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Non-equilibrium heat transfer in metal-foam solar collector with no-slip boundary condition

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ABSTRACT

Convective heat transfer in solar collectors filled with metal foams is analytically investigated with different methods, including numerical, analytical and fin-analysis methods. The Forchheimer/Brinkman/Darcy models are used to establish momentum equations for metal foams while the local thermal non-equilibrium (LTNE)/local thermal equilibrium (LTE) models are employed for energy equations. Some analytical solutions for velocity and temperature are obtained based on Darcy/Brinkman models with thermal dispersion effect considered. Numerical solution and fin solution are also obtained and compared with the analytical solutions with the pros and cons of different models discussed. Effects of some key parameters on flow and heat transfer are discussed. Present fin solution can provide more accurate estimation compared with the fin solution in the literature. The heat transfer difference between Brinkman model and Darcy model is obvious when the duct scale is small. In addition, the combined fin-LTE model is proposed for effectively evaluating thermal performance of metal foams.

1. Introduction

Due to energy crisis and environmental problems, many technologies are going through revolutionary changes to discover and harvest new kinds of energy. As an important kind of new energy, solar energy received much research interests and it is found that new efficient solar thermal energy utilization techniques are urgently needed. Since highly-porous metal foam with 3-D micro-cell structure can offer substantial extending surface area, it can be used for improving thermal performance of solar thermal applications. Moreover, metal foams own some other advantages, such as light weight, high thermal conductivity, fair mechanical performance and strong flow-mixing capability. These advantages make metal foams a special kind of functional materials for engineering applications in thermal engineering, such as heat exchangers, heat sinks, heat pipes, steam reformers, solar collectors, and so on [1–3].

Porous foams for enhancing solar utilization or effectively cooling the solar devices have drawn much attention in the past few years. Kudish et al. [4] numerically and experimentally investigated flow and heat transfer of water in a flat-plate selectively-coated polymeric double walled solar collector. Subiantoro and Tiow [5] presented a very simple analytical model with no iteration process for calculating the top heat loss of flat solar collectors. Huang et al. [6] numerically investigated the pulsating flow in a parallel-plate solar collector equipped with metal foam block. By using the method of inlet heating, Wang et al. [7] used the FLUENT software to investigate the heat absorbing characteristics of common porous media for solar air heater and Wang et al. [8] numerically investigated the thermal performance of the solar steam reformer filled with porous media. Tian and Zhao [9] reviewed the state of the art on solar thermal applications, with the focus on solar collectors and thermal energy storage subsystems, in which the applications of metal foams in solar collectors are summarized. All these publications proved that the existence of metal foams can greatly improve the heat transfer performance of thermal devices, including the solar thermal utilization.

Theoretical investigations with flow models of metal foams, such as Darcy model, Brinkman model and Forchheimer model, are published for different conditions. For Forchheimer model, the effects of viscous force of impermeable wall and inertial force are both considered compared with Darcy model. For thermal modeling in metal foams, local thermal equilibrium (LTE) model should be abandoned and local thermal non-equilibrium (LTNE) model must be adopted since the solid thermal conductivity of foam ligaments is very high. Internal flow and heat transfer in metal foams has been studied to some extent. Moutsopoulos et al. [10] presented different kinds of approximate solutions for Forchheimer equation in porous media. Hooman [11]

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Nomenclature

a_{sf}	specific surface area, m^{-1}
c	specific heat, $J\ kg^{-1}\ K^{-1}$
Da	Darcy number
E	dimensionless factor in Appendix, $(k_e + k_d)/k_{se}$
f	friction factor
h	convective heat-transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_m	mean value of convective heat-transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_s	convective heat-transfer coefficient of the smooth channel, $W\ m^{-2}\ K^{-1}$
h_{sf}	local convective heat-transfer coefficient, $W\ m^{-2}\ K^{-1}$
K	permeability, m^2
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
Nu	Nusselt number
Nu_m	mean Nusselt number
p	pressure, $N\ m^{-2}$
P	dimensionless pressure drop
q	heat flux, $W\ m^{-2}$
Q	heat, W
Re	Reynolds number, $Re = \rho_f u_0 \cdot 2H/\mu_f$
s	dimensionless factor in Eq. (14)
t	dimensionless factor in Eq. (7)
T	temperature, K
$T_{f,in}$	fluid inlet temperature, K
T_{fm}	mean temperature of the fluid, K
T_{wm}	mean temperature of the wall, K
u	velocity, $m\ s^{-1}$
u_0	inlet velocity, $m\ s^{-1}$
U	dimensionless velocity
x	axial position, m

