Energy Conversion and Management 97 (2015) 282–289

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal performance analysis on a volumetric solar receiver with double-layer ceramic foam

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ARTICLE INFO

Article history:
Received 24 December 2014
Accepted 18 March 2015
Available online 2 April 2015

Keywords:
Volumetric solar receiver
Ceramic foam
Radiative transfer
Local thermal non-equilibrium

ABSTRACT

Using porous materials has become an effective means to enhance heat transfer. Volumetric receiver is a key component inside the solar thermal systems. The novel concept using double-layer ceramic foam holds great potential for improving the efficiency. The current study aims to investigate the effects of geometric properties of each porous layer on the thermal performance. The local thermal non-equilibrium model is adopted for energy equations of the fluid and solid phases. Radiative transfer in the foam combined the concentrated solar radiation absorption is solved with the modified P1 approximation. The results indicate that the thickness of the first porous layer has significant effect on the temperature field and pressure drop. Compared with the increasing-porosity configuration, the decreasing-porosity configuration tends to achieve higher air outlet temperature and lower solid inlet temperature. In addition, the increasing design of mean cell size shows improved performance compared to the decreasing design.
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1. Introduction

Volumetric receivers with high-porosity materials appear to be the best alternative to tube receivers and are widely used in solar thermal utilization, such as hydrogen production and electricity generation [1]. Due to the low bulk density, large specific surface and high permeability, ceramic foams have been regarded as the promising materials [2]. A good receiver produces the so-called volumetric effect, which means that lower temperature could be found at the front surface in comparison with the outlet of receiver [3]. Additionally, solar-to-thermal efficiency and its influencing factors are crucial to the entire system [4]. An efficient solar receiver is characterized by both higher outlet temperature of the working fluid to give higher efficiency and lower maximum temperature to avoid the destruction of material [2]. Analysis of the complex coupled heat transfer in the porous structure has shown to be virtually significant in the optimal design of configuration, which has attracted a great deal of interest [5].

Several studies have been done to predict the thermal behavior of solar receiver with a single layer of porous media. Becker et al. [6] investigated the heat transfer performance and flow stability in porous material theoretically and numerically. A one-dimensional model was presented by Bai [7] to elucidate the influence of air velocity, porosity, pore diameter and thickness on the performance of porous media receiver. The numerical heat and mass transfer analyses with preferable volume convection heat transfer coefficient were conducted by Xu et al. [8]. Using local thermal non-equilibrium (LTNE) model with P1 approximation, the steady temperature distributions of solar air receiver were simulated by Wu et al. [9]. A fully coupled transient model was then built by Wu and Wang [10]. Analytical solution of the combined heat transfer within the receiver with Rosseland approximation and LTNE model was developed by Sano et al. [11]. The effect of thermal radiation in porous media in the presence of LTNE convection for a solar air receiver was analyzed by Wang et al. [12]. The impacts of variation in heat transfer model and thermophysical characteristics model of gas mixture on thermal performance were studied by Wang et al. [13]. Furthermore, some researchers developed the Monte Carlo Ray Tracing (MCRT) and Finite Volume Method (FVM) coupling method to study the heat transfer characteristics [14]. MCRT was used to simulate the transport of solar radiation [15]. Numerical study of a parabolic trough receiver was performed by Wu et al. using the MCRT and FVM coupling method [16]. Most of the previous investigations mainly focus on the effects of geometric parameters, thermophysical properties and operating parameters on the temperature difference between the fluid and solid matrix, rather than how to obtain a practically applicable optimal design.

Meanwhile, different porous materials have been tested and Fend et al. [17] reported that double-layer ceramic foam shows improved performance compared to a single layer material. The

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http://dx.doi.org/10.1016/j.enconman.2015.03.066
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approach combining two foam materials of different cell density was proposed in their experimental research. This concept of multi-layer can also be found in the research fields of transpiration cooling and combustion [18]. Various gradual- and constant-porosity configurations were numerically studied with local thermal equilibrium (LTE) model by Roldán et al. [19]. Besides, the radiative transfer in the porous media due to high temperature is not taken into account in their study. However, thermal radiation plays a dominant role in the heat transfer when the porous is in a high temperature environment [20]. This type of volumetric receiver consists of several parts with different porous structure. The variation in structural parameters of each layer may have a strong impact on the flow and thermal behavior, which needs a comprehensive investigation.

The flow and heat transfer simulation of a solar receiver with double-layer ceramic foam is performed in this study. Radiative heat transfer is computed with the modified P1 approximation, and the LTNE model is used to calculate the fluid and solid temperature distributions [21]. The effects of geometric parameters of each porous layer on the thermal performance are mainly discussed.

