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Flow and Heat Transfer Characteristics in High Porosity Metal Foams

Chanhee Moon
Pusan National University, School of Mechanical Engineering
San 30 Jangjeon-dong Geumjeong-gu 609-735, Busan, Republic of Korea
chmoon@pusan.ac.kr

Kyung Chun Kim
Pusan National University, School of Mechanical Engineering
San 30 Jangjeon-dong Geumjeong-gu 609-735, Busan, Republic of Korea
kckim@pusan.ac.kr

Abstract -A numerical simulation and an experiment are conducted for heat transfer of filled and hollow metal foam ligaments. Metal foam is a promising material for high heat transfer coefficient. It has random structure and high surface area. It is expected that the insertion of the metal foam into the heat exchanger will bring about effects of expanding the heat transfer area and increasing heat transfer coefficients by flow disturbances. In this study, the heat transfer characteristics between hollow and filled ligaments of metal foam was observed and the Nusselt number obtained with filled ligament shows higher than that obtained with hollow ligaments. The used metal foam in experiment is 40PPI and Weaire-Phelan model is applied to metal foam geometry for numerical simulation.

***Keywords*:** Metal foam, ligament, thickness, Weaire-Phelan structure, Numerical simulation, Heat exchanger, Heat transfer, Forced convection

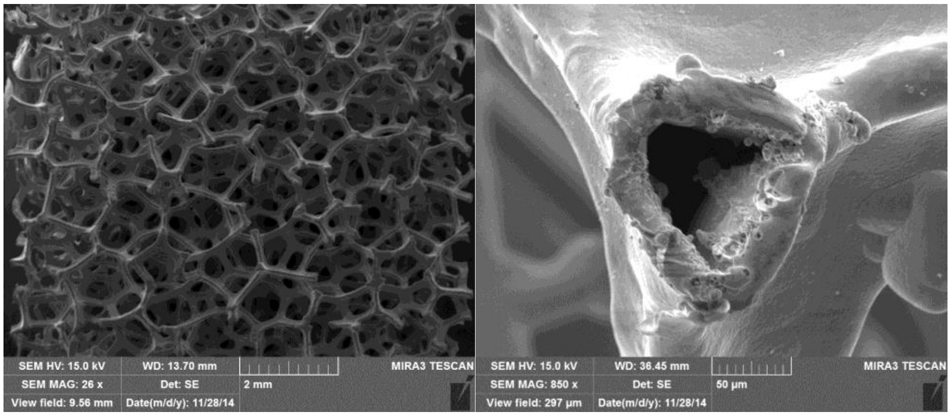
1. Introduction

Metal foam is cellular structure consisting of a porous metal with a large number of gas-filled bubbles, and it is largely divided into two groups such as close cell and open cell. Gas bubbles inside the metal are not connected to exist independently in the case of close cell metal foam. As for open cell type, gas bubbles inside the material are connected to each other, which facilitate the passage of gas or fluid, thereby providing a wider variety of uses compared to those of close cell type. In addition, open cell metal foam has a dodecahedron structure similar to that of human bones, and its fully isotropic structure exhibits superior stability compared to that of an anisotropic honey comb.

It is expected that the insertion of the metal foam into the heat exchanger will bring about effects of expanding the heat transfer area and increasing heat transfer coefficients by flow disturbances. The metal foam is characterized by its configuration due to very large and irregular ratio of volume to surface area, and the fluid flow within the metal foam has fine porous structure and takes the form of complex three-dimensional form. However, since the structure of the metal foam is very complex as shown in Fig. 1 (a), it is very difficult to conduct an analysis of the three-dimensional flow and heat transfer on the microstructure inside the metal foam. For this reason, the fluid flow in porous media and heat transfer characteristics are being analysed mainly using a simplified Darcy equation.

As many researchers had dedicated to investigate applicable potentials, characteristics and properties of metal foam are well known today. Calmidi et al. (2000) investigated the transport phenomena that arise in high porosity (> 0.85) metal foams. They dealt with incompressible fluid flow and pressure drop in metal foams. An experiment was proceeded to determine the permeability K and the inertial coefficient f. An empirical model was formulated to relate K and f to the metal foam parameters in the relevant non-dimensional form.

