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An axial type impinging receiver

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ABSTRACT

An axial type impinging receiver has been developed for a solar dish-Brayton system. By using selective reflection cavity surfaces as a secondary concentrator, the solar irradiation is reflected and concentrated on a cylindrical absorber that is located in the center of the cavity. A modified inverse design method was applied for quickly finding possible cavity receiver designs, and a numerical conjugate heat transfer model combined with a ray-tracing model was utilized for studying the detailed performance of the impinging receivers. The ray-tracing results show that the flux distribution on the cavity and absorber surfaces can be efficiently adjusted to meet the design requirements by changing the absorber diameter, the cavity diameter, the cavity length and the offset length. A candidate receiver design was selected for detailed numerical studies, and the results show that the average outlet air temperature and the radiative-to-thermal efficiency can reach 801.1 °C and 82.8% at a DNI level of 800 W/m^2. The temperature differences on the absorber can be controlled within 122.7 °C for DNI level of 800 W/m^2, and 126.4 °C for DNI level of 1000 W/m^2. Furthermore, the structure is much simpler than a typical radial impinging design.

1. Introduction

Concentrated solar power (CSP) is one of the most attractive technologies for renewable energy production for its advantages in terms of high efficiency, low operating cost, abundant supply potential and good scale-up potential [1]. However, limitations of the power grid system to handle fluctuating power supply stemming from natural intermittent characteristic of the solar irradiation (mainly caused by daily and annual cycles, as well as by local weather conditions), are becoming one of the main challenges for future large-scale CSP application as a baseload energy resource [2,3]. Therefore, it is of great importance to develop a CSP technology with a stable power output to provide baseload and dispatchable power [4]. The solar hybrid Brayton system is one of the potential solutions that can both work on solar energy and fuel to achieve stable power outputs independent of solar energy. Detailed investigations have been achieved by Buck et al. [5], Heller et al. [6], Wang et al. [7], Powell et al. [8] and Lim et al. [9]. Furthermore, by combining a solar hybrid Brayton system with a Rankine cycle [10], a Stirling cycle [11] or other cycles [12,13], higher thermal-to-electric net annual average conversion efficiencies can be achieved compared to other CSP technologies [14].

In such solar hybrid Brayton systems, the receivers are the key components where the concentrated solar irradiation is absorbed and transferred to the working fluid. In order to meet the temperature and pressure requirements of potential gas turbines, the receivers should be able to work under high temperature (1000–1600 K) and high pressure (3–30 bar) over a long period [15]. Hence, they are becoming one of the main bottlenecks in enhancing the CSP working temperature and efficiency. Recently, due to the capability of impinging jet heat transfer technology in offering a relatively high heat transfer coefficient, it has been introduced to the high-temperature solar cavity receiver design for a solar dish-Brayton system [16,17] together with an inverse design method [18]. In a typical impinging receiver design in the published literature, the round orifices/nozzles are distributed evenly in a single row or multi rows around the cylindrical wall above the peak flux region where high heat transfer coefficient is required for managing the temperature within the allowable working temperature of the material. Considering that the directions of the distributed impinging jets are in the radial direction, here, these former impinging receivers are named as radial type impinging receivers.

Based on theoretical analysis and numerical studies, a radial type impinging receiver can overcome most of the drawbacks in traditional cavity receiver designs and achieve a relatively uniform

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Nomenclature

C_d	discharge coefficient
C_p	heat capacity, J/(kg·K)
d	diameter of the nozzle or orifice, mm
D	diameter, mm
h	heat transfer coefficient
H	distance, mm
k	heat conductivity, W/(m·K)
L	length, mm
$\dot{m}$	mass flow, kg/s
Nu	Nusselt number
P	pressure, Pa
$\dot{q}'$	heat flux, W/m^2
R	radial position, m
Re	Reynolds number
s	curvilinear surface coordinates, m
T	temperature, °C
V	velocity, m/s
y_1	distance of the first grid node normal to the wall, m
y^+	dimensionless wall distance of the first grid node near the wall

Greek

β_d	the diameter ratio between the nozzle and the inlet channel
ν	kinematic viscosity, m^2/s
ρ	Density, kg/m^3

Subscripts

a	air
abs	absorber
ap	aperture
cav	cavity
conv	convection
ch	channel
jet	impinging jet
o	stagnation point
off	offset
rad	radiation

Abbreviations

ACW	absorber cylindrical wall
AFW	absorber front wall
AM	air mass
CBW	cavity back wall
CCW	cavity cylindrical wall
CFW	cavity front wall
CSP	concentrating solar power
DA	absorber diameter
DC	cavity diameter
DO	discrete ordinates model
DNI	direct normal irradiance
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
IDM	inverse design method
MGT	micro gas turbine
LC	cavity length
LO	offset distance from the vertex of absorber front wall to the aperture
SST	Shear-Stress-Transport turbulence model
UDF	user-defined functions

temperature distribution on the absorber surface which is also observed in the experimental study [19]. However, there are still several weak points in the structure that might limit the potential of these radial impinging receivers. Firstly, in these radial impinging receiver designs, the structures are still relatively complex, especially for multi-row nozzle designs. Considering that the whole radial impinging receiver has to be made of expensive heat-resistant alloy, the material cost is still high. Secondly, the precision requirement of the nozzles/orifices is high, otherwise, due to the high jet velocity, the tolerance in hole diameters might affect the uniformity in distributing the air flow significantly. However, from the manufacturing point of view, it is difficult and expensive to manufacture the small holes with a high precision. Thirdly, due to the limiting orifices/nozzles number in the circumferential direction, the temperature uniformity in the circumferential direction is a potential limitation in enhancing the receiver performance. Fourthly, for this radial impinging receiver design, the influence from the cross-flow is another potential weak point when a low channel height is required. Hence, it is of great interest to develop a simpler impinging receiver design with better manufacturability, but with similar or better performance.

In this paper, an axial type impinging receiver concept has been developed by taking into consideration the existing weak points of the radial type impinging receivers listed above. In order to evaluate the performance, an axial impinging receiver has been developed based on the same air inlet boundary conditions (0.1 kg/s, 300 kPa and 500 °C) as for the radial impinging receiver design in the authors' previous publication [17]. A ray-tracing model of an ideal parabolic dish model with 2 mrad surface slope error, based on the parameters of the existing EuroDish [20], is developed for obtaining radiative flux boundary conditions by applying a commercial non-sequential ray-tracing software FRED®. A conjugate heat transfer model is achieved by computational fluid dynamics (CFD) software ANSYS FLUENT together with user-defined functions (UDFs). The radiative flux distributions (cavity surface and absorber surface), predicted by FRED, were given to the conjugate heat transfer model as a thin wall heat source (10^{-6} m thick) by using UDFs.

2. Axial impinging receiver concept

2.1. Geometry

In this axial impinging receiver concept, as shown in Fig. 1(A), the absorber is featured with a cylindrical side wall, a front wall and a single nozzle are arranged coaxially with the cylindrical wall. The shape of the front wall can be flat, conical, semi-spherical and other curved shapes. In this study, the center region of the front wall can sustain under a higher light flux level than the regions around due to the relatively high heat transfer coefficient offered by the center-distributed impinging jet (which can be up to three times of the heat transfer coefficient offered by the flow parallel to the cooled surface with the same velocity). Furthermore, from the view of the structure mechanical, a semi-spherical shape front wall is also helpful in releasing the thermal stress in the radial direction. Unlike the radial impinging receiver which is shown in Fig. 1(B), the absorber of the axial impinging receiver is located in the center of the cylindrical-shaped cavity coaxially. The compressed air firstly