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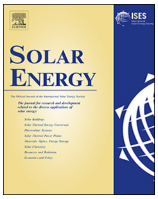

Effects of surface optical and radiative properties on the thermal performance of a solar cavity receiver

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ABSTRACT

Solar cavity receiver is one of the most crucial components in a solar power tower system, where the solar-thermal conversion process is achieved. Optimizing the surface properties (viz. absorptivity and emissivity) of a designed cavity receiver is a viable option to improve its thermal efficiency. In the present paper, an integrated simulation approach was employed to quantify the influence of surface optical and radiative properties on the thermal performance of a typical water/steam solar cavity receiver. Firstly, the different candidate surface materials, solar selective and non-coated, were compared. The results showed that the thermal efficiency of the receiver with the ideal coating and Pyromark 2500 is respectively enhanced by 12.5% and 7.8% compared with that of the non-coated receiver. And then, the effects of surface spectral selectivity on the thermal performance of the receiver were carefully analyzed. It can be found that the solar absorptivity is the most critical parameter for improving the receiver efficiency, which is enhanced by about 12.6% as the solar absorptivity rises from 0.8 to 1.0. However, the receiver efficiency shows different variation tendencies with the thermal emissivity of active surfaces, which are closely related to the infrared heat transfer direction between the passive surfaces and the active surfaces. Furthermore, with the increase of reflectivity of passive surfaces over the full spectrum, the receiver efficiency is determined by a trade-off between the increasing reflective heat loss and the decreasing radiative and convective heat losses. For the present receiver, the thermal efficiency is improved by about 4.8% with the reflectivity increasing from 0 to 1.0 due to its great cavity effect. Therefore, the passive surfaces should be highly reflective throughout the spectrum inside the present receiver.

1. Introduction

The increasing energy consumption and the growing environmental problem have both pushed the world to optimize its current energy structure. Consequently, the eco-friendly renewable energy has been of particular concern, and is gradually substituting the fossil-based energy for power generation (Behar et al., 2013; Siva Reddy et al., 2013; Wang, 2010). Concentrating solar power (CSP), as one of the most promising technologies of renewable energy, can offer an alternative option for power generation (Ho and Iverson, 2014). Due to different optical concentration ratios, there are mainly four types of CSP technical routes: the solar power tower (SPT) system, the parabolic trough system, the parabolic dish system and the linear Fresnel system. Among them, the point-focus SPT system has shown its great potential in achieving the highest solar-to-electricity efficiency and the lowest power costs in large-scale power generation. In a typical SPT system, solar receiver is a crucial component, where concentrated solar irradiation is absorbed, converted into heat and carried away by a kind of heat transfer fluid (HTF). Cavity receiver is one class of the most widely used high-temperature solar receivers for a SPT system (Wang and Laumert, 2017). Due to its cavity effect, the receiver thermal efficiency can be improved by reducing its reflective and radiative heat losses (multi-reflections of solar rays and infrared rays within the cavity), as well as its convective heat loss (a part of heated air stagnating inside the cavity).

By literature survey, a number of studies have been conducted on the heat loss analysis of cavity receivers and their connection with cavity geometries, positions, dimensions and surroundings. Wu et al. (2010) presented a comprehensive review on different convective heat losses for cavity receivers and performed a comparison. It can be concluded that the natural convective heat loss is dominated by the cavity inclination, which appears that it decreases with the increase of inclination angle when no wind is present (Clausing, 1981; Paitoonsurikarn et al., 2011; Prakash, 2014; Sendhil Kumar and Reddy, 2007; Taumoefolau et al., 2004). Although many researchers have attempted to investigate the convective heat loss of cavity receivers under

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Nomenclature

c	constant
D	depth, m
DNI	direct normal irradiance, W·m^{-2}
E	emissive power, W·m^{-2}
F	fraction
H	height, m
M	number (of grids)
$\dot{m}$	mass flow rate, t·h^{-1}
N	number (of light rays)
p	pressure, Pa
Q	energy, W
q	heat flux, W·m^{-2}
R	random number
r	reflectivity
RD	radiative heat transfer factor
RES	Residual error
S	area, m^2
T	temperature, K
V	volume, m^3
W	width, m

Greek symbols

α	absorptivity
γ	inclination angle, degree
ε	emissivity; error
η	thermal efficiency, %
θ	zenith angle, degree
κ	absorption coefficient
λ	wavelength, μm
σ	Stefan-Boltzmann constant, W·m^{-2}·K^{-4}
φ	azimuth angle, degree

