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Flow and heat transfer characteristics of nanofluid flowing through metal foams

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ABSTRACT

Forced convective heat transfer of fluid (with nanoparticles) in metal-foam duct is numerically investigated and the velocity and temperature fields are obtained. The effects of some key parameters on flow and heat transfer of nanofluid in porous media are analyzed. For nanofluid in porous media, the feasibility of field synergy principle on convective heat transfer is examined and the mechanisms for related heat transfer enhancement are discussed. Results show that both pressure drop and *Nu* number for nanofluid in metal foams increase with an increase in volume fraction of nanoparticles. But the increasing amplitude of pressure drop increases while the increasing amplitude of *Nu* number decreases, which implies that heat transfer enhancement with nanofluid cannot offset pressure drop increase. Field synergy principle for pure fluid convection cannot guide the analysis of the heat transfer enhancement for nanofluid in metal foams, which calls for the modification of existing field synergy principle.

1. Introduction

Many basic methods are provided for heat transfer enhancement, such as decreasing thermal boundary layer thickness, increasing velocity gradient near heat-transfer wall, disrupting fluid flow, increasing velocity from laminar flow to turbulent flow, increasing extending surface of heated wall and changing physical properties of surface and fluid [1–5]. These theories have been, are being and will be used in every aspect in thermal engineering. Taking heat dissipation of electronics as an example, with rapid increase in heat flux and minimization of device volume, related thermal performance is being improved from air cooling to liquid cooling, from passive cooling to active cooling, from large-scale to mini/micro-scale, and from single-phase to two-phase cooling. Highly-efficient heat transfer enhancement techniques are urgently needed in engineering. For the modern heat exchangers, density of extending surface area on the heat transfer wall is in the rising trend [6]. Open-celled metal foam is a kind of materials with sufficiently-large surface area density (500–7500 $m^2\ m^{-3}$ [7]) and it is usually sintered on the solid-wall. Additionally, it owns other thermal advantages, such as high solid thermal conductivity, strong flow-mixing capability, high porosity and low-density, which makes it useful in compact heat exchangers and heat sinks, chemical reformers, solar collectors, and efficient combustor [7–9]. Growing attention has been paid on the metal foams in both scientific research and industrial applications. Recent applications include micro-channel condensers with metal-foam in the air side [10–12], flat-plate solar water collector with metal-foam block [13], finned metal-foam heat sinks [14], metal-foam catalyst support [15,16], and so on. The main scientific problem in these applications is related with transport phenomena in metal foams.

Previous transport models of conventional porous media, such as packed bed, granular media and rocks, are no longer applicable for metal foams due to the structure and porosity difference between the conventional porous media ($0.1 < \varepsilon < 0.6$) and metal foams ($\varepsilon > 0.85$). For flow in metal foams, Darcy model, Brinkman model or Forchheimer model may be used for specific velocity range and viscous effect of impermeable wall [8]. For heat transfer in metal foams, the local thermal equilibrium (LTE) model or the local thermal non-equilibrium (LTNE) model may be used in principle. However, the foam solid materials covering copper, aluminum, nickel, iron and their alloys, own the thermal conductivity range about 10–400 W/(m K) while thermal conductivities of the conventional working fluids, water and air, are respectively about 0.026 and 0.6 W/(m K), from which the thermal conductivity difference between solid and fluid is from about 17–15,384 times. For the metal-foam fully filled duct, as a more accurate model, the LTNE model must be used according to Lee and Vafai [17]. While for the duct partially filled with metal foams [3,4], due to relatively low velocity in the foam region, the temperature difference between solid and fluid phases is minimal and the LTE model may be

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Nomenclature

a_{sf}	specific surface area, m^{-1}
c	specific heat, J kg^{-1} K^{-1}
C_I	inertial constant
Da	Darcy number
E	dimensionless factor in appendix $((k_e + k_d)/k_{se})$
f	friction factor $((dp/dx \cdot 4H)/(\rho u_{in}^2))$
H	half height of the channel, m
h	heat-transfer coefficient, W m^{-2} K^{-1}
h_{sf}	local convective heat-transfer coefficient, W m^{-2} K^{-1}
K	permeability, m^2
k	thermal conductivity, W m^{-1} K^{-1}
k_d	dispersion thermal conductivity, W m^{-1} K^{-1}
k_f	fluid thermal conductivity, W m^{-1} K^{-1}
k_{nfe}	effective thermal conductivity of nanofluid, W m^{-1} K^{-1}
k_s	solid thermal conductivity, W m^{-1} K^{-1}
k_{se}	effective thermal conductivity of solid, W m^{-1} K^{-1}
L	channel length, m
Nu	Nusselt number
p	pressure, N m^{-2}
P	dimensionless pressure drop
PEC	performance evaluation criteria $(Nu/(Re \cdot (Pr \cdot f)^{1/3}))$
Pr	Prandtl number
q_w	wall heat flux, W m^{-2}
Re	Reynolds number $(Re = \rho \cdot u_{in} \cdot 4H/\mu)$
T	temperature, K
T_{fin}	fluid inlet temperature, K
u	velocity at x axis, m s^{-1}
v	velocity at y axis, m s^{-1}
u_{in}	inlet velocity, m s^{-1}
U	dimensionless x velocity
V	dimensionless y velocity
VOL	dimensionless volume
x	axial position, m

