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Numerical investigation on forced convection of tubes partially filled with composite metal foams under local thermal non-equilibrium condition

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ABSTRACT

In the present study, fully developed forced convection in tubes partially filled with composite metal foams (CMFs) is numerically investigated. In the CMF region, the Brinkman extended Darcy flow model and the local thermal non-equilibrium model are used to predict fluid and thermal transport. At the foam-foam interface in CMF, fluid temperature and solid energy are assumed to be continuous. At the foam-fluid interface, no-slip coupling conditions are used to couple flow and heat transfer of the foam and free regions. Governing equations are solved numerically with SIMPLE algorithm. Momentum and energy equations are discretized using the SGSD finite volume scheme for convective terms. Velocity distribution, temperature profile, the friction factor and Nusselt number in partially-filled CMF tubes are obtained. The results indicate that, porosity gradient has little effect on the friction factor at a low pore density, but the effect increases with increasing pore density. For the fixed pore density gradient, Nusselt number decreases with increasing porosity, and Nusselt number firstly increases sharply and then increases lineally with increasing Reynolds number. For the fixed material gradient, Nusselt number increases lineally with increasing Reynolds number.

1. Introduction

Porous media has been widely used in the passive cooling technology. Forced convection and fluid flow through the porous media have a wide range of applications in engineering fields such as combustion, solar energy storage, purification processes, cryogenic cooling, petroleum industries, geothermal energy extraction, and heat transfer enhancement. Open-celled uniform metal foams (UMFs) are the specially man-made porous media with high surface area density (500–7500 m^2/m^3 [1]) and can be made into compact heat exchangers, chemical reformers, heat sinks, and efficient combustor [1–3] due to the advantages of high porosity, high solid thermal conductivity, and strong flow-mixing capability by tortuous flow passages. The scientific problem of fluid flow and heat transfer performance for UMFs has been investigated by many researchers [4–7]. Hsieh et al. [8] found that Nusselt number of uniform aluminum-foam in a pipe increases with the increase pore density. The experimental data obtained by Nazari et al. [9] indicated a significant improvement in the forced convective heat transfer due to flow of Al_2O_3/Water nanofluid through a circular tube filled with a UMF at the cost of a pressure drop increase. Hamadouche et al. [10] found that, compared with an empty channel with adopting lower velocity, inserting UMFs in a turbulent air flow improves the heat transfer by approximately 300%. Xia et al. [11] found that the volumetric heat transfer coefficients of Cu, Ni and SiC UMFs decrease with an increase in porosity and increase as pore density increases. As the potential porous media, composite metal foams (CMFs) developed by the present author [12,13] not only provide reasonable space for the expanding liquids or escaping growing bubbles due to enlarging pores vertical to a heating surface, but also have the advantages of high surface area, strong flow-mixing capability. CMFs are made by one uniform foam layer (bottom) and another uniform foam layer (top). To prevent oxidation of foam materials, the two uniform foam layers are sintered together by silver-copper alloy in a high temperature furnace full of argon under an atmospheric pressure. The research results [12,13] showed that, CMFs significantly enhance pool boiling heat transfer compared to single-layer uniform foams and the enhancement is heavily dependent on CMF layer thickness and pore density gradient. When the heat flux is less than a certain value, pool boiling heat transfer performance of copper-nickel foam is better than nickel-nickel foam due to the former's higher thermal conductivity. The enhancement degree of the three-layer CMF is lower than the double-layer CMF due to severe bubble escaping resistance. However, the opaqueness of metal skeletons and the complexity of the porous structure in CMFs increase the experimental measurement difficulty. In contrast to experimental study, numerical and theoretical investigation on forced convection in CMFs has the advantage of low cost.

