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Heat transfer and fluid flow analysis of porous medium solar thermochemical reactor with quartz glass cover

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ABSTRACT

In this paper, heat transfer and fluid flow of porous media solar thermochemical receiver with quartz glass cover were investigated. The Surface-to-surface radiation model and Rosseland approximation for radiation heat transfer were adopted for the transport of diffused solar irradiance and radiative transfer in the fluid phase and porous medium. An experimental test was conducted on a laboratory-scale solar thermochemical reactor. The effects of structural parameters in term of diffused irradiance intensity, the mass flow rate, heat transfer coefficient, quartz glass and inner cavity wall surface emissivity, the porosity and extinction coefficient that could affect heat transfer and fluid flow performance of the proposed solar cavity receiver were sufficiently investigated. It was found that the substantial drops in temperature were mainly attributed to the thermal losses by radiative, convective and conductive heat transfer. The numerical results are compared with the experimental data for the model validation. The thermal loss at the solar flux inlet of the receiver was obviously inevitable due to the stronger effect of heat transfer coefficient that altered the over increasing temperature and heat flux at the surface of diffuse irradiance. However, the use of optimum pore size and higher porosity material could significantly enhance the thermal performance of porous media solar thermochemical reactor.

1. Introduction

Nowadays, the major key challenge of energy accompanied by mitigating the greenhouse effect and environmental pollution hazards rely upon developing solar energy conversion technologies to meet the ever-increasing global demands for clean transportation fuels, chemicals, and electric power. Heat derived from concentrated solar irradiation has been considered the most efficient way of producing commodities such as ammonia [1], metals [2], and fuels [2–4]. However, heat transfer and fluid flow optimization within a cavity receiver are the technical challenges in achieving higher thermal conversion efficiency [5,6]. As reported by Ijaz et al. [7], the thermal process can be improved by considering the material interaction in the presence of heat and mass transfer within a cavity receiver. Moreover, the particle density and the solid volume fraction of nanoparticles significantly affect the convective heat transfer, viscous and thermal entropy generations in the reacting medium [8,9]. Thus, the thermal performance of the solar thermochemical reacting system can be greatly improved by considering the effects of the physical parameters and operating conditions of the solar cavity receiver/reactor [10,11].

The solar thermochemical process typically proceeds with high thermal reduction of raw oxide material (MO_{ox}) followed by the release of oxygen to the metal oxide containing vacant oxygen sites in the crystal lattice (MO_{red}). This step requires a high temperature that can exceed 1600 K depending on the oxide material. However, the temperature of the process decreased when the oxidizing gas H_2O/CO_2 is injected into the reactor. As a result, oxygen vacancies in the reduced oxide material extract oxygen from H_2O/CO_2 to its initial oxide state (MO_{ox}) followed by the release of H_2/CO. The solar thermochemical reacting system for converting CO_2 emission into storable CO can be described as follows.

More uniform and high-temperature distribution throughout the cavity receiver of solar thermochemical reactor is the limiting factor for achieving high efficiency of solar-to-fuel energy conversion. The research and development of high-temperature material processes for use as high-temperature thermochemical energy storage material and the geometry type of solar receiver able to minimize energy losses via heat transfer are the main issues addressed in the usage of concentrated solar radiation as an energy source for solar fuels production [12–15]. Among solar-driven thermochemical reactors, porous media receiver gained increasing

