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Simulation and experimental study of an air tube-cavity solar receiver

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ABSTRACT

High temperature air is a potential candidate as a heat transfer fluid to transport energy from concentrated solar power to gas turbines. A 15-turn helically coiled tube cavity receiver with an optical splitter at the bottom is designed and fabricated. Its performance is investigated with a five 7-kW Xe-arc lamps array system as heat source. Eight K-type thermocouples are placed from top to bottom with an equal interval. The outlet temperature experimentally ranges from 593 °C to 546 °C when the air flow rate increases from 1 m^3/h to 5 m^3/h for up-flows, while it ranges from 662 °C to 570 °C for down-flows, when the average flux on aperture is around 120 kW/m^2. The Monte-Carlo ray-tracing method and the Lambert testing method with a charge-coupled device (CCD) camera are used to simulate and evaluate the concentrating radiation energy distribution on the cavity's internal walls, and then the actual flux distribution of each turn of the helically coiled tube is obtained. A comprehensive simulation model is proposed and validated by the experimental results, where the outlet temperature deviations are within 8.0% and 2.5% for down and up-flows, respectively. The model provides a detailed analysis of heat flows at different conditions, and indicates optimization ways to improve the efficiency and reduce heat losses. The simulation results show that the outlet temperature can increase up to around 800 °C at 5 m^3/h under an average flux of 300 kW/m^2, and the thermal efficiency can be improved from around 56% to around 64% by decreasing the inner radius from 6 mm to 4 mm at the expense of increasing pressure drop of around 56 kPa.

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1. Introduction

To alleviate the energy crisis, many countries have considered solar energy as an alternative because it is clean, renewable, and abundant [1]. Concentrating solar power (CSP) has already been applied commercially for power generation [2]. It is well known that high electrical efficiency of the CSP system is highly dependent on being able to achieve a high working temperature of the heat transfer fluid (HTF) [3]. Synthetic oil has been widely utilized in solar trough plants, currently reaching around 4 GW [4] with the maximum working temperature around 400 °C [5]. Molten salt is another material to increase the working temperature up to around 560 °C [6]. Further increase in the temperature of those working fluids is difficult due to the constraints of physical properties.

Air receivers have been proposed as an alternative HTF to achieve higher working temperatures in order to obtain higher efficiency cycles for systems such as Brayton cycle [7]. The Institute of Electrical Engineering of Chinese Academy of Science developed an air intake tube receiver with bubbling particle. Concentrated solar radiation was mostly absorbed by particles and converted into thermal energy which was carried out by air flow. The maximum air outlet temperature reached 624 °C [8]. AirLight Energy installed an air-based receiver for solar trough concentrators. The receiver is 212 m long, consisting of 4608 cavities made of helically coiled tubes [9]. The receiver can deliver hot air at a temperature around 650 °C under a concentration ratio of 98 when the inlet air temperature is 120 °C. The German Aerospace Center (DLR) developed an air receiver consisting of 40 absorber tubes arranged in a cavity and connected in parallel. The outlet air temperature reached up to 800 °C at 4.5 bar, with the efficiency of the solar-hybrid micro-turbine system reaching 44% [10]. The Sweden Royal Institute of Technology (KTH) designed a gas turbine-receiver unit, in which the inlet air was first compressed by a compressor, pre-heated by a regenerator, and then heated by a solar receiver. The air outlet temperature reached 950 °C [11]. Abengoa Solar developed a volumetric solar air receiver. The maximum air outlet temperature reached up to 1000 °C [12]. The Swiss Federal Institute of Technology in Zurich (ETH) developed a pressurized solar receiver whose main component was a cylindrical silicon carbide cavity surrounded by a concentric annular reticulate porous ceramic

