International Journal of Heat and Mass Transfer 62 (2013) 247–254

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal performance analysis of porous media receiver with concentrated solar irradiation

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ARTICLE INFO

Article history:
Received 24 November 2012
Received in revised form 5 March 2013
Accepted 5 March 2013
Available online 9 April 2013

Keywords:
Solar energy
Porous media
Receiver
Monte Carlo
Radiative heat transfer

ABSTRACT

The distribution of concentrated solar irradiation has a significantly impact on the temperature distribution of porous media receiver. The thermal performance of porous media receiver is investigated by combining the Monte Carlo Ray Tracing (MCRT) method and FLUENT software with user defined functions (UDFs). The MCRT method is used to obtain the heat flux distribution on the fluid inlet surface of porous media receiver. The calculated heat flux distribution is treated as the wall heat flux boundary condition of thermal performance analysis. The local non-equilibrium thermal equation (LNTE) model with Rosseland approximation is used to investigate the temperature distributions. Typical influences of the heat flux boundary condition, radiation heat loss, porosity, emissivity, flow mass and average particle diameter on the temperature distributions are investigated.

1. Introduction

Concentrated solar thermal utilization which supplies high temperature air is a promising approach for power generation [1]. Compared to photovoltaic, concentrating solar energy onto a receiver allows cost reduction of electricity generation as the reduction requirement of materials for reflectors [2]. Since the heat transfer surface of porous media per unit volume is greatly increased compared with tube receiver [3] and the porous media can effectively damp vortex during flow [4], the utilization of porous media as solar receiver has attached much attention for research and development [5–7]. Technology achievements of porous media receiver in solar power generation have enabled the concentrated solar flux to 1 MW/m^2, with reduced weight and size of receivers, shortened startup and increased efficiency [8].

Paal et al. have developed a heat transfer performance analytical approach for volumetric porous media receiver, which has taken into the consideration of three-dimensional irradiation distribution and its influence on fluid flow [9]. The numerical results show that temperature distributions of volumetric porous media receiver are strongly influenced by solar irradiation distribution. A 1 kW thermochemical solar receiver fitted with porous foam is studied numerically by Villafán-Vidales et al. to predict the thermal transfer performance, and a Gaussian flux density distribution with 1.4 MW/m^2 peak power is adopted as the concentrated solar energy [10]. The radiation heat transfer plays a dominant role in the heat transfer when the porous is placed in a high temperature environment [11]. Wu et al. have simulated the temperature distribution of the fluid and solid phase in porous media receiver using LNTE model with a Gaussian solar flux distribution boundary condition, and the radiation transport in the porous media was modeled with P_1 approximation [12,13]. Natural convection boundary layer flow analysis of porous media receiver due to collimated beam solar irradiation is investigated by Chamkha et al. [14]. Numerical simulations of composite-wall solar collector system with porous media receiver are conducted by Chen and Liu [15] to analyze the heat transfer performance of porous media receiver. During their simulations, the heated surfaces are subjected to a uniform solar irradiation at the same time point. The numerical heat and mass transfer analysis of porous media receiver with preferable volume convection heat transfer coefficient is conducted by Xu et al. [16]. During the analysis, concentrated solar irradiation heat flux distribution on the receiver surface is appointed to be a function of temperature gradient. Badruddin et al. have conducted the heat transfer analysis of a saturated porous media enclosed in a square cavity using the LNTE model, the governing partial differential equations are non-dimensional and solved by finite element method [17].

The literature survey shows that the distribution of concentrated solar irradiation has a significantly impact on the temperature distribution of porous media receiver. However, many researchers treat the distribution of concentrated solar irradiation

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0017-9310/$ - see front matter
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.03.003

Nomenclature

c_p	specific heat, J/(kg K)
d	diameter, mm
F	inertia coefficient
h_v	heat transfer coefficient, W/(m^2 K)
k	permeability coefficient
k_α	absorption coefficient
k_e	extinction coefficient
k_s	scattering coefficient
L	length of receiver, mm
M	mass flow, kg/s
n_s	number of energy bundle
$\vec{N}_{sun}$	sunlight vector
N	total ray number
p	pressure, pa
q	heat flux, W/m^2
Pr	Prandtl number
Re	Reynolds number
T	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
μ	viscosity, m^2/s
α_{sf}	surface area per unit volume, 1/m
λ	conductivity, W/(m K)
ε	emissivity
σ	Stefan–Bolzmann constant

