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Modelling Conjugate Heat Transfer in Conjunction with High Thermal Conductivity Metal foam in a Vertical Channel

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This paper discusses about modeling of a conjugate heat transfer problem which comprises of conduction in an aluminium plate and convection from the plate to the adjacent fluid air in a vertical channel. An aluminium plate of size 150x250x10 (all in mm) is placed inside the vertical channel and metal foams are attached on either side of the plate thereby constituting a conjugate heat transfer model. This work is continuation of our previous work investigation of mixed convection heat transfer through metal foams partially filled in a vertical channel by using CFD. The metal foams are filled in the channel and for the purpose of analysis three different filling rates are analyzed such as 40%, 70% and 100%. Numerical analysis is performed based on Darcy Extended Forchheirmer and Local thermal non-equilibrium models. The results of excess temperature, velocity distribution, pressure drop and friction factor are presented in this paper. Few numerical results of the present work are validated against the available literature.

***Keywords*:** Vertical channel, Metal foam, Partial filling, LTNE

1. Introduction

Recent times, research in the area of fluid flow and heat transfer in porous media has become high priority among researchers. Especially, metal foams are considered in many thermal systems for the enhancement of heat transfer. A detailed literature review of the research in this topic is already mentioned in our previous work [1]. Figure 1(a) shows the numerical model in which a vertical channel is considered along with a heater. On either side of the plate, metal foams are placed to enhance the heat transfer. As a result, three different scenarios are considered where the metal foams are filled 40% (H_f = 0.4H), 70% (H_f = 0.7H) and 100% (H_f = H) inside the vertical channel. The size of the aluminium plate considered in the study is 150 x 250 x 3 (all in mm). The properties of the metal foam are taken from Kamath et al. [2] and are tabulated in Table 1.

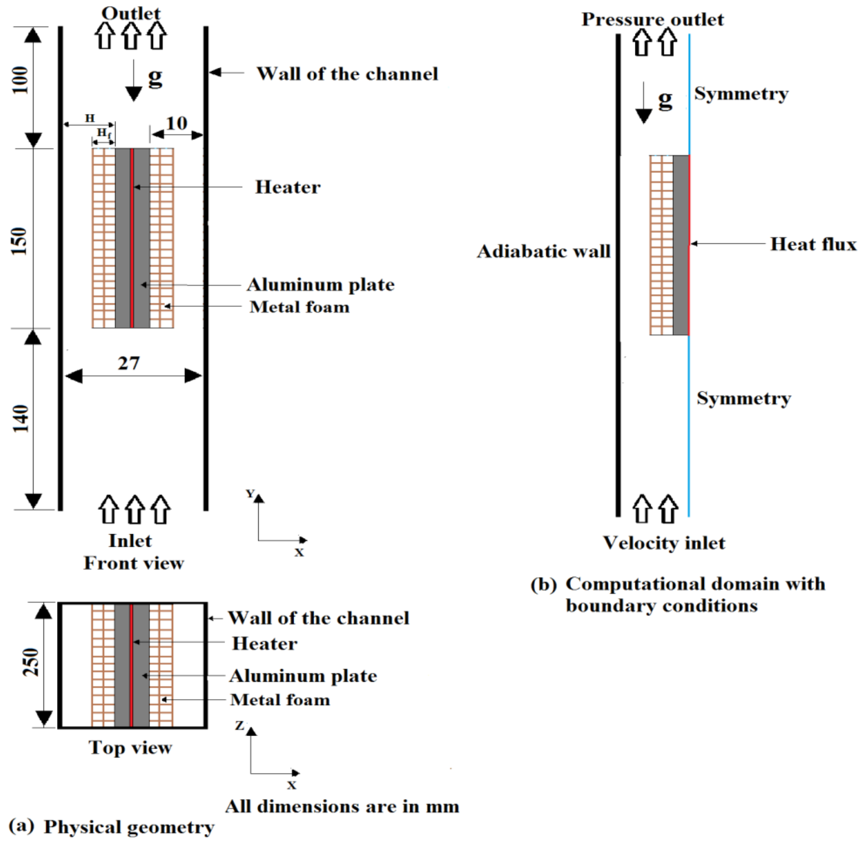


Fig. 1. Schematic of the physical geometry along with boundary conditions

Table 1.Characteristics of Metal foams [2]

