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Analytical considerations of local thermal non-equilibrium conditions for thermal transport in metal foams

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A B S T R A C T

As a new-type extending surface, metal foam owns great potential in next generation heat transfer technologies. Convective heat transfer performance in metal foams is numerically investigated based on the local thermal equilibrium (LTE) model and the local thermal non-equilibrium (LTNE) model. The solid–fluid temperature difference and relative deviation are put forward for quantifying LTNE effect. The effects of basic parameters on heat transfer are analysed in depth and the LTNE conditions in metal-foam tube for efficient heat exchangers are summarized. It is indicated that the relative deviation is a more suitable criterion for LTNE effect in metal foam than the solid–fluid temperature difference. The LTNE effect in metal foam is conspicuous for low porosity, large fluid–solid thermal conductivity difference, small duct size, low pore density, and low Reynolds number. Measures lowering proportion of local convective thermal resistance in total thermal resistance, or the ratio of thermal resistance of solid to that of fluid can weaken LTNE effect in metal foam. There is no necessary relationship between thermal performance of metal-foam heat exchangers and corresponding LTNE effect. Clarifying LTNE conditions in porous foams can lay a foundation for the demarcating criterion of LTE/LTNE models. This can also guide quick and accurate thermal design and verification of metal-foam heat exchangers.

1. Introduction

With ever-growing scale of industry and advancing technology frontiers, the standard for thermal performance of heat transfer equipments is continuously being improved. In electronics cooling, the unceasingly enhanced transistor integration not only requires larger heat dissipation capability but also calls for further miniaturization (bellow 1 mm) in compact electronic circuits and highly integrated devices. In thermal energy utilization field, efficient heat transfer techniques for heat exchanger design can improve both energy utilization efficiency and compactness of heat exchangers. For thermal control of space vehicles, the size and performance of thermal control system requires thoughtful design in order to accommodate the substantially temperature change in outer space and the limited vehicle volume.

Thus, heat transfer enhancement technologies with improved thermal performance and more compact volume are urgently called for in order to ease the global energy crisis. In history, heat transfer enhancement goes through 1st generation with bare surface [1], 2nd generation with 2-D fins [2] and 3rd generation with 3-D fins [3]. In recent decades, metal foam is treated as an excellent candidate for next generation heat transfer techniques. This is due to its multi-functional advantages, such as high thermal conductivity, low density, high porosity, large area of expanded surface, strong flow-mixing capability, reliable mechanical performance amongst many others. Owing to these advantages, metal foam can be used in heat exchangers, heat sinks, fuel cells, solar thermal utilization, and so on [4–6]. As a naturally mimetic material, metal foam can be regarded as a special artificial porous medium in principle. Many different kinds of porous media exist in both nature and man-made world. The former group can be represented by porous sand, honeycomb and rocks with oil, while the latter includes lattice frame material, metallic fibre and metal foam, as shown in Fig. 1.

Fig. 2 shows the schematic diagram of convective heat transfer through metal foam ligaments with a significant temperature difference between solid and fluid [7]. When the low-conductive fluid flows across the highly-conductive foam ligaments in a heated

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Nomenclature

a_{sf}	surface area density, m^{-1}
c	heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$
C_I	inertial constant
Da	Darcy number
E	relative deviation
f	function
f_u, f_v	body forces respectively in u,v equations, $N \cdot m^{-3}$
h	convective heat-transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h_{sf}	local convective heat-transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h_x	local heat-transfer coefficient in the axial direction, $W \cdot m^{-2} \cdot K^{-1}$
K	permeability, m^2
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
k_d	dispersion thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
k_{fe}	fluid effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
k_r	thermal conductivity ratio, $k_r = k_f/k_s$
k_{se}	solid effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
L	tube length, m
L_r	aspect ratio, $L_r = L/r_0$
Nu	Nusselt number
Pr	Prandtl number
p	pressure, $N \cdot m^{-2}$
$\dot{q}$	internal volumetric heat source, $W \cdot m^{-3}$
Q	heat transfer rate, W
r,x	radial position and axial position respectively, m
r_0	tube radius, m
R,X	dimensionless radial position and axial position
R_{ct}	contact thermal resistance, $m^2 \cdot K \cdot W^{-1}$
R_{cv}	local convective thermal resistance, $m^2 \cdot K \cdot W^{-1}$
R_f	fluid conductive thermal resistance, $m^2 \cdot K \cdot W^{-1}$
R_p	conductive thermal resistance of porous composites in LTE model, $m^2 \cdot K \cdot W^{-1}$
R_s	solid conductive thermal resistance, $m^2 \cdot K \cdot W^{-1}$
Re	Reynolds number
Re_K	Reynolds number based on permeability
t	time, s
T	temperature, K
$T_{f,in}$	fluid inlet temperature, K
T_{fm}	fluid mean temperature, K
T_w	wall temperature, K
u,v	velocity components respectively at x,r directions, $m \cdot s^{-1}$
u_{in}	inlet velocity, $m \cdot s^{-1}$
U,V	dimensionless x,r velocities
VOL	dimensionless volume