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Nomenclature

a_{sf}	specific surface area, $m^2 \cdot m^{-3}$
c	specific heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$
d_f	fiber diameter, m
d_p	pore diameter, m
Da	Darcy number
f	friction factor
CMF	composite metal foam
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h_{sf}	local heat transfer coefficient at solid-fluid contacting surface, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
k_e	effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
K	permeability, m^2
L	tube length, m
m	material
Nu	Nusselt number
p	pressure, $N \cdot m^{-2}$
P	dimensionless pressure drop
Pr	Prandtl number
q_w	heat flux exposed to the tube wall, $W \cdot m^{-2}$
r	radius, m
r_i	interfacial radius for the foam-fluid interfacem
r_m	interfacial radius for the interface between two form layers of the composite metal foamm
r_o	tube radius, m
Re	Reynolds number
R	dimensionless radius
R_i	dimensionless interfacial radius
R_m	dimensionless interfacial radius for the interface between two form layers of the composite metal foam
R_o	dimensionless tube radius
T	temperature, K
u	velocity, $m \cdot s^{-1}$
U	dimensionless velocity
UMF	uniform metal foam
x	position along x direction, m

Greek symbols

ε	porosity
ω	pore density, PPI
μ	dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
θ	dimensionless temperature
ρ	density, $kg \cdot m^{-3}$
φ	polar angle, rad

Subscripts

b	bulk
e	effective/equivalent
f	fluid/fiber/foam
fe	effective value of fluid phase
g	gradient
i	interfacial
m	mean
s	solid
se	effective value of solid phase
w	wall
x	x position

In the past decades, thermal and flow characteristics in porous media with theoretical analyze and numerical simulations have been of interest to many researchers. The temperature difference between the fluid and solid is crucial in porous media applications [14]. The first approach in investigating the energy transport in porous media is to average over a representative elementary volume encompassing both the fluid and the solid phases (one-equation model), while the other approach requires a separate averaging over each of the phases (two-equation model) [15]. In essence, the one-equation model views the porous medium as a single continuum with negligible difference between the local fluid and solid temperatures throughout the system in consideration. This implies the existence of a local thermal equilibrium (LTE) between the two phases. The local thermal equilibrium is based on a representative elementary volume which is of a macroscopic scale [15]. A number of analytical and numerical investigations to obtain temperature distributions in a porous medium are generally based on the assumption of local thermal equilibrium because the one equation model is simple and straightforward. Whitaker et al. [16–19] proposed a criterion for the validity of the assumption of local thermal equilibrium in the case where the conduction effect is dominant in a representative elementary volume (REV) enclosing both the fluid and the solid phases. Lee and Vafai [20] used analytical solutions to propose a criterion to validate the one-equation model by studying flow through a porous channel under constant heat flux condition. Kim et al. [21] found that the local thermal equilibrium assumption is valid in a porous medium heat sink when the effective thermal conductivity ratio approaches infinity and the Darcy number approaches zero. Even though investigations on forced convective flows through a porous medium have been conducted for many years, it is difficult to apply a general criterion for the local thermal equilibrium assumption validity to engineering problems [22]. Furthermore, the local thermal equilibrium assumption in the porous medium is valid when the solid phase temperature approaches to fluid phase temperature. However, in most cases, this assumption is not valid because of the temperature deviation between the solid and fluid phases by the advection and conduction effect. Thus, the local thermal equilibrium assumption should to be replaced by the local thermal non-equilibrium assumption which separately treats the solid and fluid phases. The two-equation energy model assigns individual local temperatures to the solid and the fluid, and requires the interstitial heat transfer coefficient between the two phases and the interfacial surface area [23].

In recent years, increasing attention is paid to the local thermal non-equilibrium model in a porous medium [24–28]. Jiang et al. [29,30] investigated forced convection in a channel filled with a porous medium by local thermal non-equilibrium model and found that the numerical results agree well with the experimental data. Nield et al. [31,32] analyzed velocity and temperature fields in a saturated porous channel and found that local thermal non-equilibrium reduces the Nusselt number at fluid-solid interface. Yanga et al. [33] found that local thermal non-equilibrium is essential for forced heat transfer in a tube with a heated wall covered with a porous medium layer. Dehghan et al. [34] used the perturbation method to analyze the local thermal non-equilibrium condition in the fluid saturated porous medium bounded by iso-thermal parallel. Shivakumara et al. [35] numerically studied the simultaneous effect of LTNE, vertical permeability heterogeneity, and non-uniform basic temperature gradient on the criterion for the onset of Darcy-Benard convection by the Galerkin method.

Although the research on fully filled porous tubes/channels is still very active, it is clear that it significantly enhances heat transfer with the expense of increasing pressure drops. Partial filling is a solution for the problem. Partial filled porous medium decreases the occupation of the flow volume and reduces pressure drops. In the past two decades, the research on partially filled porous tubes/channels has attracted considerable attention for various applications due to the hydraulic