Solar Energy Materials & Solar Cells 161 (2017) 177–182

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Effect of cavity surface material on the concentrated solar flux distribution for an impinging receiver

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ARTICLE INFO

Keywords:
Absorptivity
Cavity receiver
Ray tracing
Parabolic dish
Concentrated solar power

ABSTRACT

In this paper, the effects of cavity surface materials on the radiative flux distribution of solar cavity receivers have been studied with the help of a ray-tracing methodology. Three metallic substrate materials (Inconel 600, austenitic stainless steel 253 MA and Kanthal APM) and two coating materials (Pyromark® 2500 coating and YSZ TBC coating) were selected as the candidate cavity surface materials. The results show that the flux distribution and the total optical efficiency are much more sensitive to the absorptivity on the cylindrical surface than on the bottom. By using high absorptivity coating on the cylindrical surface and low absorptivity coating on the bottom, the radiative flux on the bottom can be controlled at a low level, and it can help to reduce the cavity length for an impinging receiver with jets on the cylindrical surface. Furthermore, the radiative flux distribution on the cylindrical surface can also be tailored to meet various design requirements by applying different coating designs on the cylindrical surface.

1. Introduction

Solar-Brayton technologies have shown their great potential in achieving high solar-to-electricity efficiencies and reducing the power costs [1–3]. Furthermore, these solar-Brayton systems can also be integrated with fuel-based power generating systems for hybrid operation, and stable power outputs can be achieved independently from the variation of solar energy [4–8]. In a typical hybrid dish-Brayton system, the point-focusing solar receiver is one of the limiting components, where the concentrated solar irradiation is absorbed, converted into heat and carried away by the working fluid. Cavity receivers are one group of the most widely used high temperature point-focusing receivers for solar-Brayton systems, due to their capability to meet the temperature (1000–1600 K) and pressure (3–30 bar) requirement of a typical gas turbine over a long period for obtaining a reasonable efficiency [9,10]. Moreover, the cavity effect (multi-reflections inside the cavity) lets the receiver come relatively close to a black body and has the capability in absorbing the concentrated solar irradiation with a high optical efficiency.

In the authors' previous publications, an impinging jet cooling technology has been introduced in the cavity receiver design together with an inverse design methodology [11–13]. With the help of the impinging jet cooling technology distributed above the high light flux region, the results show that the uniformity of the temperature distribution on the cavity shaped absorber surface can be greatly improved. Nevertheless, due to the limitation of the air flow from the compressor, it is difficult to cover the whole absorber area with the high cooling effect offered by impinging jet cooling. In a typical impinging receiver design, the nozzles are only distributed above the highest flux region on the cylindrical wall. For other regions, especially the bottom region of the cavity, the heat transfer coefficient is relatively low. Furthermore, in the bottom region, the compressed air has already been heated up after passing through the impinging region, so the temperature difference between the air and the wall is reduced. Hence, only when the surface light flux is kept under a low level, the surface temperature can be controlled below the material limits in this area.

Changing the cavity geometry is a widely used traditional way for controlling the surface light flux distribution [14–16]. However, for an impinging receiver design, the change of the cavity geometry might introduce a change in the heat transfer coefficient distribution of the impinging cooling system and alter the cooling efficiency in the high flux region. Another option to reduce the local flux level, the cavity geometry can be extended to shift the bottom surface further away from the focal spot of the dish. Since the impinging receiver works under pressure, the structural design challenge for the cavity structure will increase with the extension of the cavity geometry. Changing the characteristics of the cavity absorptivity could be another efficient way in controlling the surface light flux distribution. This possibility has so

Abbreviations: CSP, , concentrated solar power; DNI, , direct normal irradiance; MGT, , micro gas turbine; YSZ, , Yttria-stabilized Zirconia; TBC, , thermal barrier coating

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http://dx.doi.org/10.1016/j.solmat.2016.12.008
Received 9 November 2016; Accepted 2 December 2016
Available online 06 December 2016

Nomenclature

d	diameter of the nozzle or orifice, mm
D	cavity diameter, mm
L	cylinder length, mm
n	nozzle number
t	cavity wall thickness, mm
P_e	probability of the slope error

Greek

σ_s	standard deviation
η	efficiency

Subscripts

cav	cavity
int	intercept
opt	optical

far not received a lot of attention in previous research work. Most of the published literature is focused only on high emissivity material and coating to achieve high receiver optical efficiencies [17–19]. Studies on how to use multi absorptivity materials or coatings to obtain required flux distributions are still very rare.

In the present paper for the study of the impact of cavity materials on the inner cavity heat flux distribution, a dish and receiver published in the authors' previous work are used as the main optical system [13]. A Ray-tracing methodology is used as the main tool to study the effects of the absorber material properties to the final flux distribution on the absorber surface for a cavity receiver. A combined model for Lambertian scattering with a coating model is introduced for simulating the absorber material properties and surface conditions. Three different metallic alloys are selected and studied as the absorber substrate materials. Furthermore, various ceramic coatings are introduced and studied. By distributing different coatings with different areas at different positions, the characteristics of the surface flux distributions are studied and compared with the case without any coating. In this way, the surface flux distribution can be controlled to meet the requirements from the heat transfer design aspect.