Subscripts

A	ambient
eff	effective
f	fluid
i	*i*th elment
j	*j*th elment
MC	Monte Carlo
p	particle
r	radiation
s	solid
sun	solar irradiance
w	wall

as simplified heat flux distribution boundary condition during the thermal performance analysis of porous media receiver, and these treatments of boundary condition can not accurately reflect the temperature distribution.

In this study, the thermal performance analysis of porous media receiver which is installed on the focus plane of solar dish collector is conducted by combining the MCRT method and FLUENT software with UDFs. The MCRT method is adopted to obtain the heat flux distribution and used as the wall heat flux boundary condition of thermal performance analysis. The commercial software FLUENT was used to solve the mass, momentum and energy conservation equations in the fluid phase. For the solid phase, the energy equation and radiative heat transfer were computed using the UDFs. Typical influences of the heat flux boundary condition, radiation heat loss, porosity, emissivity, flow mass and average particle diameter on the temperature distributions were investigated.

2. Porous media receiver description

As shown in Fig. 1, the silicon ceramic (SiC) porous media receiver is placed vertically on the focal plane of solar dish collector. Solar dish collector concentrates the incoming sun irradiation on the fluid inlet surface of porous media receiver, and the porous media receiver converts the highly concentrated solar irradiation into heat by conduction. When air passes through the porous media receiver, heat is transferred from the porous media to air by conduction, convection and radiation heat transfer. The flow and heat transfer can be simplified to two dimensions [10,16]. The heat transfer process of porous media receiver is described in Fig. 2. The geometrical and physical parameters of the porous media receiver and solar dish collector used in this study are illustrated in Table 1.

3. Mathematical model

The mathematical model assumes that (1) lateral walls of porous media receiver are well insulated (adiabatic), (2) constant and homogeneous properties of the porous media, (3) the porous media is considered as a gray, optically thick, absorbing, emitting and isotropic scattering media, (4) the air flow is steady. The governing equation for the energy conservation is a volume-averaged equation. Due to the substantial temperature difference exists between the solid phase and fluid phase at the flow inlet, LNTE model is adopted in this study to provide more temperature information of the fluid phase and solid phase.

It should be noted that there are many correlations of the permeability, geometric function and volumetric convection heat transfer coefficient for porous media. Take the correlations of volumetric heat transfer coefficient as an example: Hwang [18], Achenbach [19], Dixon and Cresswell [20] as well as Wu et al. [21] have put forward different models. Many investigators have used the permeability, geometric function put forward by Ergun [22] and correlations of volumetric convection heat transfer coefficient put forward by Hwang [18] simultaneously to study the heat transfer performance of porous media or porous media receiver [16,23]. The correlations of permeability, geometric function and volumetric convection heat transfer coefficient for porous media used in this study are the same as those in Ref. [16,23].

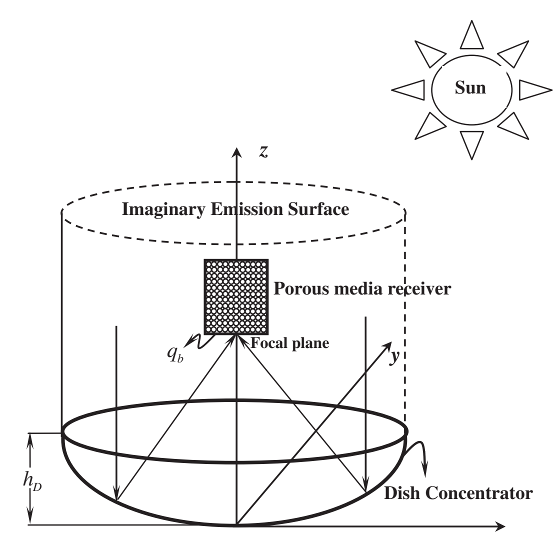

Fig. 1. Schematic diagram of the porous media receiver with solar dish collector system.