Applied Thermal Engineering 132 (2018) 381–392

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

# Numerical investigation and experimental validation of the impacts of an inner radiation shield on parabolic trough solar receivers

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ARTICLE INFO

*Article history:*
Received 22 September 2017
Revised 26 December 2017
Accepted 28 December 2017
Available online 28 December 2017

*Keywords:*
Parabolic trough collector
Radiation shield
Solar receiver
Heat loss
Concentrated solar power plant

ABSTRACT

Conventional parabolic trough solar receivers are widely used to harvest heat energy at temperatures ranging from 400 °C to 550 °C. However, high temperatures cause excessive heat loss in solar receivers. Two types of novel solar receivers with an inner metal radiation shield (RS), one with solar selective absorbing coating on the outer surface and one without, were proposed and constructed to improve the thermal performance of solar receivers. Experiments were conducted in an enthalpy difference lab, and mathematical models with spectral radiant distributions were established to predict the thermal performance of the solar receivers. A comparison between the simulated and experimental results showed satisfactory consistencies. Predictions were obtained using the models with the root mean square deviation of less than 6%. The novel solar receiver without solar selective absorbing coating on the outer surface of the RS showed superior performance at absorber temperatures exceeding 550 °C. At the absorber temperature of 600 °C, the percentage of heat loss reduction of the receiver with solar selective absorbing coating and of that without reached 23.4% and 24.2%, respectively.



## 1. Introduction

In recent years, the emission of greenhouse gases during the combustion of fossil fuels has resulted in a growing environmental challenge that currently drives research into the utilization of renewable energy. Solar energy is one of the cleanest, largest, and most practical regeneration energy resources [1,2]. Photovoltaic (PV) cells that convert sunlight directly into electricity are widely applied in the field of solar energy utilization [3,4]. Photothermal (PT) utilization [5] is another application pattern of solar energy and is the focus of the present work. Unlike the PV system, the PT system converts solar energy into thermal energy for the flowing heat transfer fluid (HTF), and then the heat energy is secondarily converted to electric energy. Heat energy quality, which is closely related to HTF temperature, determines the amount of available energy and electric energy produced. Therefore, a PT system with concentrating devices was developed to obtain high HTF temperatures and increase the amount of available energy [6,7].

Parabolic trough collectors (PTCs) are the most mature and commercialized concentrated system for harvesting solar power at operating temperatures exceeding 200 °C [8–10]; a concentrated solar power (CSP) system can even reach 400–600 °C [11,12]. As key parts of a PTC system, heat-collection elements (HCEs) locate along the focal line of each parabolic trough to intercept and absorb concentrated sunlight reflected from parabolic mirrors [13]. Conventional HCEs (CHCEs) are mainly composed of metal absorber tubes, glass envelopes, glass-metal sealing, and metal bellows [14,15].

Delivering high temperatures with good efficiency requires reliable and high-performance solar receivers. Given the long exposure of HCEs to harsh environments, their thermal load, and the bending of the absorber tube under high operating temperatures, a firm structure and reliable, resistant materials are needed to prevent HCEs from damage and maintain their desired working life [16,17]. Besides, assuming that the good working life of the HCEs is achieved, the high performance of available heat collection is required to increase the efficiency of the PTC system and the electric generation production. The available heat collection is mainly related to solar energy absorption and heat loss in solar receivers. To maximize the absorption of solar irradiation and minimize heat loss to the environment, the annular gap between absorber tube and glass envelope is evacuated to a vacuum state to prevent heat loss by conduction and convection between the hot absorber tube and air [18,19]. Solar selective absorbing coating (SSC), which has high absorption in solar irradiation wavelengths but low thermal emittance in infrared wavelengths [20,21], is covered on the outer surface of the absorber tube to absorb considerably more solar

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https://doi.org/10.1016/j.applthermaleng.2017.12.112
1359-4311/

