Applied Thermal Engineering 120 (2017) 150–159

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Pore scale numerical simulation of heat transfer and flow in porous volumetric solar receivers

Qibin Zhu, Yimin Xuan *

School of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

HIGHLIGHTS

- Coupled pore scale models based on a structured packed bed are established.
- Influence factors of reflection loss and radiation propagation are analyzed.
- The pore diameter and porosity have strong impacts on the pressure drop.
- A combined packed bed is introduced to design volumetric solar absorbers.

ARTICLE INFO

Article history:
Received 17 October 2016
Revised 23 March 2017
Accepted 25 March 2017
Available online 3 April 2017

Keywords:
Volumetric solar receiver
Packed bed
Porous medium
Pore scale

ABSTRACT

Volumetric receivers used in concentrated solar power (CSP) plants consist of porous media and transfer energy to the working fluid passing through after being heated by concentrated solar flux. Pore scale models based on structured packed bed volumetric solar receivers with three packed types are investigated in this work. The Monte Carlo Ray Tracing (MCRT) method is employed to analyze the radiation propagation in the volumetric receiver. Then the absorbed flux is used as the boundary heat source in pore scale models, and the heat transfer and flow in pore scale models are analyzed. The influences of porosity, incident angle and receiver absorptivity on the reflection loss and radiation propagation are analyzed. It is demonstrated that the sphere surface absorptivity has a great influence on the absorption process. Smaller incident angle and higher porosity can promote the radiation propagation. The pore diameter and packed type have strong impacts on the pressure drop, while the inlet velocity greatly affects the temperature distribution. Finally, a hybrid packed bed volumetric solar receiver is introduced to optimize the heat transfer and flow in the receiver.

1. Introduction

The installed capacity of concentrated solar power (CSP) plants is rapidly increasing and the CSP plants are expected to play a major role in world's renewable power supply by 2050s [1–4]. There are four major constituents in the CSP plants, i.e., the solar concentrating system, the solar receiver, the storage system and the power conversion system [1]. The solar receiver transfers energy to the working fluid passing through it after being heated by concentrated solar flux, and can significantly affect the overall efficiency of CSP plants. So far, three groups of receivers have been developed and tested, which are the volumetric receivers, the cavity receivers and the particle receivers [1]. Volumetric receivers used in CSP plants consist of porous media, and can achieve higher air temperatures than other receiver technologies, thus leading to a higher efficiency [5,6]. However due to the high working temperature, the properties of working fluid change significantly, especially the viscosity and the density, which may cause local overheating and unstable flow [5]. Therefore, it's important to optimize the heat transfer and the flow in the volumetric solar receiver.

As a popular type of volumetric receiver, the heat transfer and flow properties of the packed bed have been investigated by many researchers. Vafai et al. [7] investigated forced convective flow of gas in the packed bed, and the results indicate the particle Reynolds number and the Darcy number have great influences on the local thermal equilibrium condition, while the two-dimensional behavior of certain variables is greatly affected by thermophysical parameters. Variot et al. [8] studied the heat transfer in a two-slab selective packed bed solar receiver, and 90% efficiency was reported at 1300 K by using selective albedos. Argentot and Bouvardt [9] evaluated the radiative heat transfer

* Corresponding author.
E-mail address: ymxuan@nuaa.edu.cn (Y. Xuan).

http://dx.doi.org/10.1016/j.applthermaleng.2017.03.141
1359-4311/

Nomenclature

ρ'	reflectivity
ε	absorptivity
L_s	radiance scattered (W m^{-2} sr^{-2})
ϕ_{in}	incident irradiance (W m^{-2})
L	incident depth (m)
λ	thermal conductivity (W m^{-1} K^{-1})
h_{sf}	convective heat transfer coefficient (W m^{-2} K^{-1})
α_{sf}	specific surface area (m^{-1})
ρ	density (kg m^{-3})
Re_d	Reynolds number
U	superficial velocity (m s^{-1})
d	sphere diameter (m)
C_p	specific heat (J kg^{-1} K^{-1})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
φ	porosity
H	enthalpy (kJ kg^{-1})
m	mass flow rate (kg s^{-1})

Subscripts

f	solid phase
s	fluid phase

in the random packed bed by using the Monte Carlo Ray Tracing (MCRT) model, and a quantitative agreement is obtained in comparison with previous experimental and numerical works. Calis [10] simulated the flow and heat transfer in a structured packed bed with the commercial CFD software (CFX-5.3) in both laminar and turbulent regions and results showed that the relative error of the simulated and experimental data was acceptable. Wang [11] investigated the heat transfer performance with both random and structured packed beds by using the commercial code CFX10 based on CFD method. Guo [12] analyzed the local flow and heat transfer of the random packed bed by using a finite volume formulation, which is based on the Chimera meshing technique, and discussed the nonuniformity of flow and heat transfer caused by the random packing. Petrasch [13] investigated radiative transfer in packed bed by using a non-energy-partitioning MCRT model at pore level, and discussed the influence of micro-geometry on transparent progress. Roos and Harms [14] designed a spectrally selective two-slab packed bed volumetric receiver and investigated the heat transfer and flow properties of the receiver.

