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Optimization method for the porous volumetric solar receiver coupling genetic algorithm and heat transfer analysis

Shen Du, Ya-Ling He *, Wei-Wei Yang, Zhan-Bin Liu

Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

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ABSTRACT

The porous volumetric solar receiver shows advantages such as the volumetric absorption of solar radiation and the enhanced convective heat transfer. However, few studies were focused on the selection of the appropriate parameters of the receiver to improve its performance. In this contribution, an optimization method which couples the genetic algorithm and the heat transfer analysis of the porous volumetric solar receiver is proposed. The fluid flow and heat transfer in the receiver are evaluated by the volume-averaging simulation method based on the local thermal non-equilibrium model. By combining with the genetic algorithm, the solar receiver with high thermal efficiency and low flow resistance could be identified. The single-objective optimization results present that larger porosity and higher inlet velocity are preferable to improve the thermal efficiency of the porous volumetric solar receiver. The optimized pore size increases with the increase of the thickness of the receiver and the decrease of the inlet velocity. Meanwhile, the porosity and the pore size are optimized simultaneously through the multi-objective optimization. The Pareto front which indicates the receiver with relatively lower flow resistance and relatively higher thermal efficiency is derived.

1. Introduction

Concentrating Solar Power (CSP) technology has been developed rapidly worldwide and the solar receiver considered as one of its key components has also been investigated by many researchers [1–5]. Among many different types of solar receivers, the porous volumetric solar receiver has drawn much attention recently due to its high-efficiency performance in solar radiation absorption and heat transfer enhancement [6–8]. The volumetric absorption permits more solar energy to penetrate deeper inside the receiver and avoids an extremely high concentration of solar radiative heat flux on the surface of the receiver. The complicated three-dimensional structure of the porous media offers tortuous fluid channels and larger heat exchange surface which are favorable to the convective heat transfer. On the contrary, this complicated structure also brings a challenging task in the investigation of the fluid flow and heat transfer characteristics for the porous volumetric solar receiver.

Both experimental and numerical simulation methods have been widely used. The experimental studies were mainly focused on the thermal performance evaluation of the porous volumetric solar receiver. Experiments for the single volumetric solar receiver [9,10] and for the entire solar powered system [11,12] have been reported. Evaluation of the receiver's thermal performance has been the main research subject. Due to the restriction of temperature measurement inside the receiver, the detailed information of temperature field is difficult to be obtained. As for the numerical simulation methods, the direct pore-scale simulation method and the volume-averaging simulation method are the two main categories. The direct pore-scale simulation is performed on the reconstructed porous structure with detailed geometrical information [13–16]. Different methods such as lattice Boltzmann method and finite volume method are applied to investigate the fluid flow and heat transfer process inside the porous media. However, this simulation method requires intensive workload in porous media reconstruction and mesh generation. Large computational resources are needed during the time-consuming computational process. On the contrary, the volume-averaging simulation method offers a relatively faster method to estimate the heat transfer process in the porous volumetric solar receiver [17,18]. By adding empirical parameters into the momentum equation and energy equations, the effects of porous media to the fluid flow and heat transfer can be addressed. Local thermal non-equilibrium (LTNE) model is usually applied to investigate the heat transfer process inside the porous volumetric solar receiver because the thermal

* Corresponding author.
E-mail address: yalinghe@mail.xjtu.edu.cn (Y.-L. He).

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Nomenclature

C	correction coefficient for reflection loss
C_F	inertia coefficient
c_p	thermal capacity (J/(kg K))
d_p	pore size (m)
h_v	volumetric convective heat transfer coefficient (W/(m^3 K))
I	radiation intensity (W/(m^2 sr))
K	permeability (m^2)
k_r	radiative conductivity (W/(m K))
$\dot{m}$	mass flow rate (kg/s)
n	refractive index
p	pressure (Pa)
P	incident solar energy (W/m^2)
Re	Reynolds number
S_r	energy source due to solar radiation and radiation transfer (W)
T	temperature (K)
u	velocity (m/s)
x	penetration depth (m)

Greek symbols

β	extinction coefficient (m^{-1})
ε	porosity
η_t	thermal efficiency
λ_f	thermal conductivity of the fluid (W/(m K))
λ_{fe}	effective thermal conductivity of the fluid (W/(m K))
λ_{se}	effective thermal conductivity of the solid (W/(m K))
μ	dynamic viscosity (Pa s)
ρ	density (kg/(m^3))
σ	Stefan-Boltzmann constant

Subscripts

f	fluid
p	pressure
r	radiation
s	solid
v	volume

equilibrium for the porous skeleton and heat transfer fluid could not always be attained.