2. Physical model

In author's previous publication [13], a stainless steel 253 MA based impinging receiver, D320L400t3d10n12, was successfully designed for a 5 kW micro gas turbine (MGT) and the Eurodish system. Here, D is the cavity diameter, L is the cylinder length, t is the wall thickness, d is the nozzle diameter and n is the nozzle number. The geometry of the optical system is depicted in Fig. 1. In order to minimize the radiation and natural convection heat loss, the aperture diameter is defined as 200 mm, which can receive almost the whole concentrated solar irradiation collected by the dish [20]. By distributing 12 orifices/nozzles (d=10 mm) uniformly around the cylindrical surface, a D320L400t3d10n12 impinging receiver has been successfully designed and studied numerically. The receiver geometry is depicted in Fig. 2. The numerical results show that the peak temperature of the absorber can be controlled below 983 °C at a direct normal irradiance (DNI) level of 800 W/m^2, which is significantly lower than the allowable working temperature of the stainless steel 253 MA (1150 °C). Moreover, the temperature differences on the absorber are reduced to 130 °C (DNI=800 W/m^2) and the thermal efficiency of the D320L400t3d10n12 impinging receiver can reach 82.7% (DNI=800 W/m^2) without including the natural convection heat loss through the aperture and the conduction heat loss through the insulating layer. Hence, in order to evaluate the performances of the different cavity materials, the D320L400t3d10n12 impinging receiver is applied as the reference.

3. Material

Due to the brittle character of the ceramic materials, heat resistant alloys are preferred as the substrate material in cavity receiver design. In this paper, Inconel 600, austenitic stainless steel 253 MA and Kanthal APM (FeCrAl alloy) are selected as the candidate metallic substrate materials, due to their high resistance to corrosion, erosion, high temperature (> 1000 °C) and thermal shock.

In order to achieve a more accurate control of the concentrated solar flux on the cavity wall, high temperature coatings are introduced in this paper as well. The high temperature coatings are in wide-spread use in modern turbomachinery technology for protecting the key components (combustor chambers, turbine vanes and high pressure turbine blades) from a high temperature and oxidizing environment (> 1400 °C) [21,22]. After a long period of development, the lifetime of these high temperature coatings has been significantly enhanced. Published data shows that plasma-sprayed Alumina (Al_2O_3) [23], Zirconia (ZrO_2) [23] and Yttria-stabilized Zirconia (YSZ) thermal barrier coating (TBC) can offer very good thermo-mechanical performance as well as low solar absorptivity (LSA) between 0.3 and 0.5 [24,25]. In this paper, the YSZ thermal barrier coating is selected as the LSA coating for the study. Moreover, high solar absorptivity coating can also be used to meet the design requirements of the receiver. Pyromark® 2500 flat black paint is a kind of cermet paint with very high emissivity, and it has been widely used in concentrated solar power (CSP) industry [26]. The key properties of the candidate substrate materials (surface fully oxidized) and coating are list in Table 1.

4. Methodology

In this paper, a ray-tracing methodology is applied as the main tool for studying the optical performances of the cavities with various materials. FRED® is a commercial available non-sequential ray tracing software. In a typical FRED ray tracing process, the light source is discretized into rays, each ray with the same amount of radiative energy, meaning that higher intensity areas would have more rays. A hierarchical ray-tracing search algorithm is used for searching the

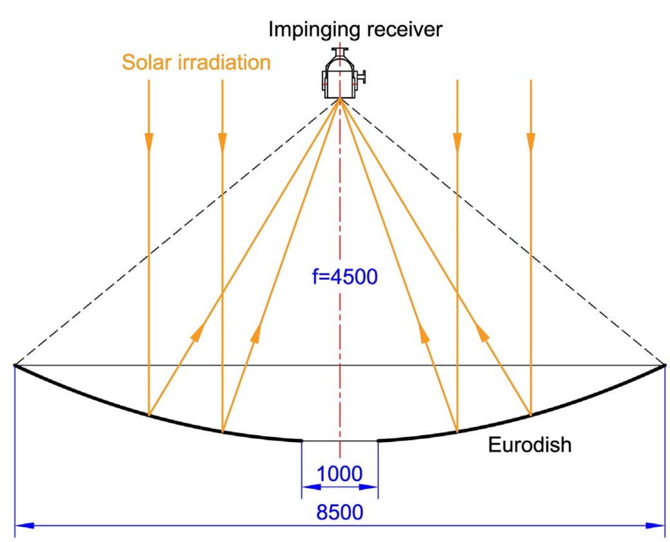

Fig. 1. Schematic of a Eurodish system with an impinging receiver.