https://doi.org/10.70750/GEP.2025.3-4.2

ALUMÍNIUM PORÓZUS KÖZEGŰ FÉMHAB HŐTELJESÍTMÉNYE

THERMAL PERFORMANCE OF ALUMINIUM POROUS MEDIA METAL FOAM

Alaa Alrudhan, Gabriella Vadászné Dr. Bognár* *

ABSTRACT

A numerical study optimized the thermal performance of an aluminium tube filled with porous media metal foam. The investigation analyzed four aluminium metal foam models, including those with and partially filled metal foam and multi-layered metal foam of different porosities. The multi-layer porosities, which represent a dual permeability setup, specifically. The porosity of metal foam varies from 0.9 to 0.92, and the pore density (PPI) varies from 10 to 30 PPI. The Darcy-Extend Forchheimer model was used for flow dynamics within the porous region. The local thermal non-equilibrium model was applied within the porous-filled region of the pipe to analyze heat transfer characteristics. The results showed that the thermal performance of a fully filled porous metal foam structure is superior to that of a partially filled structure. As well as multi-layer porosities of aluminium metal foam exhibited greater thermal efficiency than single layers.

1. INTRODUCTION

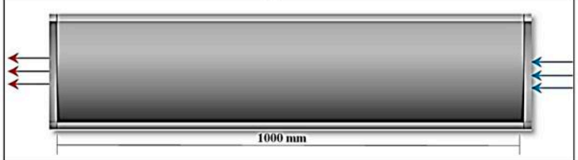
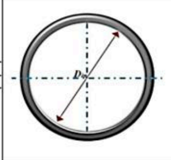
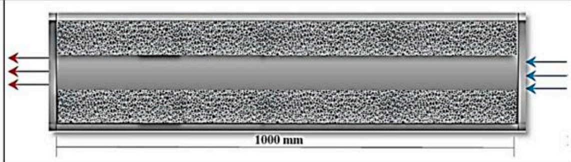
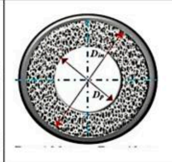
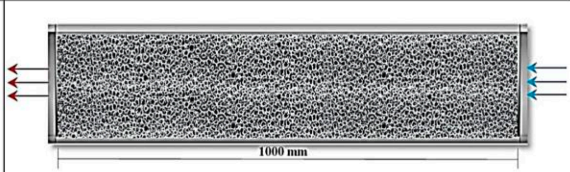
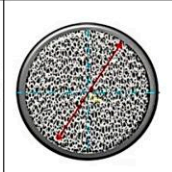
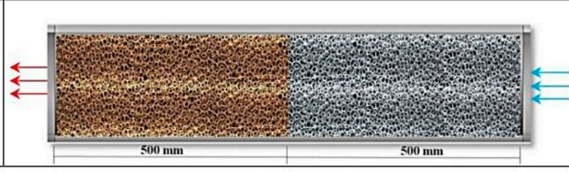
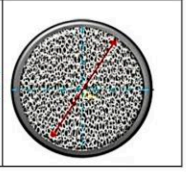
The irregular and spatially varying flow geometry within porous media significantly complicates the transport of heat and fluid. This variety often leads researchers to shift focus from the complicated local behaviors to the macroscopic ability of the medium to facilitate energy and fluid transport[1]. Metal foams have garnered significant research interest over the past few decades due to their exceptional heat transfer capabilities[2]. This has led to their broad integration into various thermal systems, such as compact heat exchangers, advanced electronic cooling devices, geothermal applications, air-cooled condensers, combustion chambers, and metal casting solidification processes. Open-cell metal foams possess a unique, complex structure characterized by a random network of irregularly interconnected pores[3]. This architecture yields a high specific surface area and promotes intense flow disturbances, making them exceptionally appealing for improving thermal performance in relevant systems. A numerical study was conducted to investigate convection heat transfer in a porous media-filled heat exchanger[5-7]. Results indicated that the mean Nusselt number (Nu) increases with the Reynolds number[8]. A numerical investigation was conducted to examine the effect of spatially varied porosity in aluminium metal foams filling a vertical pipe. Several experimental, analytical, and numerical studies have been conducted to investigate the hydrodynamic and thermal characteristics of porous media within horizontal and vertical channels. The results showed that the pressure drop was slightly lower for the spatially varied porous media compared to the uniform porosity metal foam[9-10]. Studied partially filled high porosity metallic foams in a horizontal direction pipe and the effect of heat transfer and pressure drop, the results showed thermal performance factor for a variety of PPI and porosity. This study numerically investigates the thermal performance of fully filled versus partially filled porous metal foam in a tube. The primary aim is to compare these configurations and examine the impact of multi-layered structures with varying porosities arranged in series.