Material	PPI	Porosity	Permeability 10^7, m^2	Form drag coefficient
Aluminum	10	0.95	2.480	94.98
	20	0.90	2.177	208.82
	30	0.92	1.644	148.97
	45	0.90	0.420	397.01
Copper	10	0.88	1.742	176.75

2. Boundary conditions

The numerical computations can be performed for one half of the geometry due to its symmetry about Y-axis. Subsequently, one side of the vertical channel with one side metal foam and half of the aluminium plate are considered for the further analysis. The boundary condition required for the inlet to the channel is defined with uniform velocity and the outlet of the channel is assigned with zero pressure. A known heat flux is specified for the heater and the side wall is kept adiabatic. The computational domain along with boundary conditions is shown in Fig. 1(b).

3. Details of simulation

The numerical computations are performed on the selected computational domain using commercially available software ANSYS FLUENT. Air is considered as the working fluid and flows in the channel both in open region as well as in metal foam region. A conjugate heat transfer numerical analysis is carried out with Boussinesq approximation to account for the natural convection effects in the mixed convection. The inlet velocity of the fluid is varied from 0.05 to 3 m/s and the Reynolds number varies between 150 and 9000. The transition and turbulent flow features are captured using k-kl-ω transition model and k-ω model respectively [3]. The metal foam region is considered as a homogeneous porous medium, the Darcy Extended Forchheimer and local thermal non-equilibrium models have been used for modelling flow and heat transfer through metal foam porous medium. The details of governing equations used for the simulation are given in Kotresha and Gnanasekaran [1]. The important parameters such as surface area density and interfacial heat transfer coefficient for the metal foam is calculated based on the expressions given by Calmidi and Mahajan [4].

4. Results and Discussions

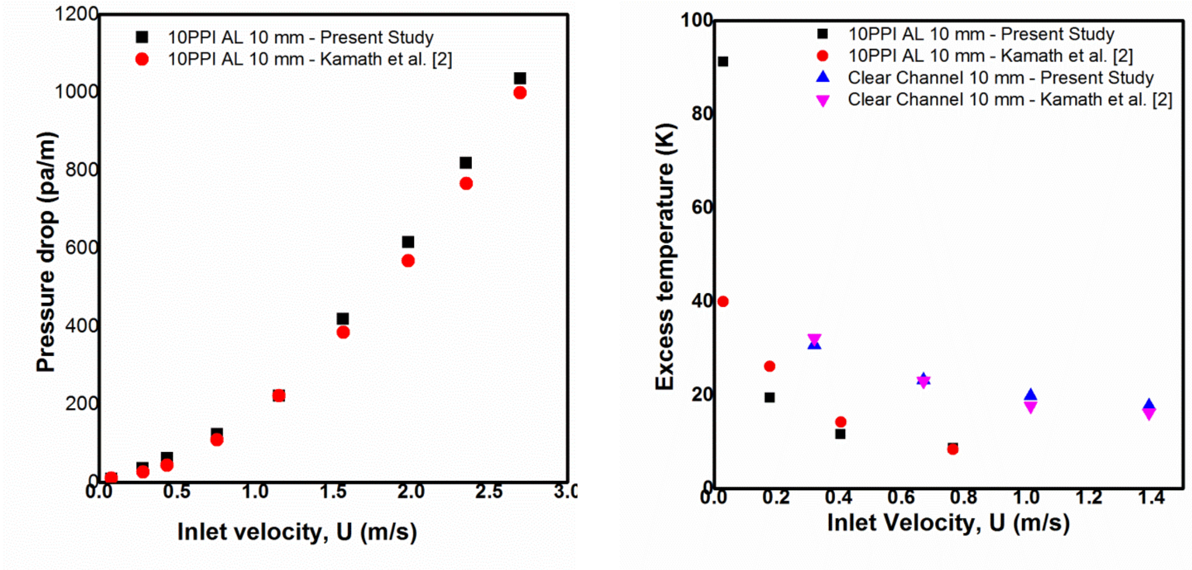
5. 1. Grid sensitivity analysis and Validation

In order to find the optimum size of the mesh for the numerical computations, grid sensitivity analysis is carried out for three different grid sizes of the mesh. The aluminium metal foam of 10 PPI with 20 W heat input for the heater is considered for finding the optimum size of the grid in 26130, 56700 and 88400 number cells. Table 2 shows the deviation of pressure drop and excess temperature obtained for three grid sizes. Based on the analysis the grid size of 56700 is selected for further numerical investigation as it shows less deviation in pressure drop and excess temperature.