Kopanidis et al. (2010) applied the Navier-Strokes equations to a direct numerical analysis by modelling metal foam module as the Weaire-Phelan structure composed of two irregular 12-sied polyhedron and six 14-sided polyhedron and compared the analysis results to experimental results with respect to the pressure drop and heat transfer performance.



(a) (b)

Fig. 1. Open-cell metal foam (a) structure (b) cutting area view.

But most researches show differences for results of Nusselt number (Nu) although they did experiments with same PPIs (pores per inch) of metal foams. These differences are coming from the metal foam manufacturing methods.

There are several techniques for manufacturing open metal foam. Especially, powder metallurgy is most general thing used. Its manufacturing steps are as followed: (a) After plasma coating to polyurethane foam with non-magnetic conductor, do electroplating on it with metal powder. (b) And it is incinerated and sintered in 400~800℃ for 1 to 10 minutes rapidly. (c) Then it is reduced at hydrogen gas atmosphere. In this process, there is one point which claims attention. That is the hollow parts inside metal foam ligaments. Incinerating the polyurethane, some hollow parts are formed as Fig. 1. Although Kopanidis et al. (2010) commented about the influence of hollow part in their paper, it is need to investigate it more deeply, so the present study added some significant supplements by conducting 3D numerical simulation and experiment with 40 PPI (pores per inch) open cell metal foam made of copper for the validation of mathematical approach.

2. Mathematical Equations

Under the Darcy-Forchheimer rigid porous model, Reynolds number about permeability of metal foam is defined as Re_K.

$$\frac{\Delta P}{L} = (\mu u_0/K) + \left(\rho I u_0^2/\sqrt{K}\right) \tag{1}$$

$\frac{\Delta P}{L}$, K are pressure gradient along the test section and permeability of metal foam. u_0, μ, ρ and I are averaged outlet velocity, viscosity, density and inertia coefficient of working fluid respectively.

$$Re_K = u_0\sqrt{K}/\nu \tag{2}$$

where ν is dynamic viscosity of working fluid. The definitions of Nusselt number (*Nu*) and heat transfer coefficient (*h*) are:

$$Nu = hd/k \tag{3}$$

where d and k is hydraulic diameter of test section and thermal conductivity of working fluid respectively. Heat transfer coefficient is defined as

$$h = \left[\dot{m}C_p(T_{out} - T_{in})\right]/[A_s(T_{wall} - T_{in})] \tag{4}$$

where $\dot{m}$ and C_p are the mass flow rate and specific heat under constant pressure of working fluid respectively. A_s is surface area of the heat source. T_{wall} is the averaged wall temperature of test section. And T_{in}, T_{out} are averaged inlet temperature and outlet temperature of working fluid respectively.

The new definition, filled ratio (ξ) are defined as:

$$\xi = \left(r_0^2 - r_i^2\right)/r_0^2 \tag{5}$$

It represents the filled area ratio of a ligament. r_0 is the outer radius and r_i is the inner radius when metal foam ligament is simplified to a circular pipe.

3. Numerical Test Section and Boundary Conditions

With CFX (ANSYS Inc.) computational fluid dynamics (CFD) program, numerical simulations were conducted. Metal foam modelling was carried out with Weaire-Phelan structure used to mimic the metal foam structure. Because the metal foam can be assumed to be a uniform structure, so this is a quite good choice to replicate. After the modelling, 2.89 by 2.89 of test section area was taken by cutting it. Fig. 2 shows the feature and boundary condition of test section.