2. NUMERICAL SOLUTION

The tube is filled with metal foam porous media, with a length of 1000 mm, an inner diameter (D_{in}) of 100 mm, and an outer diameter of 107 mm. The partial porous structure has with inside diameter (D_p = 40 mm). The uniform heat flux of 275 W/m^2 is applied over the wall of the porous media section. The inlet and outlet of the non-porous pipe section were adiabatic wall boundary conditions, 1000mm length for each one to ensure a fully developed turbulent flow rate at inlet and to prevent the back effects at the outlet as shown in Fig. 1. By using ANSYS FLUENT 25, the porous metal foam region and the clear fluid region are modeled as two distinct cell zones. The interfaces between these zones serve as coupling boundaries, enabling interaction between the porous and fluid domains. When employing the Local Thermal Non-Equilibrium model, the solid and fluid phases are treated separately. Within the porous region, the thermal and physical properties of the metallic foam are specified according to the framework to accurately capture the heat transfer behavior between the solid matrix and the fluid phase. Configurations of the models considered are shown in Table 1. To ensure

* *Institute of Machine and Product Design, Faculty of Mechanical Engineering and Informatics, University of Miskolc, 3515-Egyetemváros, Miskolc, Hungary*

Table 1: Configurations of the models considered.

Case (Model)	Model		Permeability (K) $\times 10^{-7}$ (m^2)	Configuration of porous	
	Porosity%	PPI		Longitudinal	Cross section
Non-porous **(N-P)**	-		-		
Partial porosity **(M1)**	90	10	2.4		
Single layer **(M2)**	90	10	2.4		
Two layers **(M3)**	90 + 92	10 + 30	0.36		

physical consistency at the interface between a porous medium and a clear fluid region, continuity of velocity,

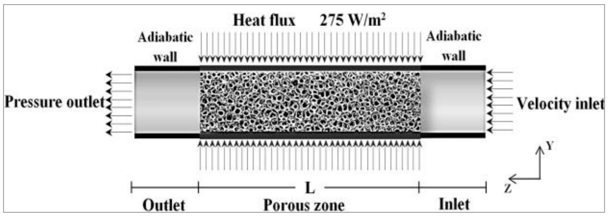


Figure 1: Geometry of the computational domain.

shear stress and heat flux must be maintained for both heat and fluid flow, as shown in Table 2.

Table 2 : Coupling conditions at the porous interface.

Property	Condition
Fluid velocity	$u\big\|_{Interface^+} = u\big\|_{Interface^-}$
Shear stress	$\frac{k_f}{\varepsilon}\frac{\partial\langle u\rangle}{\partial x}\Big\|_{Interface^+} = k_f\frac{\partial\langle u\rangle}{\partial x}\Big\|_{Interface^-}$
Fluid temperature	$T_s\big\|_{Interface^+} = T_f\big\|_{Interface^-}$
Heat flux q_w	$\left(k_{fe}\frac{\partial\langle T\rangle^f}{\partial x} + k_{se}\frac{\partial\langle T\rangle^s}{\partial x}\right)\Big\|_{Interface^+} = k_f\frac{\partial T^f}{\partial x}\Big\|_{Interface^-}$ $k_s\frac{\partial T^f}{\partial x}\Big\|_{Interface^+} = h_{sf}(T_s - T_f)\Big\|_{Interface^-}$

3. GRID INDEPENDENCE

A grid independence study is conducted to determine the optimal mesh resolution for the proposed numerical model. The equation of grid convergence analysis is also used to measure how close a numerical solution is to the exact solution as the computational grid is refined, see Eq.1and Table 3.

$$\text{Percentage Deviation} = \frac{|T_{Max2} - T_{Max1}|}{T_{Max1}} 100\% \quad (1)$$

Table 3: Mesh density and corresponding maximum temperature

Number of grid N (elements)	Maximum temperature (°C)
152,388	43.11
334,212	42.99
510,772	42.94
783,544	42.933
945,720	42.922
1,121,670	42.922 **Baseline data**

4. VERIFICATION

To verify the present approach, the predicted temperature distribution of the porous media tube is compared with the numerical study reported by Prakash H. Jadhav et. al. [13]. An aluminium metal foam of 10 PPI and porosity 92% studied. The temperature distribution at the outlet cross-section is compared for three cases: a fully porous pipe, a partially porous [11] pipe and a non-porous pipe. The inlet diameter was 0.1 m and air velocity 0.6639 m/s with heat flux 275 W/m^2 for all cases. The simulation results for the fully porous configuration demonstrate enhanced uniform temperature as compared with partially porous [11], while the non-porous pipe exhibits a steep thermal gradient due to limited heat transfer, as illustrated in Fig. 2