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interests due to the higher heat transfer performance and heat transfer and heat exchanger effectiveness [16–18]. In the recent years, several works have been developed on the thermal performance of porous media receiver in order to optimize the conversion of incident solar radiation within a cavity receiver. Kasaeian et al. [19], in the review of the latest developments on nano-fluid flow and heat transfer in porous media, reported that utilizing porous media can augment the thermal efficiency by improving heat transfer rate in ducts due to the high surface area contact. However, an increase in the pressure drop ratio was observed with the decrease of Richardson number and the volume fraction of nanoparticles and the increase of nanoparticles diameter and inner cavity wall surface emissivity [20]. In order to maximize the thermal efficiency of the porous medium solar receiver, Wang et al. have developed several works on the thermal performance analysis [21,22], and thermochemical reaction performance analysis [23,24]. Milani Shirvan et al. [25] reported that the physical parameters such as Rayleigh number, Darcy number, reactor inclination angles, the thickness of porous material, inner cavity wall surface emissivity, and the surface radiation heat transfer can significantly affect heat transfer performance in a porous media solar thermal reactor. Since radiative heat transfer cannot be neglected when studying the thermal performance of porous media receiver, several researchers adopted Monte Carlo Ray Tracing (MCRT) method, Finite Volume Method (FVM), Rosseland approximation and P1 approximation for radiation heat transfer. They found that porous medium has advantages of the high fluid-solid contact surface, low-pressure drop with good heat and mass transfer performance. Also, the porosity and mean cell size significantly affected the mole fraction of H_2 produced. Steinfeld et al. [26] discovered an increasing yield of H_2 from their experimental studies conducted on the concentrated solar-driven porous media reactor under realistic operating conditions. Moreover, as reported by Steinfeld et al. [26], Xu et al. [27], Zhao et al. [28], Agrafiotis et al. [29], the fixed ceramic foam in the receiver can serve as the solid reactant. This can avoid the tasks of moving reactant materials by allowing both processes (endothermic and exothermic reaction) to conduct in the same reactor. Besides, Shuja et al. [30], in their study on innovative design of a solar volumetric receiver stated that aerodynamic design of the absorbing blocks could minimize the pressure drop across the receiver inlet and exit ports. Thus, increasing research development on the porous media receiver would significantly improve the solar-driven thermochemical technology for hydrogen and syngas production. Since the solar thermochemical operate at high thermal radiation, the glass cover and the structure of porous material will strongly affect the thermal efficiency, heat losses, heat transfer mechanisms and heat flux distribution within the cavity receiver. Most of the studies suggested that the porous structure greatly affects solar radiative flux distribution within the porous media absorber [31–33]. Zhao et al. [34] found that extinction coefficient is strongly dependent on the porosity and pore size. Also, Rashidi et al. [35] reported that incorporated nanoparticles into the porous materials can improve the properties of porous materials. Regarding the thermochemical reaction performance for H_2O/CO_2-splitting, Teknetzi et al. [36] and Lorentzou et al. [37] in their studies on $NiFe_2O_4$ mentioned that the higher the porosity and optimum pore size distribution, the higher the capability of the samples have to reversibly deliver and pick up their lattice oxygen. Thus, the oxide material can improve the thermal conductivity, heat stability, and chemical resistance of the porous media. Besides, as for the quartz glass cover, several studies have reported that adding window can enhance heat transfer in porous media [38,39]. However, Du et al. [40] demonstrated that thermal radiation loss is inevitable at the entrance of the solar receiver. Thus, taken into account the glass efficiency in the study on porous media receiver will have relevant effects on the thermal performance of porous media solar thermochemical reactor.

In this paper, heat transfer and fluid flow analysis of porous media solar thermochemical reactor with quartz glass cover were investigated. Surface-to-surface radiation model and Rosseland approximation for radiation heat transfer were adopted for predicting the thermal characteristics of both fluid phase and porous media. The reactor temperature distribution and radiation in participating media were investigated along with the effects of cooling system and mass flow rate on the heat transfer and fluid flow performance. Moreover, the effects of quartz glass and inner cavity wall surface emissivity were analyzed and the effects of porosity and extinction coefficient on the reactor thermal performance were reported. The numerical results were compared with those of experiment.

2. Methods

2.1. Physical model

Fig. 1 shows the model of porous media solar thermochemical reactor used for the numerical simulation. This study used the model developed by Guene Lougou et al. [41] for advanced thermal analysis of the reactor filled with porous material. Details of the reactor physical parameters can be found in [41,42]. The solar reactor features a cavity-receiver containing fluid domain and porous media. The quartz glass is considered for the glass cover at the surface of diffused solar irradiance and porous $NiFe_2O_4$ is considered as porous material in the reacting medium. The reactor is filled with nitrogen gas (N_2). The quartz glass region and hot gas outlet are cooled with water.

A laboratory-scale solar thermochemical reactor was tested on seven lights solar simulator. The experiment results are shown in Fig. 2. As depicted in Fig. 2a, one light of the solar simulator is used to provide high-temperature heat flux for heating up the absorber in the inner cavity of the reactor. $NiFe_2O_4$ porous structure was heated at 5×10^{-5} kg/s of nitrogen mass flow rate and three thermocouples were used to measure the temperature variation during the thermal process. The reactor was heated for 1 h 40 min and the thermal behavior of the absorber along with the temperature distribution in the porous medium can be seen in Fig. 2b and c, respectively. The porous medium is heated up via complex coupled heat transfer and fluid flow in the inner cavity receiver. During the experiment, the heating rate of the burner was increased by increasing the light intensity as well as the flow rate from the inlet pores of the reactor. Since the front face of the reactor is heated directly by the light, the increase in the flow rate could volumetrically transport high-temperature heat flux to the porous medium. As a result, the temperature of the absorber increases as a function of time.

2.2. Governing equations

The governing equation describes the numerical procedure account of the mass, momentum, and energy equations. The inner cavity of the reactor features fluid phase and porosity zone. The governing equation describing the fluid phase of the reactor is given by the following equations.

$$\nabla \cdot (\rho u) = 0 \tag{1}$$

$$\rho(u \cdot \nabla)u = -\nabla P + \nabla \cdot \left[\mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)\right] \tag{2}$$

$$\rho C_p u \cdot \nabla T = -\nabla \cdot q + Q + Q_p + Q_{vd} \tag{3}$$