2. Solar receiver description

As shown in Fig. 1, the solar receiver consists of a cylindrical chamber (L = 0.04 m, R = 0.02 m) that contains two layers of porous ceramic structure. The front surface is subjected to concentrated solar radiation. Solar energy is absorbed in the ceramic foam gradually along the axial direction. The absorbed heat is transferred to the air stream when air passes through the ceramic foam. If strong attenuation of solar radiation occurs in the first layer, the solid matrix may reach a high temperature, which leads to local overheating. Otherwise, solar radiation penetrates deeper into the receiver causing a gradual temperature rise. Therefore, an optimized combination of geometric properties as well as material properties is necessary.

3. Mathematical model

The numerical model of combined flow and heat transfer in the solar receiver is based on several assumptions: (1) the air flow is steady and incompressible, (2) the properties of ceramic foam in each layer are constant and homogeneous and the thermal contact resistance between them is neglected, (3) the foam is considered as a gray, optically thick, absorbing, emitting and isotropic scattering medium, and (4) lateral walls of solar receiver are well adiabatic.

3.1. Governing equations

3.1.1. Mass conservation equation

$$\nabla \cdot (\rho_f \vec{V}) = 0 \tag{1}$$

where ρ_f denotes the fluid density and $\vec{V}$ is the superficial velocity.

3.1.2. Momentum conservation equation

Flow in porous media is modeled by adding a momentum source term to the standard fluid flow equations, which can be deduced and written as [22]:

$$\frac{1}{\phi}\nabla\left(\rho_f \frac{\vec{V}\cdot\vec{V}}{\phi}\right) = -\nabla p + \nabla\cdot\left(\frac{\mu_f}{\phi}\nabla\vec{V}\right) + \vec{F} \tag{2}$$

In this equation, p represents the pressure of fluid, μ_f is the dynamic viscosity, ϕ is the porosity, and $\vec{F}$ denotes the pressure drop resulting from porous media. For homogenous porous media, it can be written as $\vec{F} = -\left(\frac{\mu_f}{K_1}\vec{V} + \frac{\rho_f}{K_2}|\vec{V}|\vec{V}\right)$, where K_1 and K_2 are the permeability and inertial coefficient respectively. The model proposed by Wu et al. [23] is used here. The relationships to describe the two parameters are $K_1 = d^2/(1039 - 1002\phi)$ and $K_2 = d/(0.5138\phi^{-5.739})$, where d is the mean cell size. The correlations are valid for $0.66 < \phi < 0.93$, $10 < Re < 400$ ($Re = \rho_f u d/\mu_f$) and a cross-section of the pore channel that approaches a circle.

3.1.3. Energy equation

The LTNE model is employed to represent the energy transport within porous media [24]. For the fluid phase:

$$\nabla\cdot(\rho_f c_p \vec{V} T_f) = \nabla\cdot(\lambda_{fe}\nabla T_f) + h_v(T_s - T_f) \tag{3}$$

For the solid phase:

$$0 = \nabla\cdot(\lambda_{se}\nabla T_s) + h_v(T_f - T_s) - \nabla\cdot\vec{q}_r \tag{4}$$

where T_f and T_s are the fluid phase and solid phase temperature respectively, c_p is the specific heat of fluid, $\nabla\cdot\vec{q}_r$ is the volumetric heat source term due to radiation. λ_{fe} and λ_{se} are the effective thermal conductivity of the fluid phase and solid phase respectively, which could be determined using the Schuetz–Glicksman empirical formulas [25]:

$$\lambda_{fe} = \phi\lambda_f \tag{5}$$

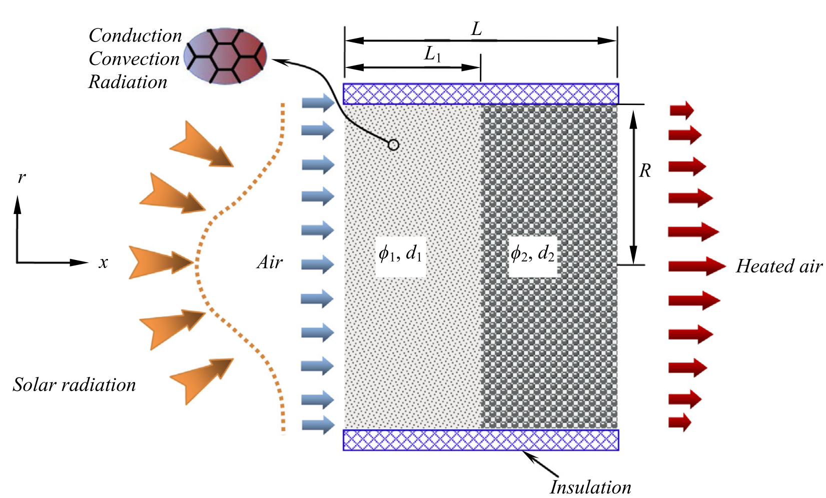

Fig. 1. Schematic of solar receiver with double-layer ceramic foam.

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