Analysis of Flow and Heat Transfer in Metal Foam Tubes under Non-Equilibrium Conditions (Postprint)

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Abstract

This study employs a thermal local non-equilibrium model to conduct numerical simulations of the flow field and temperature field within a horizontal circular tube completely filled with metal foam, investigating the influence of key structural parameters of metal foam, such as pore diameter d. and porosity., on the flow and heat transfer characteristics within the tube · The results indicate that after filling with metal foam, the flow field within the tube becomes relatively uniform; the velocity gradient at the wall surface of the metal foam circular tube is significantly higher than that of a smooth tube, and the wall boundary layer becomes noticeably thinner; the pore diameter has a greater influence on pressure drop than porosity; when the pore diameter is larger and the porosity is higher, the pressure drop is smaller; conversely, when the pore diameter is smaller and the porosity is lower, the heat transfer is stronger; comprehensively considering the influence of metal foam parameters on heat transfer and pressure drop, under the operating conditions investigated in this study, the optimal pore diameter range is 1 mm-2 mm.

Full Text

Preamble

A Local Thermal Non-Equilibrium Analysis of Hydrodynamic and Heat Transfer Characteristics in a Tube Filled with Metal Foam

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Abstract

This paper presents a numerical investigation of the flow and temperature fields in a horizontal circular tube completely filled with metal foam using a local thermal non-equilibrium model. The study examines the influence of key structural parameters of metal foam, such as pore size (dp) and porosity ( ), on flow and heat transfer characteristics within the tube. The results demonstrate that filling the tube with metal foam leads to a more uniform velocity distribution, with significantly higher velocity gradients at the wall and a substantially thinner boundary layer compared to an empty tube. Pore size exerts a more pronounced effect on pressure drop than porosity. Larger pore sizes and higher porosities result in lower pressure drops, whereas smaller pore sizes and lower porosities enhance heat transfer but at the cost of increased pressure drop. Considering the combined effects on heat transfer and pressure drop, the optimal pore size range under the investigated conditions is 1–2 mm.

Keywords: metal foam; fully filled; local thermal non-equilibrium

Introduction

Open-cell metal foams have emerged as an ideal material for heat transfer enhancement due to their high porosity, low density, and large specific surface area, attracting considerable research attention in recent years. Numerous experimental and numerical studies on forced convection in metal foams have been conducted worldwide. Zhao and Kim [1] performed experimental and numerical analyses of air forced convection in flat channels filled with FeCrAlY metal foam under vacuum and atmospheric pressure, investigating the effects of porosity, pore density, and solid thermal conductivity on heat transfer. Calmidi and Mahajan [2-3] conducted numerical simulations and experimental studies on forced convection in flat channels filled with aluminum foam, employing a local thermal non-equilibrium model with thermal dispersion effects to achieve good agreement with experimental data. Boomsma et al. [4] experimentally investigated the performance of compressed aluminum foam in compact heat exchangers using water as the cooling medium, demonstrating that the thermal resistance of compressed aluminum foam heat exchangers is 2–3 times lower than that of the best commercial heat exchangers under the same pumping power. Lu and Zhao [5-6] performed theoretical analysis and analytical modeling of metal foam applications in double-pipe heat exchangers, obtaining analytical solutions for both inner tube and annular space configurations, which revealed that metal foam heat transfer tubes can significantly enhance heat transfer. Most existing experimental studies on metal foam heat transfer enhancement have focused on flat channel configurations, while numerical simulations have predominantly employed the local thermal equilibrium model, which assumes equal temperatures between the fluid and solid phases. This assumption introduces significant errors when the solid phase has high thermal conductivity. The present study employs a local thermal non-equilibrium model to numerically simulate convective heat transfer in a horizontal tube completely filled with metal foam, investigating the influence of key structural and performance parameters on the flow and temperature fields.

1. Physical Model

The physical model considered in this study is illustrated in [Figure 1: see original paper]. A horizontal circular tube with a radius of 2 mm is completely filled with homogeneous, isotropic metal foam. A hot fluid with average velocity uin and temperature Tin flows through the tube and its internal metal foam structure, exiting at the right end after cooling. The tube wall maintains a constant temperature Tw, where Tw $<$ Tin.

2. Mathematical Model

The following assumptions are adopted in this study: (1) the fluid is incompressible; (2) natural convection and radiation heat transfer are negligible; (3) thermal dispersion and viscous dissipation effects are ignored; (4) all thermophysical properties are constant. Based on these assumptions, the dimensionless governing equations describing the flow and heat transfer processes are derived using the Darcy-Brinkman-Forchheimer momentum equation and the local thermal non-equilibrium (LTNE) model.

The continuity equation and momentum equations in the z and r directions are formulated accordingly. The energy equations for the fluid and solid phases are also established. To enhance the generality of the computational results, the following dimensionless parameters are defined: the Darcy number (Da) characterizes the permeability of the porous medium. The permeability K depends on the structure of the porous medium and can be determined from empirical correlations derived from experimental data. In this study, the experimental correlations proposed by Calmidi [2] are employed to calculate K and the inertia coefficient F. The expressions are as follows: [MATH_FORMULA]. Here, dp represents the average pore diameter of the metal foam, and df denotes the fiber diameter of the metal skeleton, which relates to dp as: [MATH_FORMULA].

