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Technical Note

Numerical investigation on porous media heat transfer in a solar tower receiver

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ABSTRACT

In order to investigate the steady heat transfer characteristics of a porous media solar tower receiver developed in China, this paper applies the steady heat and mass transfer models of the porous media to solar receivers, chooses the preferable volume convection heat transfer coefficient model, solves these equations by using the numerical method, and analyzes the typical influences of the porosity, average particle diameter, air inlet velocity, and thickness on the temperature distribution. The following conclusions have been drawn: in the same position or relative position along the downstream, the bigger the average particle diameter is, the higher the solid matrix dimensionless temperature is, the higher the air dimensionless temperature is. The bigger the porosity is, the lower the solid matrix dimensionless temperature is, the bigger the porosity is, the higher the air dimensionless temperature is. The bigger the thickness is, the lower the solid matrix dimensionless temperature is, the higher the air dimensionless temperature is. In a certain depth, the bigger the air inlet velocity is, the higher the solid matrix dimensionless temperature is. After a certain depth, the bigger the air inlet velocity is, the lower the solid matrix dimensionless temperature is, and the bigger the air inlet velocity is, the higher the air dimensionless temperature is. The paper can provide a reference for this type of receiver design and reconstruction.

1. Introduction

Solar power tower plant (SPTP) is a promising approach for solar thermal utilization that supplies the high temperature air for Brayton cycle power generation. The air receiver in SPTP is the main component of the system, in which the concentrated solar energy is absorbed and transferred to the working media [1–3]. Since the 1980s, the high temperature air receiver has attracted much attention in research and development. Different types of air receivers were examined. However, most receivers are volumetric receivers in which solar radiation is absorbed. According to air medium receiver, when air passes through the receiver, the forced convection heats the air and it reaches 800 to 1000 °C at the outlet. Control strategies were developed to achieve an automated process during startup, steady and transient operations, and shutdown of the SPTP [4,5]. Technology advancements in SPTP have enabled the solar thermal flux to reach 1 MW/m^2, with reduced weight and size of the receivers, shortened startup and transition time, and increased efficiency [6,7].

To further increase the receiver performance, porous media is considered. Buck et al. [8] studied the relationship between solar flux and flow speed in the receiver. Fend et al. [9] investigated the relationship between the pressure drop and porous media characteristics of the receiver. Becker et al. [10] investigated the flow stability in the receiver and Pitz-Paal et al. [11] researched the performance and flow stability of different types of open volumetric absorbers under non-homogeneous irradiation. These studies concluded that porous media is a form factor for the solar volume receiver. In this paper, silicon carbide (SiC) foam ceramic is considered.

SiC has high thermal conductivity, strong strength, high thermal shock resistance, and high antioxygenic properties, and it can be molded to form three-dimensional honeycomb-structured receivers. The honeycomb structure was shown to achieve high (volumetric) efficiency convective heat transfer for the SPTP [12]. Fig. 1 shows the micro structure of SiC foam ceramic made by the Chinese Academy of Sciences. This novel material, which is also cost competitive, will be used to fabricate the high temperature solar receivers. This paper reports a numerical analysis that characterizes the performance of SiC foam ceramic receivers. The effects of foam ceramic porosity, average particle diameter, air inlet velocity and thickness on the temperature distributions of the receiver are investigated.

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Nomenclature

ρ_f	density of the fluid (kg/m^3)
x, y	coordinates in the flow region (m)
u	velocity in streamwise (x-direction) (m/s)
v	velocity in cross-stream direction (y-direction) (m/s)
p	pressure (Pa)
d_p	average particle diameter (mm)
T	temperature (K)
c	specific heat (J kg^{-1} K^{-1})
h_v	volumetric convection heat transfer coefficient (w m^{-3} K^{-1})
h_{sf}	heat transfer coefficient between the fluid and the porous matrix (w m^{-2} K^{-1})
Pr	Prandtl number
k	permeability coefficient of the porous media
F	inertia coefficient of the porous media
q	heat flux (w m^{-2})
A	heat absorbing surface area (m^2)
RE_d	Reynolds number, $Re_d = \varepsilon \rho_f u_p d_p / \mu_f$
Re_h	Reynolds number, $Re_h = Re_d/(1-\varepsilon)$
k_f	thermal conductivity of the fluid (w m^{-1} K^{-1})
Nu_{sf}	Nusselt number for convection heat transfer between solid matrix and the fluid

