Solar Energy 173 (2018) 640–650

Contents lists available at ScienceDirect

Solar Energy

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

Preliminary performance study of a high-temperature parabolic trough solar evacuated receiver with an inner transparent radiation shield

Qiliang Wang, Honglun Yang, Mingke Hu, Xiaona Huang, Jing Li, Gang Pei*

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

ARTICLE INFO

Keywords:
Parabolic trough collector
Solar receiver
Transparent radiation shield
Heat loss

ABSTRACT

Solar evacuated receiver as a key part of parabolic trough collector (PTC) suffers considerable heat loss at high operating temperature, which exerts significantly negative effects on the overall performance of PTC system. Based on the fact of maldistributed solar irradiation around the inner absorber tube, a novel solar evacuated receiver with an inner transparent radiation shield (TRS) is proposed and designed. The heat loss of the proposed solar evacuated receiver is numerically studied by the established heat transfer model based on the spectral parameters. The heat-collecting efficiency of a commercial UrssaTrough solar collector installed with PTR 70 receivers using therminol VP-1 as heat transfer fluid is investigated to validate the performance of the proposed solar receiver. Moreover, the influences of the property parameters of films on the two sides of the TRS on the solar receiver are also studied. Comparisons between simulated and experimental results show the differences of their heat-collecting efficiencies are lower than 1%, which demonstrates that the model can yield satisfactory consistency with the experimental results. The simulation results show that the novel receiver exhibits dramatically superior thermal performance to that of the traditional receiver. The heat loss reduction percentages of the novel receiver can reach approximately 15.7% and 14.9% when the absorber temperatures are 400 °C and 600 °C, and the thermal efficiency can be enhanced by 0.93% and 4.42% at inlet temperatures of 400 °C and 580 °C, respectively.

1. Introduction

A solar parabolic trough power plant generates electricity using concentrated sunlight as the heat source for its power cycle (Price et al., 2002; Müller-Steinhagen and Trieb, 2004). Rows of axis-tracking, linear parabolic mirrors comprise a solar field that concentrates sunlight onto parabolic trough solar evacuated receivers, which are heat-collection elements (HCEs) located along the focal line of each parabolic trough (Burkholder and Kutscher, 2008; Burkholder and Kutscher, 2008). HCEs are composed mainly of a metal absorber tube, a glass envelope, glass–metal sealing, and metal bellows (Wang et al., 2017), they can reach high temperature of 400 °C in general power plants (Rolim et al., 2009).

HCEs, which are key parts of a parabolic trough collector (PTC), are popularly applied in thermal utilization areas with medium–high operating temperatures (Jebasingh and Herbert, 2016; Coventry, 2005; Tian and Zhao, 2013). Apart from the concentrated solar power (CSP) plant (Behar et al., 2013; Paskevicius et al., 2015) mentioned above, applications with medium running temperature include solar cooling (El Fadar et al., 2009; Chidambaram et al., 2011; Mittelman et al., 2007) and solar desalination (Calise et al., 2014; Xiao et al., 2004). HCEs are designed for not only maximizing absorbed solar irradiation but also minimizing heat loss to environment and thus obtain maximum useful energy from solar irradiation. For example, the annular gap between absorber tube and glass envelope is evacuated to vacuum state to prevent heat loss by conduction and convection in the hot absorber tube with air (Price et al., 2006; Zambolin and Col, 2010). Solar-selective absorbing coating with high absorptivity in solar irradiation wavelengths but low thermal emittance in infrared (IR) wavelengths (Kudish et al., 2002; Kennedy, 2002) is covered on the outer surface of absorber tube for absorbing a large amount of sunlight and meanwhile radiating a small amount of heat. However, the radiated heat from the absorber tube dramatically increases under high operating temperatures achieved by HCEs, such as 400–550 °C in CSP plants, because the radiated heat is proportional to temperature to the fourth power. Moreover, the emittance of the selective coating obviously increases at high temperature compared with the low thermal emittance at low temperature (Selvakumar and Barshilia, 2012). These factors result in considerable radiation heat loss of HCE under high operating temperatures; significantly decrease the operating efficiency of PTC in

* Corresponding author.
E-mail address: peigang@ustc.edu.cn (G. Pei).

https://doi.org/10.1016/j.solener.2018.07.065
Received 24 December 2017; Received in revised form 21 June 2018; Accepted 22 July 2018