**Nomenclature**

| | |
|---|---|
| A | ambient |
| B | blackbody |
| C | convection |
| G | glass envelope |
| K | transparent radiation shield |
| Ki | inner surface of the radiation shield |
| Ko | outer surface of the radiation shield |
| R | radiation |
| Re | reduced |
| Ref | reflected |
| S | absorber tube |
| $A$ | area, $m^2$ |
| $A'$ | unit area, m |
| $D$ | diameter, mm |
| $E$ | blackbody emissive power, $W/m^2$ |
| $Er$ | error |
| $F$ | view factor |
| $P$ | percentage, % |
| $Q$ | net heat flux, W/m |
| $Q_{irra}$ | solar irradiance, $W/m^2$ |
| $R_{\lambda,s}$ | surface radiative resistance of the surface of the absorber tube |
| $R_{\lambda,g}$ | surface radiative resistance of the glass envelope |
| $R_{\lambda,k}$ | surface radiative resistance of the radiation shield |
| $R_{\lambda,gsky}$ | space resistance between glass envelope and sky |
| $R_{\lambda,sg}$ | space resistance between absorber and glass envelope |
| $R_{\lambda,sk}$ | space resistance between absorber tube and inner surface of radiation shield |
| $R_{\lambda,ssky}$ | space resistance between absorber tube and sky |
| $R_{\lambda,kg}$ | space resistance between radiation shield and glass envelope |
| $F_{sk}$ | view factor of absorber tube with respect to radiation shield |
| $F_{kg}$ | view factor of radiation shield with respect to glass envelope |
| $F_{kig}$ | view factor of inner surface of radiation shield with respect to glass envelope |
| $F_{kiki}$ | view factor of inner surface of radiation shield with respect to itself |
| $F_{kis}$ | view factor of inner surface of radiation shield with respect to absorber tube |
| $E_{\lambda,b,s}$, $E_{\lambda,b,g}$ | blackbody spectral emissive power of absorber and glass envelope, $W/(m^2 \cdot \mu m)$ |
| $E_{\lambda,b,k}$, $E_{\lambda,b,sky}$ | blackbody spectral emissive power of the radiation shield and sky, $W/(m^2 \cdot \mu m)$ |
| $Q_{irra}$ | solar irradiance, $W/m^2$ |
| $Q_{irra\text{-}s}$ | solar energy absorbed by absorber, W/m |
| $Q_{irra\text{-}k}$ | solar energy absorbed by radiation shield, W/m |
| $Q_{re,irra\text{-}k}$ | solar energy reflected by radiation shield, W/m |
| $Q_{r,ssky}$ | net radiation heat flux between absorber and sky, W/m |
| $Q_{r,sg}$ | net radiation heat flux between absorber and glass envelope, W/m |
| $Q_{r,gsky}$ | net radiation heat flux between glass envelope and sky, W/m |
| $Q_{r,ksky}$ | net radiation heat flux between radiation shield and sky, W/m |
| $Q_{r,kg}$ | net radiation heat flux between radiation shield and glass envelope, W/m |
| $Q_{r,sk}$ | net radiation heat flux between absorber tube and radiation shield, W/m |
| $Q_{loss}$ | total heat loss of original evacuated receiver, W/m |
| $Q_{c,ga}$ | convection between glass envelope and environment, W/m |
| $R$ | radiative resistance |
| $T$ | temperature, K |
| $V$ | voltage, V |

*Greek symbols*

| | |
|---|---|
| $\theta$ | angle, ° |
| $\varepsilon$ | emissivity |
| $\alpha$ | absorptivity |
| $\rho$ | reflectivity |
| $\tau$ | transmittance |
| $\lambda$ | wavelength, μm |

*Abbreviation and subscripts*

| | |
|---|---|
| PTC | parabolic trough collector |
| CHCE | conventional solar receiver |
| NHCE | novel solar receiver |
| CSP | concentrated solar plant |
| PO | power, W |
| HTF | heat transfer fluid |
| *exp* | experiment |
| *sim* | simulation |

energy and emit little radiation heat. However, at a high collecting temperature, the blackbody radiant power from the absorber tube is proportional to the temperature to the fourth power [22]. The emittance of the selective absorbing coating also increases along with the elevated absorber temperature [23]. These factors lead to a large amount of radiation heat loss in HCEs at high operating temperatures, consequently resulting in a significant decline of heat-collecting efficiency. As mentioned previously, a high collecting temperature equates to useful energy and high thermoelectric conversion efficiency for Rankine steam turbines in CSPs [24,25]. Hence, substantial efforts are made by the related researchers to further improve collecting temperature. To date, several molten salt parabolic trough (MSPT) plants that use molten salt as HTF are already in operation [26]. The collecting temperatures of these plants reach 550 °C, which is a huge boost compared with the 400 °C operating temperature in conventional CSP using thermal oil as the HTF [27]. Therefore, effectively decreasing the radiation heat loss of HCEs at high temperatures, such as 400–550 °C, is a challenge for researchers and relevant enterprises.

Researchers and solar energy enterprises have long explored new materials for the key components in HCEs to reduce heat loss and improve the performance of solar receivers at high temperatures through the optimization of material properties. The performance of SSC exerts a significant effect on the radiation heat transfer in HCEs. Therefore, researchers are continuously seeking new target coatings with superior properties of low emittance in the infrared band and high absorptivity in the solar irradiance wavelength. According to literature, the emittance and absorptivity of commercial coatings used in high-temperature evacuated receivers are generally 7–10% and 95–97% (400 °C), respectively [28–30]. Aside from selective coatings, new glass envelopes with high transmittance to allow a large amount of sunlight through envelopes [28] and a novel glass–metal sealing with the same expansion coefficients for the glass and metal to improve sealing reliability and vacuum level [31] have also been widely studied.

However, the effects of using advanced materials to promote improvements in the thermal performance of HCEs are limited, especially at high absorber temperatures. Another effective