Greek symbols

ε	porosity
μ	dynamic viscosity (N s m^{-2})
λ	thermal conductivity (w m^{-1} K^{-1})
α_{sf}	specific surface area of per unit volume (m^{-1})
θ	dimensionless temperature
β	correction coefficient

Subscripts

eff	effective
f	fluid
s	solid
p	particle
w	wall
ref	reference
sf	between solid and fluid
0	inlet
L	thickness or outlet

There are four types of volume convection heat transfer coefficient models for porous media heat transfer described in literature. However, no investigations show which one is preferable in the context of porous media solar tower receivers. Meanwhile, there is no numerical research on the heat transfer characteristics of the porous media solar tower receiver from the literature. This paper develops the steady mass and heat transfer models of the porous media solar receiver, chooses the preferable volume convection heat transfer coefficient model, solves these equations by using the numerical method, and analyzes the typical influences of the porosity, average particle diameter, air inlet velocity, and thickness on the temperature distributions.

2. Mathematical model

The foam ceramic receiver surface absorbs the solar thermal radiation. The heat is conducted along the solid matrix. When air passes through the porous media, heat is transferred from solid matrix to air. The flow and heat transfer can be simplified to two dimensions. The heat transfer process is described in Fig. 2.

The main assumptions behind the mathematical model are (i) steady and incompressible flow, (ii) homogeneous properties of the gas and solid phase, and (iii) constant properties of the gas and solid phase. Following [13], the thermal equilibrium assumption is not made. Conversely, the gas and solid phases can be at different temperatures, and the local thermal non-equilibrium equations are used. The resultant transport models are as follows.

2.1. Continuity equation

$$\frac{\partial\left(u\rho_f\right)}{\partial x}+\frac{\partial\left(v\rho_f\right)}{\partial y} = 0 \quad (1)$$

where ρ_f is the fluid density, u and v are velocities in streamwise (x-direction) and cross-stream direction (y-direction).

2.2. Momentum equation

The momentum exchange in porous media was calculated by Brinkman–Forchheimer Extended Darcy equation [14–16]:

$$\frac{\rho_f}{\varepsilon}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x}+\mu_{eff}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\left(\frac{\mu_f}{k}+\frac{\rho_f F\varepsilon}{\sqrt{k}}u\right)u \quad (2)$$

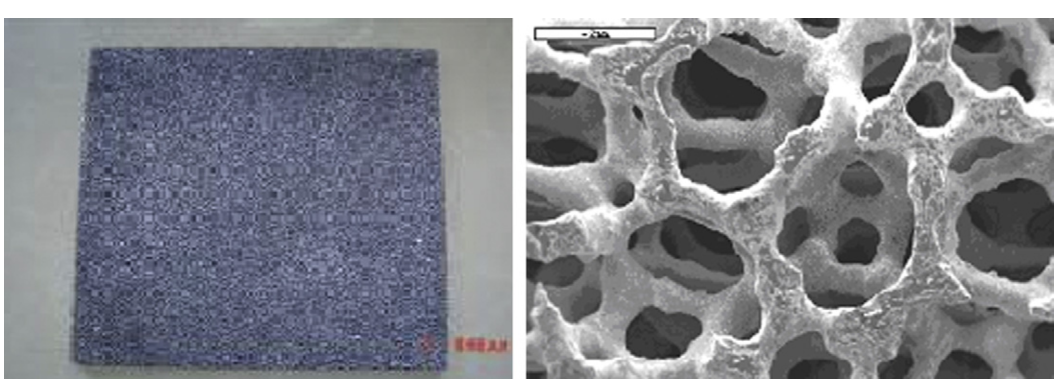

Fig. 1. SiC porous foam ceramic structure made in Academy of Chinese science.