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Thermal performance analyses of porous media solar receiver with different irradiative transfer models

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ABSTRACT

There are two commonly used methods for irradiative transfer problems in porous media: P1 approximation and Rosseland approximation. In this study, the effects of irradiative transfer models on heat transfer performance of porous media solar receiver under concentrated heat flux distribution are numerically investigated. By combining the Monte Carlo Ray Tracing (MCRT) method and FLUENT software with user defined functions (UDFs), the local non-equilibrium thermal equation (LNTE) model with both the Rosseland approximation and modified P1 approximation are established. The numerical results indicate that the maximum temperature difference of porous media solar receiver between the modified P1 approximation and Rosseland approximation is small. The thickness of thermal non-equilibrium region is smaller for the Rosseland approximation condition than that for the modified P1 approximation condition.
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1. Introduction

Due to the unique structural properties, porous media has several advantages, such as: large heat transfer surface per unit volume, effectively damp vortex during flow [1,2]. The utilization of porous media has received much attention in recent years, for example: catalyst supports in chemical reaction, heat exchangers in electrical cooling, burners for combustion and volumetric receivers in concentrated solar energy [3–6].

Porous media made of silicon carbide (SiC) or metal coated with catalyst layer is commonly used as thermo-chemical receivers due to several advantages: (I) solid transport is avoided due to the utilization of solid reactant fixed in the receiver; (II) the interplay of thermochemical receiver is avoided, and the endothermic process and exothermic process could be conducted in the same thermochemical receiver; (III) the reticulated structure of porous media provides high surface to volume ratios which results in high activity per unit volume with low pressure drop [7–9].

Many researchers had adopted porous media coated with catalyst layer as thermochemical rector for chemical reaction. Steinfeld et al. had set up a solar cavity receiver with porous media which was subjected to concentrated solar irradiation under realistic operating conditions, and the experimental process demonstrated high rate H_2 production from H_2O without the need of complex material structures and system design [7]. Sang et al. had investigated the solar reforming of natural gas over metal porous media based monolithic catalysts. The experimental results indicated that porous media coated with catalyst layer exhibited high catalytic activity and long term stability of H_2 production [10]. The CNRS-PROMES laboratory had developed a 1 kW thermochemical porous media receiver for hydrogen production from two-step solar thermochemical cycles, and numerical models coupled with fluid flow, heat and mass transfer, and chemical reactions were developed to predict the thermal behavior under different operational conditions. During the numerical simulation, the front surface of thermochemical solar receiver was subjected to a Gaussian distribution solar flux density, and the P1 approximation was adopted to solve the irradiative heat transfer for the solid phase energy equation [11]. The solid oxide fuel cells (SOFCs) can be operated in a reversed mode for H_2 production from H_2O electrolysis, and Ni had developed a 2D heat and mass transfer model coupled with chemical reaction kinetics for SOFCs to research the effects of various structural and operating parameters on reaction rate of H_2 production [12]. In order to investigate the thermochemical reaction performance of steam methane reforming, the steady state heat and mass transfer model coupled with thermochemical

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Nomenclature

c_p	specific heat, J/(kg · K)
C_R	concentration ratio
d_s	mean cell size, mm
D_m	mass diffusion coefficient
D_T	thermal diffusion coefficient
E_{sun}	solar irradiance, W/m^2
G	integrated intensity, W/m^2
h_i	partial enthalpy of species i, J
h_v	volumetric heat transfer coefficient, W/(m^3 · K)
k_α	absorption coefficient
k_e	extinction coefficient
k_s	scattering coefficient
k_r	irradiative conductivity
L	length of receiver, mm
n	refractivity
p	pressure, pa
R	radius, m
S	source term of energy equation
T	temperature, K
T_0	environmental temperature, K
u	velocity in x direction, m/s
v	velocity in y direction, m/s
x, y	coordinates in flow region, m

Greek symbols

ρ	density, kg/m^3
ϕ	porosity
α	absorptivity
μ	dynamic viscosity, kg/(m · s)
α_{sf}	surface area per unit volume, 1/m
λ	conductivity, W/(m · K)
ε	emissivity
σ	Stefan–Boltzmann constant
ω	albedo coefficient
τ	optical thickness ($\tau = k_e \times L$)

Subscripts

conv	convective heat transfer
eff	effective
f	fluid phase
rad	irradiative heat transfer
s	solid phase
w	wall

reaction kinetics was developed by Wang et al. for the volumetric porous media solar thermochemical receiver, and a Gaussian heat flux distribution was adopted as the heat source [13].