Subscripts

a, A	aperture
c	cavity
cb	back walls of cavity
cf	front walls of cavity
conv	convection
cut	cutoff
f	fluid
IR	infrared
sat	saturated
sol	solar
tw	(distance) between tube panel to cavity wall

windy conditions (Flesch et al., 2015; Loni et al., 2017; Reddy et al., 2016; Shen et al., 2016; Xiao et al., 2012), some of the results conflict each other. In several studies, the authors believe the head-on wind causes higher convective heat loss than the side-on wind (Flesch et al., 2014; Jilte et al., 2014; Prakash et al., 2009). However, some authors (Fang et al., 2011; Hu et al., 2017; Ma, 1993; Reddy et al., 2015) hold an opinion that the maximum convective heat loss appears in the presence of side-on wind. These different conclusions were accounted to the different geometries and dimensions of cavity receivers (Flesch et al., 2014). Besides, Wu et al. (2015) indicated that no simple rules can exactly describe the influence of wind directions. The radiation heat transfer is also of great significance to the cavity receivers (He et al., 2013; Martinek and Weimer, 2013; Wang et al., 2016; Weinstein et al., 2014), and more scientific studies focused on the conjugate heat transfer process by radiation and convection (Chang et al., 2014; Li et al., 2010; Montiel-González et al., 2015; Nouanegue et al., 2008; Tu et al., 2015). Generally, the radiative heat loss of the cavity receiver is dependent on the wall temperature, the shape factors and the surface properties, while it is independent of the cavity inclination (Prakash et al., 2009).

For a designed solar cavity receiver, optimizing the internal surface properties (viz. absorptivity and emissivity) can be a viable option to improve its thermal efficiency. Therefore, current cavity receivers are usually coated with spectral selectivity layers (solar selective coatings) applied over the bare surfaces of absorber tubes. An ideal solar selective coating exhibits high absorption in the solar spectrum to maximize energy capture and low emission in the infrared (IR) spectrum to minimize thermal radiation loss in the desired operation temperature range (Atkinson et al., 2015; Fang et al., 2014; Hall et al., 2012; Kennedy, 2002; Larrouturou et al., 2016, 2014; López-Herraiz et al., 2017; Teichel et al., 2012). High-temperature Pyromark 2500 is a commercial standard coating commonly used on CSP central receivers, whose optical properties have been characterized (Persky and Szczesniak, 2008). And some other novel coatings and deposition methods have also been studied (Hall et al., 2012; Shah et al., 2015; Wang et al., 2015). In addition, the optimization of surface optical properties could also be an efficient way to homogenize the heat flux distributions inside the CSP receivers, which has already been performed by Tu et al. (2015), Wang et al. (2017) and Wang and Laumert (2017).

To the best knowledge of the authors, the previous studies related to optimizing the surface properties of cavity receivers still have shortcomings: (1) A typical solar cavity receiver consists of the active surfaces and the passive surfaces. For the active surfaces, they can directly receive the solar irradiation concentrated by heliostats and then transfer heat to the HTF. The remaining surfaces inside the cavity are the passive surfaces, which cannot receive the direct solar irradiation and can only obtain the low heat flux. Being different from an external receiver, within a cavity receiver, the heat is transferred not only between the internal surfaces and the external environment, but also between the active surfaces and the passive surfaces. When the thermal emissivity of the active surfaces increases, the radiative heat loss definitely increases. However, their absorptivity in the IR spectrum also increases because it equals the thermal emissivity according to Kirchhoff's law. Consequently, the active surfaces can absorb more infrared energy emitted by both the passive surfaces and themselves, which has a positive effect on the improvement of receiver efficiency. Therefore, a trade-off exists between the increasing radiative heat loss and the more infrared energy gained by the active surfaces. Unfortunately, this possibility has so far received little attention in the previous research work. (2) In Teichel's (Teichel et al., 2012) and our previous work (Fang et al., 2017; Tu et al., 2015), it enables to conclude that the temperature of passive surfaces is the crucial factor to influence the thermal efficiency of the cavity receiver. While the changes of surface properties would have significant impact on the temperature distributions inside the receiver, especially greatly affect the temperature of passive surfaces. However, the studies on the relationship between surface properties and temperature distributions inside the cavity receiver are still very rare.

The objective of the present paper is to quantify the influence of surface optical and radiative properties on the thermal efficiency, heat losses as well as heat flux and wall temperature distributions of a typical solar cavity receiver. In the first step, the specific case study was conducted in order to compare the thermal performance of the receiver