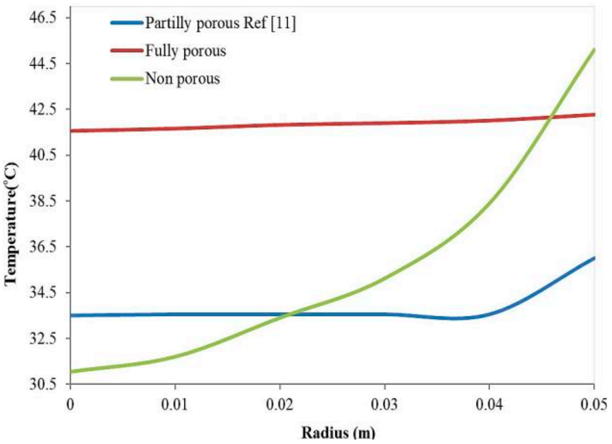


Figure 2: Verification of temperature distribution through the exit area of porous section.

5. RESULTS

The temperature contours of spatial thermal behavior within a porous media metal foam-filled tube, which is shown at Fig. 3. In a non-porous pipe contour refers to classic thermal boundary layer development. A thin layer of higher temperature fluid is confined to the wall, while the center core of flow remains at a low temperature. In contrast, the porous media models having a much more uniform temperature distribution across the pipe cross-section. Model 1 of PPI 10 and porosity 90%, due to the effectiveness of heat transfer, a medium degree of temperature appears because the partial porous media metal foam structure and the center fluid flow will decrease the temperature as compared with the porous region. Model 2 with constant pore density and porosity presents and single layer of metal foam fully filling a tube with a slightly more uniform and overall higher temperature profile at exit. Model 3 of double layers of metal foam shows the clear transition. The first section low pore density and high porosity, has a low temperature profile. At the interface, the air enters the higher PPI region, where enhanced surface area and increased flow mixing lead to more effective heat transfer and more rapid temperature enhancement.

6. CONCLUSION

Three–dimensional numerical simulations were conducted to investigate the impact of dual permeability porous media metal foam fully filling a horizontal pipe (0.1 m in diameter, 1 m in length, and 0.07m thickness). the key findings are summarized below:

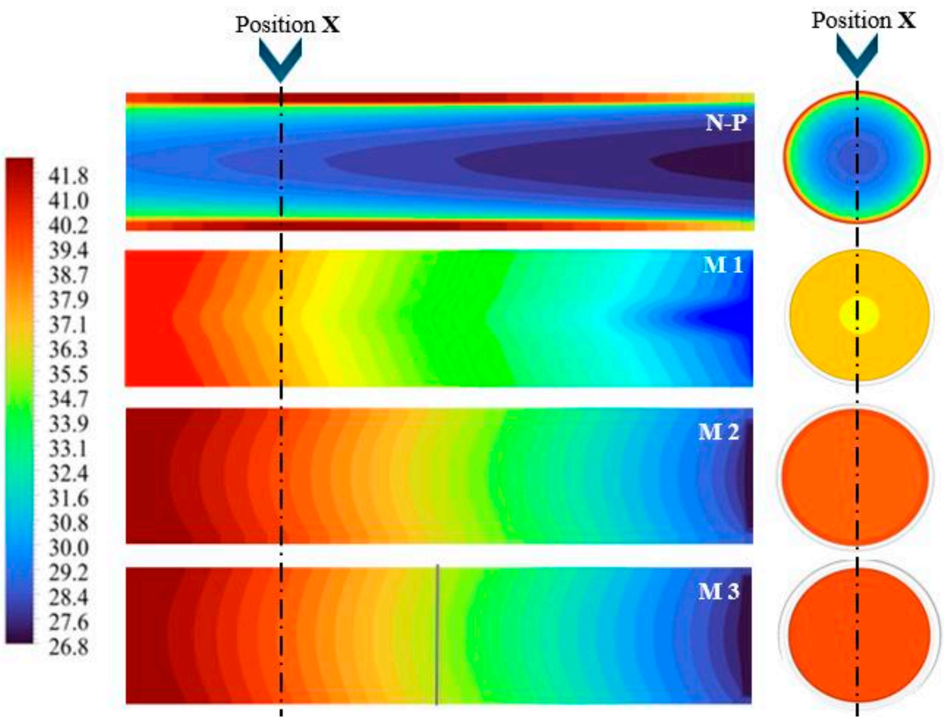


Figure 3: Comparison of temperature contours for porous and clear pipe models at an air velocity 0.66 m/s.

