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Heat transfer analysis of a volumetric solar receiver with composite porous structure

Xue Chen [a,b], Xin-Lin Xia [b,*], Xue-Wei Yan [c], Chuang Sun [b]

[a] School of Energy and Power Engineering, Northeast Electric Power University, 169, Changchun Street, Jilin 132012, PR China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, PR China
[c] School of Chemical Engineering, Northeast Electric Power University, 169, Changchun Street, Jilin 132012, PR China

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ABSTRACT

A volumetric solar receiver with composite porous structure is proposed, where a porous foam with different pore parameters from that in the other region of receiver is placed in the inlet near-wall region. Thermal performance of the solar receiver is numerically investigated. The local thermal non-equilibrium model is utilized to represent the energy transport within the porous foam. Radiative transfer in the porous foam due to high temperature combined with the transport of concentrated solar radiation inside the receiver is solved using the P1 approximation. Thermal behavior comparison is made between the receiver with composite porous structure and that with single porous layer. The effects of different pore parameter designs are discussed. The results indicate that there exists a large temperature gradient in the solid phase for a solar receiver with single porous layer. Using low porosity and small mean cell size in the inlet near-wall region for the receiver with composite porous structure can reduce the solid temperature gradient and increase the mean fluid outlet temperature.

1. Introduction

Volumetric solar receiver with high-porosity material is the key component in the solar thermal applications, such as electricity generation [1] and hydrogen production [2]. Due to the porosity and large extinction volume, the incoming concentrated solar radiation penetrates into the receiver and is volumetrically absorbed inside the porous material. The absorbed heat is then transferred by convection to a working fluid when the fluid passes through the porous structure [3]. A high-performance receiver should minimize the power losses by reflection and re-emission, promote radiation propagation and encourage the heat transfer to the working fluid [4]. Therefore, the choice of receiver characteristics (material, geometrical parameters and configuration) is crucial to the solar-to-thermal conversion efficiency [5]. Besides, a comprehensive understanding of the complex coupled heat transfer mechanism within the receiver is also important.

Several studies have been conducted to investigate the heat transfer performance of volumetric solar receivers, in order to optimize the design and increase the efficiency. One dimensional analysis of the heat transfer process inside a ceramic foam receiver was performed by Bai [6]. Villafán-Vidales et al. [7] developed a numerical model to predict the heat transfer inside the volumetric solar receiver, coupling the fluid flow, heat and mass transfer and the chemical reactions. The influences of porosity, average particle diameter, thickness and inlet velocity on the heat transfer characteristics of a porous media solar tower receiver were outlined by Xu et al. [8]. Wu et al. [9] obtained the temperature distributions in a volumetric solar receiver by modeling the fully coupled heat transfer. A solar absorber was simulated by Gómez et al. [10] with the discrete ordinates method to solve the radiative flux. The Monte Carlo Ray Tracing (MCRT) and Finite Volume Method (FVM) coupling method was employed by Cheng et al. [11] to simulate the heat transfer in a solar receiver with the local thermal equilibrium (LTE) model. Using MCRT and FVM, Wang et al. [12,13] predicted the temperature fields in the porous media receivers with single dish and multi-dish collectors, respectively. A simplified one-dimensional model was developed by Kribus et al. [14] to investigate the potential performance of volumetric receivers as a function of geometry and material properties. Using the Bouguer-Beer-Lambert law to model the radiative transfer, heat transfer in a SiC ceramic foam receiver was analyzed by Andreozzi et al. [15] with the local thermal non-equilibrium (LTNE) model. A one-dimensional unified heat transfer model was presented by Wang et al. [16] for the energy transport analysis in a pressurized volumetric receiver. The solar receiver with single porous layer which has uniform property parameters is investigated in the above

* Corresponding author.
E-mail addresses: Hit_chenxue@163.com (X. Chen), Xiaxl@hit.edu.cn (X.-L. Xia).

