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Numerical simulation of fluid flow and convection heat transfer in sintered porous plate channels

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Abstract

Fluid flow and convective heat transfer of water in sintered bronze porous plate channels was investigated numerically. The numerical simulations assumed a simple cubic structure formed by uniformly sized particles with small contact areas and a finite-thickness wall subject to a constant heat flux at the surface which mirrors the experimental setup. The permeability and inertia coefficient were calculated numerically according to the modified Darcy's model. The numerical calculation results are in agreement with well-known correlation results. The calculated local heat transfer coefficients on the plate channel surface, which agreed well with the experimental data, increased with mass flow rate and decreased slightly along the axial direction. The convection heat transfer coefficients between the solid particles and the fluid and the volumetric heat transfer coefficients in the porous media predicted by the numerical results increase with mass flow rate and decrease with increasing particle diameter. The numerical results also illustrate the temperature difference between the solid particles and the fluid which indicates the local thermal non-equilibrium in porous media.

Keywords: Fluid flow; Convection heat transfer; Porous media; Permeability; Inertia coefficient; Temperature distributions

1. Introduction

Fluid flow and convection heat transfer in porous media have been widely investigated experimentally and numerically for many years due to the many important applications, such as catalytic and chemical particle beds, petroleum processing, geothermal energy extraction, transpiration cooling, packed-bed regenerators, solid matrix heat exchangers, micro-thrusters and many others. Porous media can intensify fluid mixing and increase the surface area in contact with the coolant, so porous structures are an effective heat transfer augmentation technique.

There have been numerous investigations with theoretical analyses and numerical simulations of convection heat transfer in fluid-saturated porous media. Vafai and Tien [1] investigated the nature and importance of the boundary and inertial effects on the flow and heat transfer in porous media. They showed that for the flow field, the boundary effects are confined to a very thin momentum boundary layer and often have no significant effect on the overall flow field. The effect of the boundary on the heat transfer, however, can be quite important. The inertial effects increase with permeability and decrease with fluid viscosity. The velocity gradients tend to increase near the wall, thereby increasing the viscous resistance at the boundary. The influence of the non-Darcian effects, variable porosity, variable properties and thermal dispersion in the porous medium on the fluid flow and heat transfer have been widely studied [2–7]. A comprehensive review of the heat and fluid flow characteristics in packed beds was published by Achenbach [8].

Numerical simulations of convection heat transfer in porous media are normally based on two different models for the energy equation, i.e. the local thermal equilibrium model and the local thermal non-equilibrium model. In recent years, the local thermal non-equilibrium model has

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Nomenclature

a	Forchheimer parameter (1/m)
c_p	specific heat (J/kg K)
D_e	porous plate channel hydraulic diameter (m)
d_p	particle diameter (m)
F	inertia coefficient
h_{sf}	heat transfer coefficient between solid particles and fluid (W/m^2 K)
h_v	volumetric heat transfer coefficient (W/m^3 K)
h_x	local heat transfer coefficient (W/m^2 K)
H	enthalpy (J/kg)
K	porous medium permeability (m^2)
L	channel length (m)
Nu	Nusselt number
Δp	pressure drop (Pa)
q_{w0}	heat flux (W/m^2)
Re	Reynolds number based on the particle diameter ($=\varepsilon \rho u_p d_p/\mu$)
T	temperature (K)
u	fluid velocity (m/s)
U	velocity vector (m/s)
x, y, z	coordinates (m)

Greek symbols

ε	porosity
λ	thermal conductivity (W/m K)
μ	absolute viscosity (N s/m^2)
ρ	fluid density (kg/m^3)

Subscripts

0	inlet
b	bulk mean temperature
f	fluid
i	interface
s	solid particle
w	wall
x	local

been used more frequently in theoretical and numerical research of convection heat transfer in porous media [7,9–11] to more accurately model the convection heat transfer processes in porous media. With the thermal non-equilibrium model, the volumetric heat transfer coefficients between the solid particles and the fluid in the porous media and the treatment of the boundary conditions for the energy equation significantly affect the numerical simulation results. A number of papers have analyzed this problem [11–19]. Golombok et al. [20] employed the heat regenerator technique to measure the heat transfer coefficient between the flowing gas and the metal fibers of a burner. Their results showed that the heat transfer coefficient for laminar flow increased rapidly with increasing gas flow. Vafai and Sozen [21] analyzed the thermal-fluid characteristics for flow through a packed bed of spherical particles using fluid-to-solid heat transfer coefficients from an empirical correlation established by Gamson et al. [22]. Their results showed that the local thermal non-equilibrium condition was very sensitive to the particle Reynolds number and the Darcy number. Ichimiya [23] evaluated the convective heat transfer between the fluid and the solid material of aluminum–ceramic foam by comparing the measured and predicted Nusselt numbers on the heated wall of a porous channel. The constant heat flux boundary condition in porous media can be applied in several different ways. Alazmi and Vafai [11] analyzed eight different forms of constant wall heat flux boundary conditions in the local thermal non-equilibrium model. They found that different boundary conditions may lead to substantially different results, and selecting one model over the others is not an easy issue. In addition, the mechanics of splitting the heat flux between the two phases is not yet resolved.

Jiang et al. [17–19,24] experimentally and numerically investigated forced convection heat transfer of water and air in plate channels filled with non-sintered porous media (packed beds) or sintered porous media using a local thermal non-equilibrium model. They investigated the influences of boundary conditions on the convection heat transfer in porous media and the differences between the convection heat transfer in sintered and non-sintered porous media. Their results showed that for numerical simulations of convection heat transfer in porous media, the boundary condition model significantly influences the numerical results and the proper model must be chosen for the numerical simulation to agree well with the experimental data.

The present paper presents numerical simulations of the fluid flow and convection heat transfer in a simple cubic structure formed by uniform particles with small contact areas in a channel with a finite-thickness wall subject to a constant heat flux at the surface. The purpose of this study is to numerically determine the permeability, K, the inertia coefficient, F, the local heat transfer coefficient on the plate channel surface, h_x, the convection heat transfer coefficients between the solid particles and the fluid, h_{sf}, and the volumetric heat transfer coefficient, h_v, for convection heat transfer in porous media. The temperature distributions in the porous media are also analyzed. To the best of our knowledge, there is no other such analysis in the literature of the convection heat transfer in porous media. The direct numerical simulations of the fluid flow and convection heat transfer in porous media in the present paper establish a very good basis for further investigations of the boundary characteristics and internal phenomena controlling heat transfer in porous media.