Greek symbols

γ	synergy angle, degree
ε	porosity
θ	dimensionless temperature
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ϕ	volume fraction
ω	pore density, PPI (pores per inch)

Subscripts

b	bulk
d	dispersion
e	effective
f	fluid
mf	metal foam
nf	nanofluid
np	nanoparticle
ref	reference
s	solid

employed. Related research on convective heat transfer has been implemented to some extent [8,18–20]. Xu et al. [8] theoretically investigated forced convective heat transfer in metal-foam filled parallel-plate channel and provided the ranges of foam parameters for saving energy. Lu et al. [18] presented convection heat transfer in metal foams in theory by treating the micro-structure of metal foam as the cubic cylinders perpendicular with each other and found that the thermal performance of metal foams is attractive even though with simplified model. Lu et al. [19] conducted analytical study on forced convection in metal-foam tubes and pointed out that metal foams have great thermal potential. Zhao et al. [20] conducted analytical study on forced convection in metal-foam annuli and found that the metal-foam double-pipe heat exchanger own more excellent thermal performance compared with the conventional finned tubular heat exchangers.

Even with attractive thermal performance for metal foams, heat transfer in metal foams still needs further enhancement by other assistant methods in some electronics and heat exchangers with high heat transfer rate. Adding nanoparticles into fluid, which can improve the fluid thermal conductivity, is such a direct method. Nanoparticle based coolant (nanofluid) was first proposed by Choi et al. [21] in Argonne National Laboratory of USA in the middle 90s of last Century, after which many investigators performed various studies on this area. Lazarus Godson et al. [22] presented the experimental study on the convective heat transfer of silver-water nanofluid in counter-flow heat exchanger from laminar to turbulent regime. Li and Xuan [23] experimentally investigated forced convection of Cu-water nanofluid in a tube and presented empirical correlations for laminar and turbulent flow. Bhadauria and Agarwal [24] presented the analytical and numerical study on linear and non-linear stability of nanofluid flow and heat transfer in porous media. Dalkilic et al. [25] reviewed the recent publications from 2003 to 2012 on forced convection of nanofluid in terms of empirical correlations, research methods and fluid mechanics and indicated that the experimental data for nanofluids of nanoparticles within refrigerants is absent due to the difficulty in establishing the pressurized test rig. They held that main reasons for heat transfer enhancement of nanofluid are the increase in thermal conductivity and chaotic movement of nanoparticles. Xuan and Roetzel [26] classified recent theoretical models of nanofluid into two types: (a) treating nanoparticle and base-fluid as a single-phase flow; (b) treating the nanoparticle and the base-fluid as two different phases. Choi [27] pointed out that the heat transfer enhancement effect of nanofluid is more obvious compared with other enhancing techniques, but the understanding for transport mechanisms of nanofluid is still poor.

Aiming at combining the flow-mixing capability of 3-D metal foams with the obvious improvement in fluid thermal conductivity of the ultrafine particles, this paper presents a numerical analysis on the forced convective heat transfer of nanofluid in metal-foam channels with the LTNE model, which can be used in the cooling of high heat flux electronics with large temperature difference heat exchangers. The effects of porosity, pore density and volume fraction on the overall heat transfer are analyzed. Effects of nanofluid and metal foam on enhancing convective heat transfer are discussed and the evaluation possibility of field synergy principle on this kind of dual heat transfer enhancement is explored.

2. Problem description

The schematic diagram of metal-foam channel for nanofluid forced convection is shown in Fig. 1(a) and the practical structure of metal foam (copper) is shown Fig. 1(b). The channel height is $2H$ and channel length is L. Constant heat flux q_w is imposed on the channel wall, which is dissipated with metal foams. The ultrafine