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Analytical solution of forced convective heat transfer in parallel-plate channel partially filled with metallic foams

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ABSTRACT

The forced convection flow and heat transfer characteristics in parallel-plate channel partially filled with metallic foams have been studied analytically. To predict fluid and thermal transport in the bottom heated partially filled channel, the Brinkman-extended Darcy momentum model and Non-equilibrium heat transfer model for porous media were employed for the foam filled region coupling with the momentum and energy conservation equations for foam free region. The interface between foam filled region and foam free region are subject to continuous temperature and energy balance to derive the analytical solutions for fully developed flow and convection heat transfer in entire plate channel including foam filled region and non-foam region. Then, the velocity and temperature distributions were predicted for the whole region of the parallel-plate channel based on the analytical solutions. The effects of key parameters on flow resistance and heat transfer performance has been investigated. Unlike the completely filled channel, the influences of pore density and porosity on flow and heat transport are dependent on the height of the foam.

1. Introduction

Metal foam has very wide range of applications and attracts more and more attention because it has advantages of lower density, high strength structure and large surface area in finite volume. Recently, the reduced manufacture cost gives metallic foams great potential for heat transfer related applications beyond aerospace and defence industry, e.g. applications in compact heat exchangers.

The metal-foam related applications in heat transfer enhancement field have been investigated by many researchers. Kopanidis et al. [1] drew a 3D simulated structure model of high porosity open-cell metal foam material to study the mechanism of heat transfer taking place in metal foams, which made it can be very intuitive to understand the structure of the metal foam. Based on the comprehensive analysis and experimental research, Bhattacharya et al. [2] determined the thermal physical parameters of metal foam with high porosity, such as the effective thermal conductivity (k_e), permeability (K), etc., which are the key parameters to study the flow and heat transfer through metal foams and additional methods have been used to study the heat transfer of metal foams. Furthermore, the performance of metal foam for fluid flow and heat transfer has been extensive studied. Odabaee et al. [3] presented analysis of thermal management of fuel cell systems using metal foam heat exchangers. They pointed out that fuel cell systems using metal foams can commendably reduce pumping power. Lu and Zhao [4] and Zhao et al. [5] studied the flow boiling heat transfer in metal-foam filled tube experimentally and explored that the influence of metal foam on heat transport is different for different flow patterns. Zhu et al. [6] explored the flow boiling heat transfer in small diameter horizontal tubes filled with metal-foam. And put forward a prediction method for flow boiling heat transfer coefficients of refrigerant in metal-foam filled tubes. Simone Mancin et al. [7] experimentally investigated heat exchange performance of various copper and aluminum foam samples with different parameters, and give some models and calculation procedures which can be used for optimizing heat transfer performance. Kamath et al. [8] studied on convection heat transfer of aluminum and copper foams in a vertical channel by experiment. Qu et al. [9] provided experimental study of air natural convection inside metallic foam filled plate channels. Under the condition of natural convection. The optimized inclination range and aspect ratios of the plate have been discussed. It is clear that metal foam fills to duct that can effectively promote heat transfer efficiency in practical engineering applications.

To modeling the heat transfer in porous medium like metal foams, there are two commonly used models: one-equation equilibrium model and two-equation non-equilibrium model

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Nomenclature

a	height of plate channel
a'	height of foam free region
a_{sf}	surface area density (m^{-1})
C_f	heat capacity of fluid (J/kg K)
d_f	diameter of fiber of metal foam (m)
d_p	pore size (m)
f	friction factor
h	heat transfer coefficient (W/m^2 K)
h_{sf}	interfacial heat-transfer coefficient of metal foams in foam filled region (W/m^2 K)
h'_{sf}	interfacial heat-transfer coefficient of metal foams at interface between foam filled and foam free regions (W/m^2 K)
H	dimensionless height of foam region, $H = (a - a')/a$
k	thermal conductivity (W/m K)
k_e	effective thermal conductivity, (W/m K)
K	permeability
L	length of plate channel
Nu	Nusselt number, $\text{Nu} = 2\,ha/k_f$
Nu_{sf}	local Nusselt number, $\text{Nu}_{sf} = h_{sf}d_f/k_f$
p	pressure (Pa)
Pr	Prandtl number, $\text{Pr} = c_p\mu_f/k$
q_w	heat flux (W/m^2)
Re	Reynolds number, $2ua/\upsilon$
Re_d	local Reynolds number
T	temperature (K)
u	velocity along z direction, (m/s)
u_m	mean fluid velocity along z direction (m/s)
X	foam region flow ratio