It is recognized that the flow and heat transfer properties of the volumetric receiver are complex, and the real structure model of porous media in the volumetric receiver is hard to establish due to the geometric complexity. Therefore, many works treated the porous media in the volumetric receiver as homogeneous participating media and discussed the flow and heat transfer processes by using effective parameters [15–17]. However, few studies describing the coupled simulation of heat transfer and flow in the volumetric receiver have been reported in the literature. By using the pore scale numerical simulation, one can account for pore geometries instead of ignoring real pore structures and using effective parameters [18,19]. Therefore, it is better to understand the influence of pore scale properties on the macroscopic flow and heat transfer behavior. In this work, the pore scale models of the structured packed bed are established since compared with the random packed bed, the pressure drop in the structured packed bed can be greatly reduced and have a better heat transfer performance [11]. A frequently used tool for modeling solar radiation distribution is the MCRT method, in which the optical properties are investigated by generating and tracing a large number of rays [20–23]. Thus the MCRT method is employed to analyze the radiation propagation in the volumetric receiver in this work. Then the absorbed incident radiation flux is used as the boundary heat source for the pore scale model based on the Local Thermal Non-Equilibrium (LTNE) theory.

The motivation of this work is to explore the heat transfer and flow properties of the packed bed volumetric solar receiver by using pore scale direct numerical simulation, and try to get insight into the mechanism of affecting the heat transfer and flow in a volumetric solar receiver and provide the detailed information for designing high-performance of volumetric solar receivers.

2. Numerical model

2.1. Pore scale model

Fig. 1 illustrates the scheme of the packed bed volumetric solar receiver. The receiver is heated by concentrated solar flux, and transfers thermal energy to the air passing through it, and then the heated air is further used in traditional energy cycles (Rankine, Brayton or Stirling) [24].

Fig. 2 presents the pore scale model used in this work, which is a unit packed channel of structured packed bed, and a quarter unit cell of packed channel is used during simulation to take advantage of symmetry. Three types of cubic close packing are used in the pore scale model, in other words, Simple Cubic (SC), Face-Centered Cubic (FCC) and Body-Centered Cubic (BCC). The volumetric porosities of three packed types are 0.476, 0.395 and 0.260, respectively. The incident radiation flux is 1 MW/m^2. The incident angle θ is chosen as $\pi/4$ and $\pi/3$ to investigate the influence of incident angle on the radiation propagation.

The air temperature of the inlet boundary is set at 293.15 K. The gauge pressure of the outlet boundary is set at 0 Pa. Without loss of a generality, one can select a representative volume from the receiver to study heat and flow features inside the receiver. With respect to the structured packing of the receiver, the symmetry conditions are used for heat transfer and flow at the lateral planes, and the specular boundary conditions for radiation are applied to the lateral planes. Thus, any ray that exits from the elementary cell and hits on the specular boundaries is reflected inward, which can be considered as an incoming ray from an adjacent elementary cell [25,26]. The transparent boundary is set on the outlet plane, so the

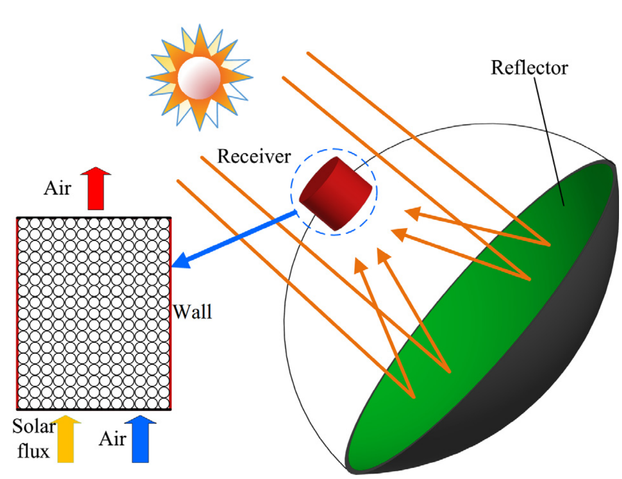

Fig. 1. Scheme of the packed bed solar receiver.