Greek symbols

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

Subscripts

b	bulk
e	effective
f	fluid
in	inlet
m	mean
s	solid/smooth
w	wall

analytically investigated the fully-developed forced convection in a porous media duct with two isoflux parallel-plates and obtained the corresponding asymptotic solution for Forchheimer model. For the fully-developed forced convection in porous media filled tube, Hooman and Gurgenci [12] obtained the asymptotic solution of Forchheimer model. Overall, all the analytical investigations for Forchheimer equation in published papers are not the exact solutions. Calmidi and Mahajan [13] presented the numerical and experimental study on the forced convective heat transfer in metal foams and finally indicated that the LTNE effect in metal foams is obvious and the thermal dispersion effect is not obvious for air but water. Bhattacharya and Mahajan [14] experimentally investigated the forced convective cooling of air in metal-foam finned heat sinks and finally presented an empirical correlation for heat transfer of internal flow. Wade [15] performed experimental study on natural convection of water in the metal-foam filled enclosure under uniform heat flux heating. Mancin et al. [16] presented experimental data for air forced convection in metal-foam channels and established some empirical modeling correlations from the experimental data. Xu et al. [17] numerically investigated the flow characteristics and thermal performances of metal-foam filled counter-flow double-pipe heat exchangers by considering the effect of tube-wall thickness.

As for analytical works with explicit expressions for flow and heat transfer in metal foams, the research emphases are now focused on Brinkman model and the LTNE model. Lu et al. [18] presented the analytical solution of forced convective heat transfer in metal-foam tubes with Brinkman model. Alazmi and Vafai [19] implemented numerical simulation on the boundary condition effect on flow and heat transfer in porous media. Yang and Vafai [20] analytically investigated various flow and heat transfer cases in porous media parallel-channel with the local thermal non-equilibrium model. Xu et al. [21] presented the combined analytical, numerical and fin-theory-based solutions. Yang and Vafai [22] presented the analytical solution of thermal response in porous media with the local thermal equilibrium model. Zhao et al. [23] obtained an analytical solution of forced convective heat transfer in the metal-foam annulus with Brinkman model, in which the inner wall is under the uniform heat flux and the outer wall is adiabatic. Yang et al. [24] analytically investigated the forced convection in a porous annulus with the inner-wall heated and outer-wall adiabatic using Darcy model. From their temperature distributions [23,24], the fluid temperature is not equal to the solid temperature at the adiabatic wall, which needs to be corrected. For the two solid walls sandwiching metal foams, if one solid boundary is with the uniform-heat flux condition and the other with the adiabatic condition, the equality condition of fluid temperature and solid temperature should hold at both walls. In addition, forced convective heat transfer can also be effectively estimated with the fin theory. The method of fin theory is first extended to analyze convective heat transfer in metal foams by Lu et al. [25]. Nihad [26] used this method to analyze the heat transfer in 10-PPI foam and found good agreement with experimental data. Xu et al. [21] used the revised fin analysis method to investigate the forced convective heat transfer in metal-foam channel with two uniformly heated parallel plates. In that paper, the predicting accuracy is improved but there still exists room for predicting accuracy improvement with the fin theory method.

The aim of this paper is to compare different flow and heat transfer models for the wall-heated solar collector. The models include Darcy model, Brinkman model and Frochheimer model for flow and LTE model, LTNE model for heat transfer. In addition, a revised fin analysis method is also provided. Furthermore, the benchmark solution of the porous foam duct for solar energy adsorption is presented and the parameter optimization is conducted.

2. Problem description and numerical model

Fig. 1 shows the schematic diagram of the solar collector filled with metal foams. The height of the collector duct is H and the length along the flow direction is L. The mid-section of upper