Greek symbols

ε	porosity
θ	surplus temperature, $\theta = T - T_w$
ρ	density (kg/m^3)
μ_f	dynamic viscosity (kg/m s)
υ	kinematic viscosity (m^2/s)

Subscripts

b	bulk
f	fluid
s	solid
w	wall

Others

∂	partial differential

(accounting for the effect of the local thermal non-equilibrium). One-equation equilibrium model assumes that there is no temperature difference between the local fluid and solid phase, while two-equation non-equilibrium model consider the fluid and metal foams separately, thus consider the local temperature difference between them. The latter is more difficult to apply because it requires knowing the interfacial heat transfer coefficient, which it is usually obtained by experimental study [10]. However, when the temperature difference between local fluid and solid is small enough, one-equation equilibrium model can be used. But Lee and Vafai [11] pointed out that temperature difference between local fluid and solid cannot be ignored in metal foam filled heat exchanger, otherwise the result isn't accurate. So the two-equation non-equilibrium heat transfer model is the mostly used model to analyze heat transfer performance of metal foam filled tube. Dukhan and Chen [12] studied the forced convection heat transfer in rectangular blocks of metal foam with the method of deduction analysis and experiment. And authors found calculation result of two-equation non-equilibrium model commendably consistent with experimental results. Lu et al. [10] presented an analytical solution for the forced convection heat transfer characteristics in metal-form filled tube. The Brinkman-extended Darcy momentum model and two-equation heat transfer model for porous media had been employed in their research. Dukhan et al. [13] used experiments to measure the fluid temperature inside metal foam, and compared that to flow convection analysis solution which used Brinkman–Darcy model. Yang et al. [14] used local non-thermal equilibrium to analyze a tube with a layer of porous medium and realized that the local thermal non-equilibrium is essential for the case. Therefore, two-equation non-equilibrium model was adopted in this paper for energy conservation equations.

Recently, the applications of metal foam are extended to enhance the heat transfer of phase change materials, nano-fluids, etc. Qu et al. [15] investigated the effects of several key parameters of metal foam on the thermal performances of the heat sinks with paraffin–copper foam. Li et al. [16] and Qu et al. [17] used porous metal foam saturated with phase change materials to investigate the passive thermal management system for high-powered lithium ion batteries experimentally and numerically. Xu et al. [18] investigated nano-fluid flowing through metal foams with numerical method. Siavashi et al. [19] numerically investigated the flow characteristics, heat transfer and entropy generation of nano-fluid flow inside an annular pipe partially or completely filled with porous media using two-phase mixture model. Yang et al. [20] presented an improved model on the effective thermal conductivity of metal foam.

From all available literatures and research summarized by Zhao [21], it can be seen that use of metal foam can greatly improve the heat transfer performance, but also bring greatly increase of the pressure drop. Therefore, Lu [22] and Xu et al. [23] proposed to study the tubes partially filled with metal foam. The partially filling can be center filling or inserting [24], near wall filling [23,25–27] or foam block filling [28]. Although the partially filled double pipe heat exchangers have been investigated analytically and numerically [19,23,27], the parallel-plate channel partially filled with a layer of metal foam may have good heat transfer performance with low pressure loss. Numerical method has been used by some researchers to study the heat transfer performance in this kind of channel. Piller et al. [25] numerically investigated natural convection heat transfer of an inclined parallel-plate channels partially filled with metal foams. Hajipour and Dehkordi [29] investigated the thermal performances of a vertical rectangular channel partially filled with open-cell metal foam used mixed-convection flow of nano-fluids by experiments and numerical modeling. Alhusseny et al. [30] investigated the heat transfer of square channel partially filled metal foam with numerical model and predicted the effect of rotation on heat transfer. However, the researches on forced convection taking place in near wall filling parallel-plate channel (which is commonly used for compact heat exchanger) are rare. Therefore, analytical method, which can reveal the essential flow and heat transfer mechanism, is used in this paper to study the heat transfer performance and forced flow in a parallel-plate channel with a layer of metal foams attached to the heated wall. The analytical solutions of Brinkman-extended Darcy momentum equation and two-equation non-equilibrium energy equations