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Nomenclature

Q_{in}	incident irradiation on the receiver (W)
Q_{ref}	reflective loss of incident irradiation (W)
$Q_{1,rd}$	heat radiation loss between the glass cover and the atmosphere (W)
$Q_{2,rd}$	heat radiation loss between the shell wall and the atmosphere (W)
$Q_{1,cv}$	heat convection loss between the glass cover and the atmosphere (W)
$Q_{2,cv}$	heat convection loss between the shell wall and the atmosphere (W)
$Q_{3,rd}$	heat radiation loss between the cavity inner wall and the atmosphere (W)
h_{cv1}	convection heat transfer coefficient between the glass cover and the atmosphere (W/(m^2 K))
h_{cv2-1}	convection heat transfer coefficient between the shell up surface and the atmosphere (W/(m^2 K))
h_{cv2-2}	convection heat transfer coefficient between the shell side surface and the atmosphere (W/(m^2 K))
h_{cv2-3}	convection heat transfer coefficient between the shell bottom surface and the atmosphere (W/(m^2 K))
s	thickness of the glass cover
ρ	reflectivity of the glass cover
T_i	inlet air temperature (K)
T_o	air outlet temperature (K)
A_g	area of the glass cover (m^2)
$Q_{absorbed}$	energy carried away by the air (W)
L	characteristic length (m)
$Q_{2-1,cv}$	heat convection loss between the shell up surface and the atmosphere (W)
$Q_{2-2,cv}$	heat convection loss between the shell side surface and the atmosphere (W)
$Q_{2-3,cv}$	heat convection loss between the shell bottom surface and the atmosphere (W)
$Q_{2-1,rd}$	heat radiation loss between the shell up surface and the atmosphere (W)
$Q_{2-2,rd}$	heat radiation loss between the shell side surface and the atmosphere (W)
$Q_{2-3,rd}$	heat radiation loss between the shell bottom surface and the atmosphere (W)
$Q_{3-1,rd}$	heat radiation loss between the outer wall of the coils and the atmosphere (W)
$Q_{3-2,rd}$	heat radiation loss between the optical splitter and the atmosphere (W)
T_g	average glass temperature (K)
T_a	average atmosphere temperature (K)
ε_g	glass cover emissivity
σ	the Stefan–Boltzman constant

(RPC) foam. The outlet temperature of the air flowing through the RPC reached up to 1060 °C at 5 bar under an input solar power of 32–38 kW [13]. The Weizmann Institute of Science divided the aperture of the solar receiver into separate stages according to irradiance distribution to minimize heat losses. The air temperature was initially raised up to 750 °C by preheaters, i.e., cavity tubes. Subsequently, a directly irradiated annular pressurized receiver (DIAPR) was used. The receiver was capable of supplying hot air at a temperature of 1300 °C under a pressure of 10–30 bar [14]. The first demonstration of the use of air as HTF in a solar power plant was through a 1.5 MW tower power system with a ceramic volumetric receiver in Jülich, Germany. The receiver produced hot air with a temperature of 680 °C and was in operation successfully in September 2008 [6].

For scaling up and design optimization purposes, a reliable comprehensive predictive model describing performance of the air solar receiver is highly desired. Wang et al. [15] used a 3D numerical model with a uniform flux distribution on tube surface for a coiled tube receiver to analyze temperature distribution and thermal stress of the tube. Paitoonsurikarn et al. [16] numerically investigated the effects of different shapes on the convective losses of solar cavity receivers by assuming an isothermal wall temperature. Prakash et al. [17] computed convective heat losses of a cylindrical cavity receiver under different inclination angles assuming an adiabatic boundary condition on cavity external wall.

The foregoing modeling and simulation efforts focused on analyzing the effects of various heat transfer modes. However the incident radiation flux on the cavity wall has often been simplified by assuming a uniform or arbitrarily varying distribution. Since the radiation flux is the most important factor for characterizing the solar receiver performance, a realistic model for the distribution of the radiation heat flux is necessary.

In this work, a generic air tube cavity solar receiver is considered. Monte-Carlo ray tracing technique is used to accurately obtain the realistic radiation flux distribution on the air tube external wall in order to build a comprehensive simulation model coupling optical and heat transfer processes of high-temperature air solar receiver, which considerably affects the distributions of wall temperature and the heat loss at the external walls. A 15-turn helically coiled tube cavity receiver with an optical splitter at the bottom is designed and fabricated in order to assess the efficacy of the comprehensive model. The experiments on the cavity receiver were performed under a five 7-kW Xe-arc lamps array system. Good agreements were obtained between the measurement and the model calculation. The comprehensive simulation model is subsequently used to conduct a parametric investigation to understand the performance of the cavity receiver under different operating conditions and to find ways to optimize solar air receiver performance.

2. Experimental set-up and methods

A solar simulator consisting of five 7-kW Xe-arc lamps, as shown in Fig. 1, is employed to heat an air tube-cavity receiver. An experimental flowchart is shown in Fig. 2(a). Air is pumped into

Fig. 1. Solar simulator with five 7 kW Xe-arc lamps.

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