Wu et al. [19] coupled the LTNE model and P1 approximation to investigate the heat transfer process of ceramic foam volumetric solar air receiver. Parametric studies were performed to analyze the influences of inlet velocity, porosity, mean cell size, and thermal conductivity of the solid phase. The reliability of the simulation results was checked by comparison with experimental data of a lab-scale volumetric open air receiver. In the studies of Wang et al. [20,21], the Monte Carlo Ray Tracing (MCRT) method and Finite Volume Method (FVM) were applied to solve the fully coupled heat transfer problem of volumetric solar receiver. The MCRT method was applied to determine the concentrated heat flux distribution on the surface of the receiver which was then treated as the secondary boundary condition to the energy equations. The parametric studies revealed that both the geometrical parameters and working conditions have a great influence on the thermal performance of the porous receiver. Different irradiation models such as Rosseland approximation and P1 approximation were compared and differences in the simulation results imposed by these two models were identified. Chen et al. [22] studied the different coupling methods of solar radiation to the volumetric solar receiver. When the solar radiation is treated as collimated incident radiation, the simulation results agreed with that obtained by determining the solar radiation transfer inside the receiver with the MCRT method. Meanwhile, the thermal boundary condition for solar radiation overestimated the front solid temperature and underestimated the outlet air temperature. Moreover, transient thermal performance of the porous volumetric solar receiver was reported in several studies [23,24]. The influences of the different types of heat flux changes and the thermophysical properties of the material on the transient heat transfer were analyzed which are essential in the design and operation of the receiver.

In order to improve the efficiency in solar radiation absorption and heat transfer, the volume-averaging simulation method was also applied to investigate the porous volumetric solar receivers with different structures. A cup-shaped Al_2O_3 volumetric solar receiver was proposed by Meng et al. [25]. The numerical simulation and experiment presented that the cup-shaped design is beneficial for limiting the heat loss and decreasing the maximum solid temperature, which leads to a uniform temperature distribution of the receiver. Thermal performance evaluation of different absorber configurations for a volumetric solar receiver was conducted by Roldán et al. [26]. Receivers with constant porosity, gradual porosity in the radial direction, and gradual porosity according to depth were investigated with local thermal equilibrium (LTE) model. The simulation results showed that the decreasing porosity according to depth is the best design which exhibited higher thermal efficiency and lower thermal gradient. Chen et al. [27] studied the volumetric solar receiver with composite porous structure. Different geometrical parameters such as porosity and mean cell size in the near-wall region influenced significantly the thermal performance of the receiver.

From the above literature review, it could be concluded that the current numerical simulations of volumetric solar receiver were mainly focused on the parametric study of a single parameter to the heat transfer process. However, these parameters influence the heat transfer process collectively and a combination of analytical results for the single parameter could not guarantee the best thermal performance of the volumetric solar receiver. The method to select the appropriate parameters which guarantee a high efficiency of the volumetric solar receiver is not proposed in the previous studies.

Therefore, in this paper, a method which couples the optimization algorithm and heat transfer analysis is proposed to select the appropriate parameters that guarantee the best performance of the porous volumetric solar receiver. In part 2, the numerical model of the fluid flow and heat transfer for the volumetric solar receiver is reviewed. In part 3, the coupling method of the optimization algorithm and the numerical model in part 2 is presented. The solution procedure is elaborated in detail. In part 4, the optimization results under different simulation conditions are presented and analyzed.

2. Numerical model

2.1. Governing equations and empirical parameters

To investigate the fluid flow and heat transfer characteristics inside the porous volumetric solar receiver, the mass conservation equation, momentum equation, and energy equations of both fluid phase and solid phase need to be solved simultaneously. The effects that brought by the porous structure to the fluid flow and