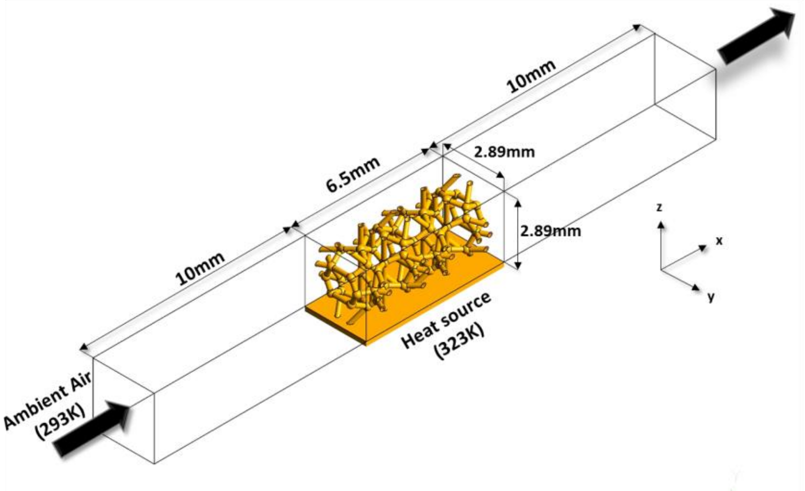


Fig. 2. Numerical test section and boundary conditions

Total length of test section is 6.5mm. And for the fully developed flow totally 20mm of channel was extended. Constant temperature condition was given by 323K and compressible working fluid was ambient air having temperature of 293K. And also translational periodicity condition was granted to + y-axis and – y-axis. And adjusting filled ratio of the metal foam ligament, CFD simulation was made progress. Proximity and Curvature function were used to generate mesh. Inflation method was added to wall boundary and aspect ratio was 2.96 and double precision conditions are selected at solver so possibility of errors was minimized. Porosity of the model is 0.93.

4. Experimental Test Section and Boundary Conditions

Fig. 3 shows the schematic of test equipment to investigate single phase flow in metal foams. Air at ambient temperature is used as a working fluid, a suction style blower and an inverter are used to control velocity of flow in the metal foam channel. According to ISO 5167 (International Organization for

Standardization), a proper orifice was designed and employed to predict velocity in the flow system. Pressure is measured by pressure transducers (PSC, Sensys) which were located at both ends of test section. All experiment was carried out on atmospheric condition, and tow pressure transducer and five thermocouples were placed in the test section, and a pressure transducers and a thermocouples among them were located before and after the plate type heat exchangers respectively. To convert pressure and temperature data, data acquisition device (cDAQ-9174) and modules (NI9203, NI 9213), which is produced by National Instrument, was used.

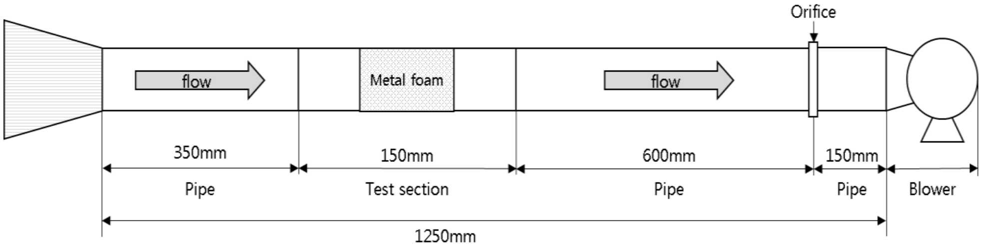


Fig. 3. Schematic of experiment

All of experimental data can transfer to PC through Ethernet. The total length of test section for experiments is 150mm, and the width is 60mm. Height of test sections of which pore size is 40 PPI (pores per inch) is 5mm and porosity is 0.95. Diffusion bonding method was used to bond 2mm thickness of metal plates and metal foams. Two flanges are located on test section to replace test section easily. Five k type thermocouples are located on wall of test section along flow direction. Nusselt number (Nu) derived from measured temperature for test section. A plate heater was used to measure heat transfer and located on at the top and bottom sides of test section. To minimize heat loss, the test section was wrapped by insulating materials.

5. Results and Discussion

The Fig. 4 represents similarity between real 40 PPI metal foam and CFD simulation result. Under the Darcy-Forchheimer, Eq. (1), permeability K is appeared with $2.394*10^{-8}$ m^2 at CFD and $2.63*10^{-8}$ m^2 for the experiment.