Table 2. Results of the grid independence study for 10 PPI aluminium metal foam

Cells	Pressure Drop (ΔP)	Temperature Difference (ΔT)	Deviation (%)	
			|ΔP|	|ΔT|
26130	27.60	7.74	0.22	0.94
56700	**27.56**	**7.70**	**0.07**	**0.42**
88400	27.54	7.66	**Base Line**	

The numerical results are initially compared with experimental results of Kamath et al. [2] for the purpose of validating the methodology. Figure 2 shows variation of pressure drop and excess temperature obtained for 10 PPI metal foam for completely filled channel ($H_f = H$). The numerical results of pressure drop obtained in the present study matches well with the experimental results of Kamath et al. [2]. The excess temperature results shows more deviation at very low velocities of the fluid but this deviation goes on reduces and matches well the experimental results at higher velocities. A similar kind of results is observed by Lin et al. [5].



(a) (b)

Fig. 2. Validation of numerical results (a) Pressure drop (b) Excess temperature

5. 2. Velocity distribution

The velocity distribution obtained in the present study for 10 PPI metal foam is compared with analytical results obtained by Lu et al. [6] as shown in Fig. 3. The velocity distribution obtained in the present study matches very well with the analytical results. The velocity in the foam free region increases with increase in the filling rate of the metal foam in the channel. The effect of porosity can also be seen from the plot, the velocity increases in the foam region and decreases in the foam free region as porosity of the metal foam increases for the same filling rate. It is also observed that the velocity increases in the foam and foam free region as filling rate increases. This is because the amount of fluid entering into the metal foam increases as filling rate increases.

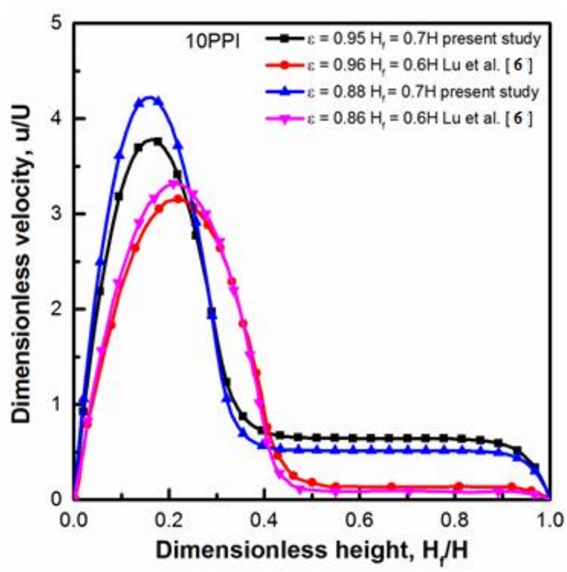


Fig. 3. Comparison of Velocity distribution with analytical benchmarks

5. 3. Effect of porosity and thermal conductivity

Figure 4 shows the pressure drop and friction factor with respect to Reynolds number for both 10 PPI aluminium and copper metal foams. The pressure drop and friction factor is higher for copper metal foam compared to aluminium foam because the porosity of the copper is lesser compared to aluminium metal foam. The friction is more in case of copper metal foam compared to aluminium metal foam because the permeability is low for copper metal foam compared to aluminium metal foam.

5. 3. Thermal results

The effect of inlet velocity and pore density of the metal foam on the excess temperature is shown in Fig. 3. The temperature excess decreases with increasing inlet fluid for all the thicknesses of the metal foam, shown in Fig. 5 (a). However, the temperature excess decreases with increasing metal foam thickness in the channel at a particular velocity. Similar type of result is also observed for other PPI metal foams. The temperature difference in general decreases as pore density increases at a particular velocity for all the thicknesses as shown in Fig. 5 (b). But the temperature excess increases slightly for 45 PPI metal foam of partially filled channel. This may be due to the fact that the porosity of the 45 PPI (0.90) metal foam is smaller compared to 30PPI metal foam (0.92).

