the selective surface coating and double glass cover could reduce heat loss coefficient significantly. Li et al. [21] tested the performance of a solar absorption cooling system using a triangular cavity receiver. The refrigeration efficiency was about 1.2 in high solar irradiance. Bader et al. [22] evaluated the thermal performance of a tubular cavity receiver using air as the heat transfer fluid. 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. [23] adopted the geometrical-optical method to analyze the absorptivity of cavity receivers. It was shown that the results could agree well with that of Monte Carlo Method. Dabiri et al. [24] analyzed the heat transfer rate and heat loss of a trapezoidal cavity receiver. The results indicated that the heat transfer rate to the absorber tubes increased with rise of the cavity angle, and heat loss to the glass cover and wall insulation was enhanced about 31.9% as the sizes of tubes became bigger.

The optical and thermal performance of the cavity receivers have been analyzed and discussed in Refs. [16–24]. These studies promoted the development of this kind of receiver in parabolic trough or other line-focus solar collectors. Though different types of cavity receivers have been proposed and studied, their larger heat loss compared to the metal-glass evacuated tube could not be eliminated effectively at present.

We presented a new kind of cavity receiver with a novel movable cover for PTCs and have analyzed the thermal efficiency in Ref. [25]. In this work, the effects of the movable cover on reducing heat loss and overheating protection of the cavity receiver are studied. If the solar irradiance is high enough, the movable cover is turned on and the system collects the concentrated solar energy. The movable cover is turned off when the solar irradiance is too low or at night for reducing heat loss, compensating the non-vacuum design of cavity receivers compared to a metal-glass evacuated tube. This study evaluated the thermal performance of the cavity receiver experimentally and numerically. Effects of ambient temperature, wind speed, inlet temperature, rotation angle of the collector and on-off state of the movable cover on heat loss were investigated. In addition, the movable cover can be used for overheating protection when the solar irradiance is too high or the system can not consume the heat gain. This may occur at summer noon if there is no thermal storage design in the system. The overheating protection function of the movable cover was studied and compared to the common method of rotating the reflector experimentally.

2. Model description

2.1. Physical model

The cross-section and photograph of the cavity receiver presented in this work are shown in Figs. 1 and 2 respectively. The absorber consists of a center tube and two inclined fins. The solar irradiance is firstly reflected by the parabolic trough reflector as shown in Fig. 2(b). Subsequently, the concentrated solar energy is absorbed by the absorber and transferred to the working fluid in the center tube. The shell of the cavity receiver is rectangular. The absorber and shell are connected by fourteen bolts on each side (total twenty-eight). The space between the absorber and shell is filled with aluminum silicate fiber (insulation material 1) and asbestos-rubber sheet (insulation material 2), and their locations are given in Fig. 1. The cavity aperture is covered by a glass plate to reduce heat loss. The movable cover can rotate around the axles fixed at two sides of the shell. If the solar irradiance is high enough,