Fig. 5 shows that the numerical simulation results at Re_K = 42.25 (5m/s) for various filled ratio (ξ). Indications about temperature differences among the results are very clear. Metal foam temperature of (a) display that all parts are in red (323K). But as filled ratio (ξ) is decreased, some parts is getting lower temperature area. Despite of (a), (b) shows intervals of 317K to 323K and it is wider at (c). Finally at filled ratio (ξ) = 0.199, (d), intervals from 311K to 323K are appeared. And temperature gradient has a positive slope along the x-axis. Simplifying the test section to internal flow forced convection in a circular pipe, the heat transfer phenomenon fits well. For the temperature distribution of working fluid, because of the heating plate, bottom side there is no significant change but, for y-axis, upper site have impressive variation of temperature change. Especially, (d) shows that working fluid take more heat energy from the metal foam. It is come from the interacting area between metal foam ligament and heat source. For a constant r_o, higher r_i can get more energy from the heat plate.

Fig. 6 shows the calculated Nusselt number (Nu) according to each Reynolds number (Re_K). The result demonstrates that forced convection becomes pronounced as both Reynolds number (Re_K) and filled ratio (ξ) are increased. As the Reynolds number (Re_K) is increasing, the effect of filling ratio on Nusselt number (Nu) becomes dominant. There is excellent agreement between experiment and numerical simulation with considering the ligament filling ratio. At the low Reynolds number (Re_K) less than 5, there is no effect of filling ratio because of low convection. However, the higher effect the higher Reynolds number due to the limited conduction cannot be balanced with the higher convection in case of low filling factor. It is confirmed from the temperature variation between wall temperature (T_{wall}) and outlet temperature (T_{out}). As Reynolds number is increasing, outlet temperature (T_{out}) becomes to be constant but wall temperature (T_{wall}) is being decreased consistently.