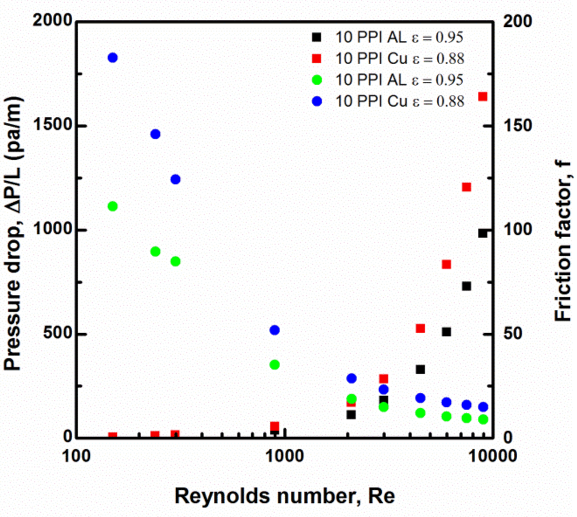


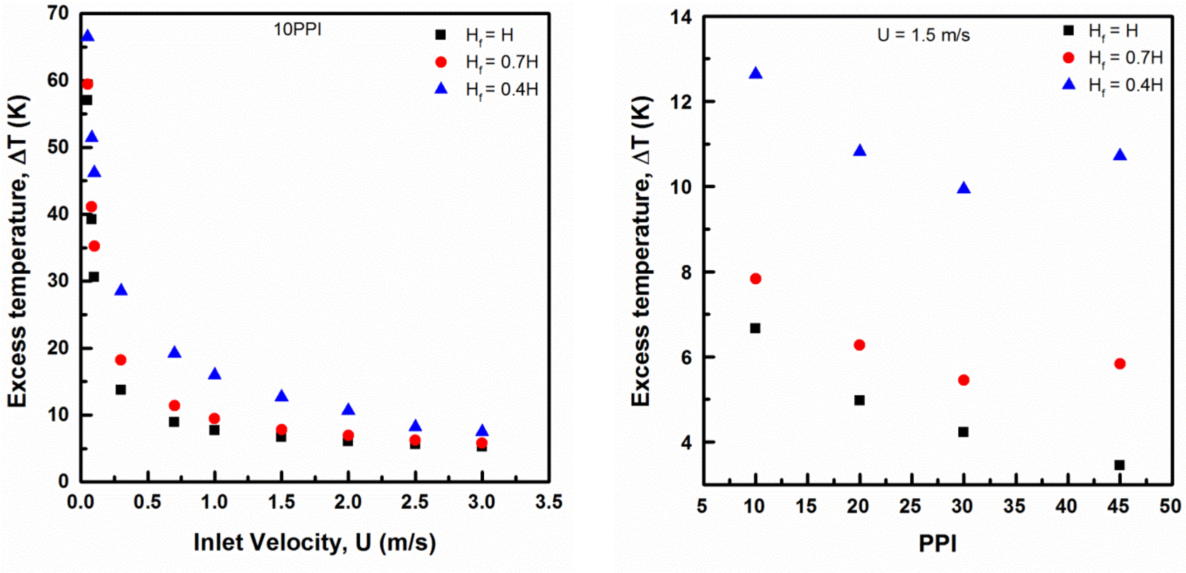
Fig. 4. Comparison of variations of pressure drop and friction factor with respect to Reynolds number for 10 PPI aluminum and copper metal foams

5. Conclusions

A two dimensional numerical simulation of mixed convection through partially filled aluminium metal foams is performed using commercial ANSYS FLUENT. The problem domain considered consists of a vertical channel in which aluminium plate heater assembly is placed at the centre and heat transfer is enhanced by placing metal foams on either side of the aluminium plate in the channel. The flow and heat transfer through the metal foam porous medium is modelled using Darcy Extended Forchheimer and local thermal non-equilibrium models. The numerical results are compared with experimental results for the purpose of validation of the methodology. The silent conclusions based on the study are as follows.

- The velocity in the foam region and foam free region increases as filling rate increases.
- The velocity in the open region increases and decreases in the metal foam region as porosity increases. This is due to the fact that the flow resistance increases in the metal foam region as porosity increases in the metal foam region, hence the fluid flows towards the open region of the channel.

- The excess temperature decreases with increasing the metal foam filling at a particular velocity and shows a general decrease with increase in fluid inlet velocity.
- The excess temperature decreases with increase in the partial filling of the metal foam in the channel for a particular pore density of the metal foam.



(a) (b)

Fig. 5. Excess temperature (a) Effect of filling rate (b) Effect of pore density

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