3. Mesh Generation

The computational mesh employed in this study is shown in [Figure 2: see original paper]. Due to relatively large gradients in fluid temperature and velocity at the inlet and near the wall regions—where computations are prone to divergence—mesh refinement is applied in these areas to better capture parameter variations. Conversely, coarser mesh is used in other regions to reduce computational time. The numerical solution is obtained using the finite volume method to discretize the governing equations. The SIMPLE algorithm is employed for pressure-velocity coupling, and a second-order upwind scheme is used for convection terms. The under-relaxation factors for velocity and temperature are set to 0.7. Convergence is achieved when the residuals of the continuity and energy equations drop below 1e-8 and 1e-10, respectively.

4.1 Velocity Distribution

[Figure 3: see original paper] presents the axial velocity distribution in the metal foam-filled tube under different pore sizes, compared with that in an empty tube. The results indicate that filling the tube with metal foam yields a more uniform velocity profile, with significantly increased velocity gradients at the wall and a noticeably thinner boundary layer. The axial velocity increases with pore size because, at a fixed porosity, larger pore sizes reduce the number of pores per unit length, thereby decreasing flow resistance and increasing the axial velocity.

4.2 Temperature Distribution

[Figure 4: see original paper] illustrates the influence of metal foam structural parameters on the temperature field within the filled tube. As shown in Figure 4: see original paper, pore size substantially affects both solid and fluid temperatures. Decreasing pore size reduces both fluid and solid temperatures while also diminishing the temperature difference between the phases. Figure 4: see original paper reveals that reducing porosity from 0.95 to 0.85 significantly increases both solid and fluid temperatures from the wall to the tube center, though the temperature difference between phases remains relatively unchanged.

4.3 Pressure Drop

[Figure 5: see original paper] demonstrates the effect of metal foam structural parameters on pressure drop within the tube. As shown in Figure 5: see original paper, pressure drop decreases sharply when pore size increases from 0.5 mm to 1 mm, and continues to decrease with further pore size enlargement, albeit less significantly. Figure 5: see original paper indicates that for smaller pore sizes, pressure drop decreases dramatically as porosity increases because the solid volume fraction obstructing flow decreases proportionally, reducing flow resistance. However, when pore size exceeds 1 mm, porosity variation has minimal impact on pressure drop.

4.4 Heat Transfer Characteristics

[Figure 6: see original paper] shows the influence of metal foam structural parameters on the heat transfer coefficient. As depicted in Figure 6: see original paper, the fully developed Nusselt number decreases gradually with increasing pore size. Combined with the pressure drop trends in Figure 5: see original paper, the optimal pore size range under the investigated conditions is 1–2 mm. For pore sizes below 1 mm, pressure drop increases sharply while the Nusselt number continues to increase at the same rate. Figure 6: see original paper shows that the Nusselt number decreases with increasing porosity because higher porosity reduces the volume fraction of the high-thermal-conductivity solid phase, decreasing the effective thermal conductivity and consequently impairing heat transfer.

5. Conclusions

This paper presents a numerical analysis of flow and temperature fields in a horizontal circular tube completely filled with metal foam, examining the effects of pore size, permeability, and flow parameters on hydrodynamic and thermal performance. The main conclusions are:

(1) Filling the tube with metal foam alters the fully developed velocity profile from a parabolic distribution to a more uniform one, with substantially higher velocity gradients at the wall and a significantly thinner boundary layer compared to an empty tube.

(2) Increasing the pore size of the metal foam enhances the axial velocity while also increasing the boundary layer thickness.

(3) Decreasing pore size significantly reduces the temperature difference between fluid and solid phases, whereas porosity reduction has minimal effect on this temperature difference.

(4) Larger pore sizes and higher porosities result in lower pressure drops, with pore size exerting a greater influence than porosity.

(5) Smaller pore sizes and lower porosities enhance heat transfer but simultaneously increase pressure drop.

(6) Under the investigated operating conditions, the optimal pore size range is 1–2 mm.

References

[1] ZHAO Changying, KIM T, LU Tianjian, et al. Thermal Transport in High Porosity Cellular Metal Foams [J]. Journal of Thermophysics and Heat Transfer, 2004, 18(3): 309-317.

[2] Calmidi VV. Transport Phenomena in High Porosity Fibrous Metal Foams [D]. USA: University of Colorado, 1998.

[3] Calmidi VV, Mahajan RL. Forced Convection in High Porosity Metallic Foams [J]. ASME Journal of Heat Transfer, 2000, 122(3): 557-565.

[4] Boomsma K, Poulikakos D, Zwick F. Metal Foams as Compact High Performance Heat Exchangers [J]. Mechanics of Materials, 2003, 35(12): 1161-1176.

[5] LU Wei, ZHAO Changying, Tassou SA. Thermal Analysis on Metal-Foam Filled Heat Exchangers. Part I: Metal-Foam Filled Pipes [J]. International Journal of Heat and Mass Transfer, 2006, 49(15-16): 2751-2761.

[6] ZHAO Changying, LU Wei, Tassou SA. Thermal Analysis on Metal-Foam Filled Heat Exchangers. Part II: Tube Heat Exchangers [J]. International Journal of Heat and Mass Transfer, 2006, 49(15-16): 2762-2770.

Note: Figure translations are in progress. See original paper for figures.