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Numerical investigation on self-coupling heat transfer in a counter-flow double-pipe heat exchanger filled with metallic foams

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HIGHLIGHTS

- Model with self-coupling heat transfer is established.
- Fully-developed region in counter-flow heat exchanger with metallic foams is identified.
- Applicable condition for local thermal non-equilibrium model is presented.
- Optimal porosity and pore density ranges are obtained for higher effectiveness.

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ABSTRACT

The self-coupling heat transfer in a counter-flow double-pipe heat exchanger filled with metallic foams is numerically investigated. The Forchheimer extended Darcy equation with a quadratic term is adopted for the momentum equation, whereas the local thermal non-equilibrium model is applied for establishing energy equations with thermal dispersion. The domain-extension method, pressure correction near the porous-solid interface, and the large coefficient method are specially employed for the porous/fluid-wall-porous/fluid coupling problem. The velocity and temperature fields of solid and fluid are obtained. The effects of various parameters on pressure drop per unit length, heat transfer coefficient, and heat-exchanger effectiveness are also presented. The thermally fully developed region is located in the middle section of the heat exchanger, where the local convective heat coefficient is unalterable. Effectiveness can be improved by decreasing porosity, increasing pore density, or increasing the foam solid thermal conductivity. The applicable range of the thermal conductivity ratio for the local thermal equilibrium model is $k_{f1}/k_{s1} > 10^{-2}$. The local thermal non-equilibrium model should be adopted when $k_{f1}/k_{s1} < 10^{-3}$. Ranges for porosity (less than 0.9) and pore density (greater than 10 PPI) are recommended to ensure higher effectiveness (greater than 0.8).

1. Introduction

Metallic foams are excellent candidate materials for exchanging a large amount of heat within a small volume for their advantages such as low density, high specific surface area, high solid thermal conductivity, and strong flow-mixing capability. Potential applications of metallic foams in thermo-fluid engineering include solar collectors, fuel cells, heat sinks, heat exchangers, and so on. Over the last two decades, thermal transport in metallic foams has been theoretically and practically developed. In particular, the development of the co-sintering technique and new manufacturing methods for metallic foams facilitated the use of the new heat transfer enhancement material in compact heat exchangers, thus motivating the research on convective heat transfer in metallic foams.

The convective heat transfer in metallic foams has been studied to some extent [1–8]. Lu et al. [1] theoretically investigated the flow and heat transfer in metallic foams based on the fin analysis theory, in which the structure of the metallic foam is simplified as a cubic with inter-connected cylinders. Calmidi and Mahajan [2] performed experimental and numerical studies on forced convection in parallel-plates filled with metallic foams and obtained good agreement between the findings by adjusting some empirical parameters. Zhao et al. [3] conducted similar experimental and numerical studies on forced convection in a rectangular duct filled with metallic foams as well as a parameter study on flow and heat transfer. Calmidi [4] performed an experimental study on heat conduction in metallic foams filled with air and water and presented a large amount of experimental data on the effective thermal conductivity of metallic foams. Based on the experimental data, Boomsma and Poulikakos [5] considered the metallic foam cell as a three-dimensional tetrakaidecahedron and developed an analytical

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Nomenclature

a	thermal diffusivity, $m^2\ s^{-1}$
a_{sf}	specific surface area, m^{-1}
c	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
C_I	inertial coefficient
Da	Darcy number
d_f	fiber diameter, m
d_p	pore diameter, m
h	convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_{sf}	local convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
k_d	thermal dispersion conductivity, $W\ m^{-1}\ K^{-1}$
k_f	thermal conductivity of fluid, $W\ m^{-1}\ K^{-1}$
k_s	thermal conductivity of solid, $W\ m^{-1}\ K^{-1}$
K	permeability, m^2
L	length of double-pipe heat exchanger, m
Nu	Nusselt number
Nu_m	mean Nusselt number
p	pressure, $N\ m^{-2}$
P	dimensionless pressure
Pr	Prandtl number
q	heat flux, $W\ m^{-2}$
r	radial position, m
r_1	inner radius of inner tube, m
r_2	outer radius of inner tube, m
r_3	inner radius of outer tube, m
R	dimensionless r coordinate
Re	Reynolds number
Re_d	pore Reynolds number
T	temperature, K
T_{fin1}	inlet temperature for fluid in inner pipe, K
T_{fin2}	inlet temperature for fluid in annular duct, K
u,v	x,r velocity components, $m\ s^{-1}$
u_{m1}	mean velocity of fluid in inner pipe, $m\ s^{-1}$
u_{m2}	mean velocity of fluid in annular duct, $m\ s^{-1}$
u_{mr}	mean velocity ratio
U,V	dimensionless velocity components in X,R direction
x	axial position, m
X	dimensionless x coordinate