- The inclusion of fully filled porous media inside the pipe results in a higher and more uniform temperature distribution compared to a partially filled configuration.
- The uniformity enhances thermal performance by maintaining the temperature within a consistent range.
- The comparison between pipes with and without porous media highlights a significant improvement in heat transfer efficiency when porous media is present. Specifically, the temperature reduction in the pipe without porous media was about 45%, demonstrating the superior heat transfer capabilities of the porous-filled pipe.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and resources provided by the Institute of Machine and Product Design. Special thanks to the Faculty of Mechanical Engineering and Informatics, University of Miskolc.

NOMENCLATURE

PPI	Pores per inch
LTNE	Local thermal non-equilibrium model
K	Permeability (m^2)
T_s	Temperature of solid (k)
T_f	Temperature of fluid (k)
k_s	Thermal conductivity of solid (W/m.K)
k_f	Thermal conductivity of fluid (W/m.K)
ε	Porosity
h_{sf}	Interfacial heat transfer coefficient (W/m^2.K)
u,	Air velocity in direction of X (m/s)
v	Air velocity in direction of Y (m/s)
w	Air velocity in direction of Z (m/s)
D_{in}	Inner diameter of pipe (m)
D_p	partial diameter of pipe (m)
Nu	Nusselt number
q_w	Heat flux (W/m^2)
N	Number of grid
eff	Effective

REFERENCES

[1] Miao, L., Wang, Y., Kavtaradze, R., Liu, S., Zhang, S. *Experimental and numerical analyses of thermal-hydraulic characteristics of aluminium flying-wing fins*, Applied Thermal Engineering, 203 (2022), 117928.

[2] Wang, C.-C., Chen, K.-Y., Liaw, J.-S., Tseng, C.-Y. *An experimental study of the airside performance of fin-and-tube heat exchangers having plain, louver, and semi dimple vortex generator configuration*, International Journal of Heat and Mass Transfer, 80 (2015), 281–287.

[3] Okbaz, A., Pınarbaşı, A., Olcay, A.B. *Experimental investigation of effect of different tube row-numbers, fin pitches and operating conditions on thermal and hydraulic performances of louvered and wavy finned heat exchangers*, International Journal of Thermal Sciences, 151 (2020), 106256.

[4] Andreozzi, A., Bianco, N., Iasiello, M., Naso, V. *Natural convection in a vertical channel with open-cell foams*, Journal of Physics: Conference Series, 1599 (2020), 012013.

[5] Milani Shirvan, K., et al. *Heat transfer and sensitivity analysis in a double pipe heat exchanger filled with porous medium*, International Journal of Thermal Sciences, 121 (2017), 124–137.

[6] Kiran Kumar, K., et al. *Effect of spatial porosity of metal foams on heat transfer filled in a vertical channel,* Materials Today: Proceedings, 51 (2022), 1539–1547.

[7] Xu, Z.G., Gong, Q. *Numerical investigation on forced convection of tubes partially filled with composite metal foams under local thermal non-equilibrium condition*, International Journal of Thermal Sciences, 133 (2018), 1–12.

[8] Jadhav, P.H., Nagarajan, G., Perumal, D.A. *Conjugate heat transfer study comprising the effect of thermal conductivity and irreversibility in a pipe filled with metallic foams*, Heat and Mass Transfer, 56 (2020), 1985–1997.

[9] Duan, X., Pei, J., Chen, X., Wang, Y., Ding, C. *Enhanced heat transfer in sandwich heat transfer unit with metal foam: A numerical investigation*, Applied Thermal Engineering, 256 (2024), 124144.

[10] Kotresha, B., Gnanasekaran, N. *Investigation of mixed convection heat transfer through metal foams partially filled in a vertical channel by using computational fluid dynamics*, Journal of Heat Transfer, 140 (2018), 072601.

[11] Jadhav, P.H., et al. *Performance evaluation of partially filled high porosity metal foam configurations in a pipe*, Applied Thermal Engineering, 194 (2021), 117081.

[12] Huang, Z.F., Nakayama, A., Yang, K., Yang, C., Liu, W. *Enhancing heat transfer in the core flow by using porous medium insert in a tube*, International Journal of Heat and Mass Transfer, 53 (2010), 1164–1174.