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Nomenclature

c_p	specific heat, J kg^{-1} K^{-1}
d_c	mean cell size, mm
F	source term of momentum equation
G	integrated intensity, W m^{-2}
h_v	volumetric heat transfer coefficient, W m^{-3} K^{-1}
L	length of receiver, m
p	pressure, Pa
q	heat flux, W m^{-2}
R	radius of receiver, m
Re	Reynolds number
s_1, s_2	dimension of region II, m
S_r	source term of energy equation
T	temperature, K
$\vec{U}$	superficial velocity, m s^{-1}
$\vec{U}_p$	physical velocity, m s^{-1}
u	velocity in x direction, m s^{-1}
v	velocity in r direction, m s^{-1}
x, r	coordinates in flow region, m

Greek symbols

ε	emissivity
κ_a	absorption coefficient, m^{-1}
κ_s	scattering coefficient, m^{-1}
κ_e	extinction coefficient, m^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	Stefan-Boltzmann constant
τ	optical thickness
χ	conduction-radiation parameter
ϕ	porosity

Subscripts

e	effective
f	fluid
in	inlet
r	radiation
s	solid
w	wall

researches. Besides, they mainly focus on the temperature distribution along the flow direction.

The design concept of composite porous structure in the solar receiver has been adopted by a few researchers. Fend et al. [17] conducted an experimental study and found that double-layer foam materials with different cell densities along the flow direction could achieve a high efficiency. Gradual-porosity configurations were numerically studied by Roldán et al. [18] based on an exponential law of solar radiation extinction with the LTE model. Using the P1 approximation, Chen et al. [19] analyzed the effects of structural parameters in each porous layer on the thermal performance of solar receiver with double-layer ceramic foam along the flow direction. Additionally, a newly designed cup-shaped Al_2O_3 porous receiver was numerically studied by Meng et al. [20], using the energy balance and view factor concept to solve the inner radiative exchange.

From the literature survey, it can been seen that the thermal behavior of solar receiver with single porous layer has been extensively investigated. Moreover, the flow and heat transfer processes in the solar receiver are very complicated, and the coupled heat transfer problem is simplified to one dimension in some investigations. The other mostly focus on the temperature variation along the flow direction, whereas the radial distribution is scarcely analyzed. In addition, the investigations on solar receiver with different pore parameter combinations are very limited. Due to the non-homogeneous solar intensity at the focal plane and large extinction of the porous structure, the high temperature part mainly occurs at the central region near the front surface of receiver. Thus, for the solid phase, there may exist high temperature gradient in the inlet region, which may cause hot-spots and high levels of stresses, even a material failure [21]. For instance, a temperature difference nearly 1000 K on the front surface can be found from the experimental data in Ref. [9], while nearly 750 K from the simulation results in Ref. [22]. On the other hand, the heat loss by re-emission may account for a large part of the overall losses in the process of solar thermal conversion. In this study, a volumetric solar receiver with composite porous structure is proposed, adding a porous foam with different pore parameters in the inlet near-wall region (see Section 2) in order to reduce the solid temperature gradient. The temperature field is predicted using the LTNE model with P1 approximation [9,23]. The thermal behavior and the effects of pore parameters are discussed.

2. Solar receiver description

The solar receiver investigated in this study is schematically depicted in Fig. 1. Due to the symmetry of receiver geometry, a two-dimensional axisymmetric problem is considered here. The length and radius are L and R ($L = 0.05$ m, $R = 0.03$ m), respectively. Two regions are included: region I has a porous foam with the pore parameters (porosity and mean cell size) ϕ_1, d_{c1}, and the inlet near-wall region (region II: $0 \leqslant x < s_1, s_2 \leqslant r \leqslant R$) with the pore parameters ϕ_2, d_{c2}. The front surface of receiver is exposed to highly concentrated solar radiation, which may penetrate into the porous structure causing a gradual temperature rise. The lateral walls of the solar receiver are surrounded by an insulator.

3. Mathematical model and methods

3.1. Governing equations

Several assumptions are employed: (1) the flow is steady and incompressible [9,13], (2) the porous foam is considered as a gray, absorbing, emitting and isotropic scattering medium, (3) the

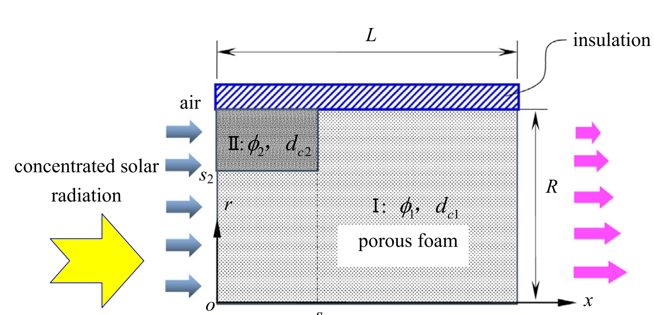

Fig. 1. Schematic diagram of heat transfer in the volumetric solar receiver with composite porous structure.