Greek symbols

γ	binary parameter
ε	porosity
$\overline{\varepsilon}$	effectiveness
θ	dimensionless temperature
μ	dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
ρ	density, $kg\ m^{-3}$
ρ_r	density ratio
ϕ	heat, W
ϕ_{m1}	heat transfer at the inner surface of the inner tube, W
ϕ_{m2}	heat transfer at the outer surface of the inner tube, W
ω	pore density ($0.0254/d_p$), PPI (pores per inch)

Subscripts

e	effective
f	fluid
I	inertial
int	interface
m	mean
nb	neighbor
p	porous
P	point
r	relative
s	solid
w	wall
1	physical quality for the inner pipe
2	physical quality for the annular space

correlation of effective thermal conductivity of metallic foams. Zhao et al. [6] performed an experimental study on natural convection in a vertical cylindrical enclosure filled with metallic foams and then numerically investigated the local thermal non-equilibrium effect under experimental conditions. Xu et al. [7] theoretically investigated the forced convective heat transfer in a channel filled with metallic foams using analytical, numerical, and fin-analysis methods. Phanikumar and Mahajan [8] conducted experimental and numerical work on natural convection in the metallic foam layer placed in an open enclosure. They highlighted that the local thermal non-equilibrium effect is significant [6–8]. Overall, the use of metallic foam as heat transfer enhancement materials is feasible, but at the expense of significant pressure loss. For the low pressure-drop flow in an enhanced metallic-foam duct, the configuration of a partially filled metallic-foam duct is recommended [9–12].

Based on basic duct structures, metallic foams can be employed in compact heat exchangers by sintering on solid plates or tubes. The conjugation of the heat transfer on both sides of the solid wall has to be well handled for fluid dynamics computation, which is a special porous/solid conjugate problem. Early works on convective heat transfer in porous media employed the local thermal equilibrium model. Alkam and Nimr [13] and Targui and Kahalerras [14] respectively performed numerical simulations on the thermal performance of a double-pipe heat exchanger filled with porous substrates and of a double-pipe heat exchanger filled with porous baffles employing the local thermal equilibrium model, which neglected the thermal resistance of the tube wall. Lee and Vafai [15] indicated that the local thermal equilibrium assumption is inaccurate when the thermal conductivity difference between solid and fluid is large, and the thermal performance for convective heat transfer should be addressed using the local thermal non-equilibrium model. Lee et al. [16] and Betchen and Straatman [17] theoretically proposed a discretizing method with the local thermal non-equilibrium model for the flow and heat transfer at the porous-solid interface, but the implementation of this method was not presented. Lu et al. [18,19] obtained analytical solutions for the fully developed forced convective heat transfer in a double-pipe heat exchanger filled with metallic foams, but the dividing-wall heat flux is artificially set as uniform without the quadratic and thermal dispersion terms. Du et al. [20] numerically studied the heat transfer performance of a double-pipe heat exchanger with parallel flow with local thermal non-equilibrium model, but the heat flux along the tube was derived from the fluid temperature without considering the internal temperature distribution.

Based on above review, the effect of the solid wall is usually neglected, and the practical thermal coupling process of the two sides of the fluid separated by the interface wall under the local thermal non-equilibrium model can rarely be observed for the numerical modeling of the heat exchanger filled with porous medium. To this end, by considering the local thermal non-equilibrium, thermal dispersion, and tube-wall heat conduction effects, the conjugate flow and heat transfer in double-pipe heat exchangers filled with metallic foams with counter flow is numerically simulated. Flow characteristics, thermal performance, and effectiveness are presented.