Thermal performance analyses of volumetric porous media receiver under concentrated solar irradiation distribution was conducted by Pitz-Paal et al. [14], and the numerical results indicated that heat flux distribution had significant influence on temperature distribution of volumetric porous media receiver. Besides, the concentrated heat flux was commonly treated as Gaussian distribution or uniform heat flux during the numerical simulation of porous media for hydrogen production and power generation under concentrated solar irradiation [11,13,15]. However, Wang et al. had adopted MCRT and Finite Volume Method (FVM) coupling method to solve the irradiation, conduction and convection coupled heat transfer problems of porous media receiver with dish collector [16,17].

The working temperature for power generation and hydrogen production using porous media receiver/reactor under concentrated solar irradiation is about 1200 K [7,11], or higher up to 1600 K, and the typical working temperature for SOFCs is about 1073 K [12]. The irradiative transfer plays a dominant role in the heat transfer when the porous media is placed in a high temperature environment [18,19]. There are several methods to calculate irradiative transfer, for example: P_N, DOM, FEM, MCRT, DRESOR and Ray Tracing method [20–23]. Since porous media strongly absorbs solar irradiation, porous media is generally large optically thickness with a short irradiative transport mean free path and the optical thickness is generally larger than five. The Rosseland approximation [16,17] and P1 approximation methods which was firstly introduced by Cheng for irradiative transfer [24,25] are suitable for large optical thickness problems with little time consuming.

Without the consideration of irradiative transfer effects between the porous strut structures, Xu had investigated the steady state heat transfer characteristics of porous media solar tower receiver under uniform heat flux distribution [15]. Rashidi et al. had adopted the differential transform method with Rosseland approximation to investigate the heat transfer problems of a micropolar fluid through a porous media with radiation [26,27]. Vidales and Wu et al. had adopted the P1 approximation for irradiative heat transfer for porous media solar receiver while Gaussian distribution was used as the concentrated solar irradiation distribution [11,28]. The LNTE model with Rosseland approximation was set up by Wang et al. to investigate the temperature distributions of porous media solar receiver under concentrated solar irradiation [16,17].

From the literature survey, it can be seen that LNTE model with P1 approximation or Rosseland approximation for porous media solar receiver have been developed by several researchers previously. However, the LNTE model with P1 approximation for porous media solar receiver under concentrated heat flux calculated by MCRT method was not reported. Besides, the thermal performance comparisons between the P1 approximation and Rosseland approximation for porous media solar receiver were not investigated and reported. In this study, heat transfer performance analyses of porous media solar receiver are conducted by combining the MCRT method and FLUENT software with UDFs. The MCRT method is used to obtain the heat flux distribution on the fluid entrance surface of porous media solar receiver. The irradiative transfer between the porous media strut is solved by both the P1 approximation and Rosseland approximation via UDFs in the Fluent software.

2. Description of porous media solar thermochemical receiver

As shown in Fig. 1, the porous media solar receiver is placed on the focal plane of a parabolic dish collector [17]. The fluid entrance surface of porous media solar receiver is subjected to concentrated solar irradiation supplied by a parabolic dish collector. The dimensions and physical parameters of the parabolic dish collector and porous media solar receiver are illustrated in Table 1. The thermophysical parameters of the porous media solar thermochemical receiver used in this study are the same as Ref. [11]. Generally, the porous media solar receiver is made of silicon carbide (SiC). If chemical reactions are involved, the porous media solar receiver would be coated with catalyst layer (i.e. Ni/α-Al_2O for H_2 production using methane reforming) [13]. The thermophysical properties of the porous media solar receiver coated with catalyst

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