Greek symbols

ε	porosity
θ	dimensionless temperature
$\Delta\theta$	dimensionless temperature difference
μ	dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
ρ	density, $kg \cdot m^{-3}$
ω	pore density, PPI(pores per inch)

Subscripts

d	dispersion
e	effective
f	fluid
in	inlet
m	mean
s	solid

duct, heat is firstly transferred to the solid phase and then transferred to surrounding fluid at the solid–fluid contact surface, which means three main heat transfer modes exist in metal foams, solid heat conduction, internal convective heat transfer and fluid heat conduction.

Inhomogeneity and complexity of porous structures make heat and mass transfer in porous media very complicated. Macroscopic transfers in porous media are usually modelled by the volume-averaging method in a specified representative elementary volume (REV) [8]. For porous foams made of low-conductive materials, such as nickel, iron, ceramic and their alloys, thermal transport can be handled by the widely-used local thermal equilibrium (LTE) model, especially when fluid thermal conductivity is comparable to 1% of metal thermal conductivity (for example, water). Poulikakos and Kazmierczak [9], Vafai and Kim [10], Chikh et al. [11] and Gong et al. [12] performed analytical investigations on forced convective heat transfer in porous media using LTE model. By means of numerical simulation, Marpu [13], Alazmi and Vafai [14] and Huang et al. [15] established energy equations for porous media with LTE model.

For highly-conductive foams (such as copper and aluminium), thermal conductivity of solid is usually three to five orders of magnitudes higher than that of fluid. The LTE model neglecting the solid–fluid temperature difference in such foams usually overestimates the heat transfer result. While, in the local thermal non-equilibrium (LTNE) model, two coupling energy equations for solid and fluid phases coexist, especially for significant temperature bifurcation of solid and fluid phases. Lots of scholars devoted their efforts to LTNE transport in porous media. Hsu [16] investigated unsteady heat conduction in porous media by neglecting advection in porous media. Phanikumar and Mahajan [17] performed numerical simulation on natural convection in an enclosure filled with a metal-foam layer with LTE/LTNE models and indicated that LTNE model is superior to LTE model in estimating thermal transport in metal foams with a porous–fluid interface. Khashan et al. [18] conducted numerical simulations on forced convective heat transfer in a porous tube under the boundary condition of constant wall temperature with LTE/LTNE models. Wang et al. [19] used LTNE model for thermal performance of porous-foam solar receiver combined with FLUENT software. Ghafarian et al. [20] used the LTE model to investigate the unsteady oscillating flow through a metal-foam channel. Buonomo et al. [21] analytically investigated the thermal transport in porous microchannel with the LTNE model. They indicated that the LTE model can be applied when the thermal conductivity ratio of fluid and solid (k_f/k_s) is relatively large. Some researchers used the thermal conductivity ratio of fluid and solid (k_f/k_s) as a basic parameter to quantify LTNE effect in porous media (Phanikumar and Mahajan [17], Lu et al. [22], and Zhao et al. [23]).

When metal foam is saturated with fluid, thermal characteristics through the solid/fluid composite mainly depend on effective thermal conductivity. Effective thermal conductivity for composite foam and fluid is an important parameter in macroscopic thermal modelling. It depends on fluid, the porous structure and the solid material of porous medium. Effective thermal conductivity with early models is calculated by taking the weighted arithmetic, geometric or harmonic means of solid and fluid thermal conductivities [8]. Calmidi [24] developed empirical correlation of foam effective thermal conductivity, which is in accordance with experiment in a way. Bhattacharya et al. [25] obtained another empirical model for effective thermal conductivity of metal foams using the