Nomenclature

a	ambient
f	fluid
g	glass envelope
k	radiation shield
s	absorber tube
A	area, m^2
A'	unit area, m
D	diameter, mm
E	emissive power, W/m^2
F	view factor
G	direct normal irradiance, W/m^2
I	intensity, W/m^2
J	radiosity per length, W/m
K	conductivity, W/(m K)
L	length, m
P	percentage, %
Q	net heat flux per length, W/m
R	thermal resistance
T	temperature, K
W	width, m
c	convection
c_p	specific heat capacity, J/(kg K)
m	mass flow rate, kg/s
h	heat transfer coefficient, $W/(m^2 K)$
q	heat flow, W/m^2
r	radiation
j	friction factor
ki	inner surface of radiation shield
ko	outer surface of radiation shield
ap	aperture
irra	irradiance
exp	experimental
sim	simulated
re	reduced
opt	optical
en	energetic
in	inlet
out	outlet
Nu	Nusselt number
Re	Reynolds number
Ra	Rayleigh number
Pr	Prandtl number

Greek symbols

θ	angle, °
β	incident angle, °
ε	emissivity
α	absorptivity
ρ	reflectivity
τ	transmittance
λ	wavelength, μm
η	efficiency

Abbreviation and subscripts

PTC	parabolic trough collector
THCE	traditional heat-collection element
NHCE	novel heat-collection element
CSP	concentrated solar power
TCO	transparent conductive oxide
TRS	transparent radiation shield
HTF	heat transfer fluid
IR	infrared

worse conditions, and exert negative impacts on the performance of CSP plant.

For a CSP plant, high collecting temperature indicates high thermoelectric conversion efficiency gained by Rankine steam turbine (Tchanche et al., 2011). Thus, high collecting temperature is the direction of future development for improving power generation. The first molten salt parabolic trough (MSPT) plant in the world was built in July 2010 by ENEL in Priolo Gargallo of Italian Island of Sicily with a collecting temperature of HCEs higher than 400 °C (Maccari et al., 2015). In July 2013, the first stand-alone MSPT plant, located adjacent to the Archimede Solar Energy Manufacturing Plant in Massa Martana (Italy), started its operation. After one year of operation, the outlet temperature of the solar field was reliably and smoothly kept at a temperature of 550 °C (Ruegamer et al., 2014). Apart from those in Italy, some solar-power enterprises in China and other areas also conducted demonstration projects. All these projects have illustrated that enhancing high collecting temperature in HCEs is a development direction for PTCs, thus it is pretty important to decrease excessive radiation heat loss in HCE with high temperatures.

Researchers in relevant fields have attempted to reduce HCE heat loss by optimizing the key components' parameters in HCEs. Given the rapid emittance growth of selective coating with the increase in temperature, many researchers have optimized the performance of coating by developing different absorbing layer materials. The solar absorbance and thermal emittance for commercial selective coatings used in PTC receivers can reach 93–97% and 7–10% (at 400 °C) (Zhang, 2000), respectively. Schott Company in Germany covered the outer and inner surfaces of a glass envelope with an antireflection film to allow penetration of a large amount of sunlight in HCE and obtained transmittance of glass of 96.2% (Solar and Schott, 2011). Schott also developed a metal that characterized the same coefficient of expansion with a glass to reduce the glass–metal sealing stress and improve the sealing reliability and vacuum level in HCEs.

Using advanced materials can improve the thermal performance of HCEs, but their effects are limited. Another easy and effective way to decrease HCE heat loss is to change and optimize the HCE structure by introducing a radiation shield or an insulating material to a certain position of annular space and thus intercept the radiation heat loss. For low-temperature HCEs in nonconcentrated solar collector system, evacuated-tube solar collectors with heat shields exhibit superior performance to these without heat shields (Zhang et al., 2014). The position of the heat shield is at the lower portion of the annular space in the HCE, the shield exerts no effect on receiving solar irradiation for absorber tube but intercepts much radiated heat loss.

Unlike nonconcentrated solar collector system, the concentrated sunlights reflected from parabolic mirrors in a concentrated solar PTC system irradiate at the lower portion of absorber tube and nonconcentrated sunlights directly from the Sun with low energy density project at its upper portion. The distribution of solar irradiance around the receiver tube of PTR 70 in UrssaTrough collector is depicted in Fig. 1 (Solar and Schott, 2011), the bottom half part of the absorber tube receives high-energy density solar irradiance, and the other half part only receives low-energy density solar irradiance. On the basis of this fact, Grena (2011) covered an IR-reflecting layer on the part of the glass envelope to reduce the thermal emission from the glass-covered receiver tube of a trough collector. Al-Ansary and Zeitoun (2011) and Chandra et al. (2017) introduced a new PTC receiver with gas-filled annuli using thermal insulation material, which was fitted into the portion of the receiver annulus that does not receive concentrated sunlight. The heat loss from a receiver using this technique was reduced