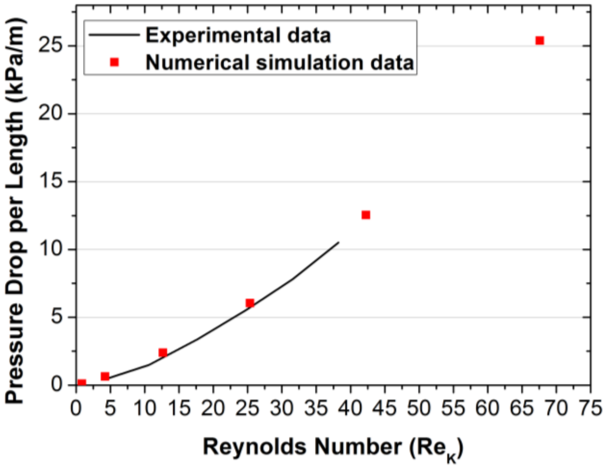
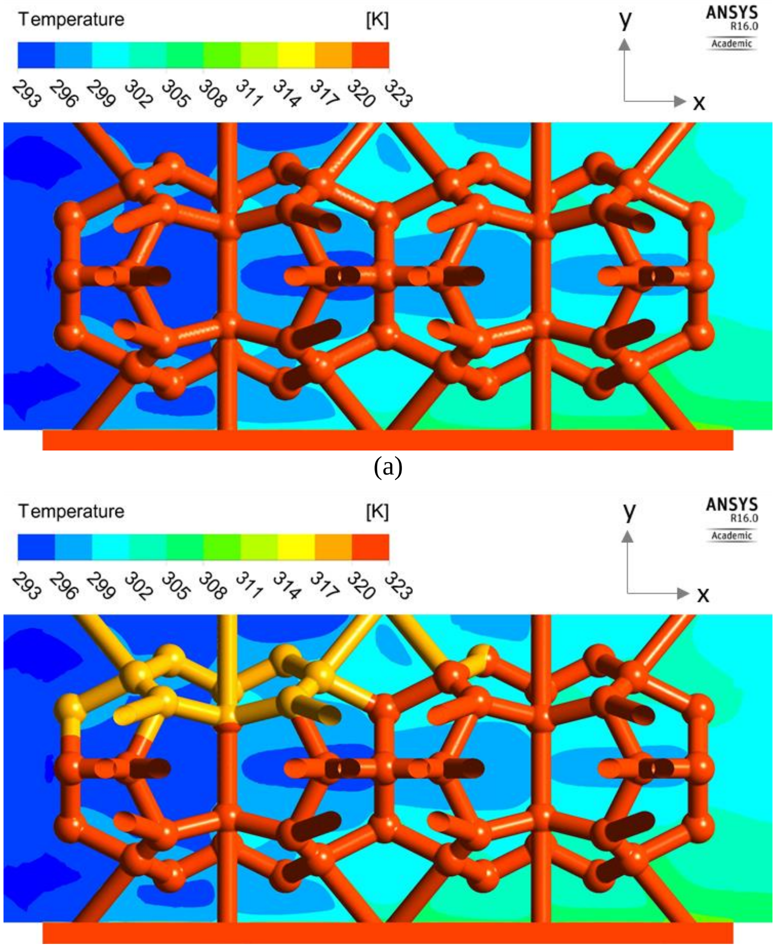
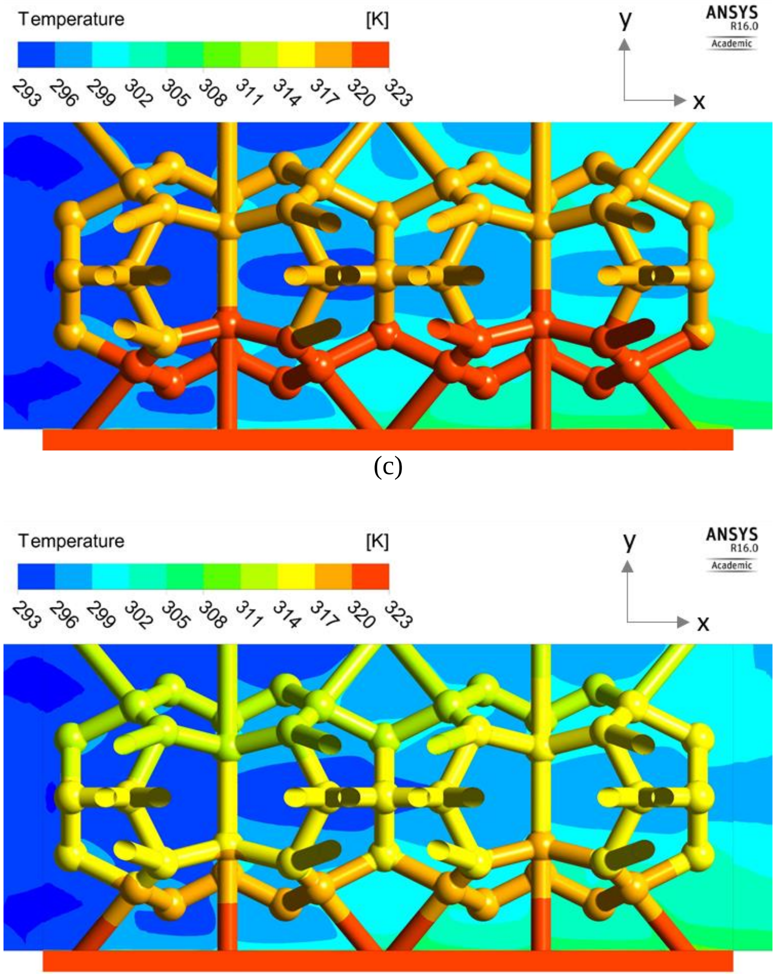


Fig. 4. Pressure drop per length of experimental data and numerical simulation data.



(a)

(b)



(c)

(d)

Fig. 5 Numerical simulation results when Reynolds number for Permeability (Re_K) is 42.25 (5m/s) at various filled ratio (ξ) (a) $\xi = 1$ (b) $\xi = 0.776$ (c) $\xi = 0.532$ (d) $\xi = 0.199$.

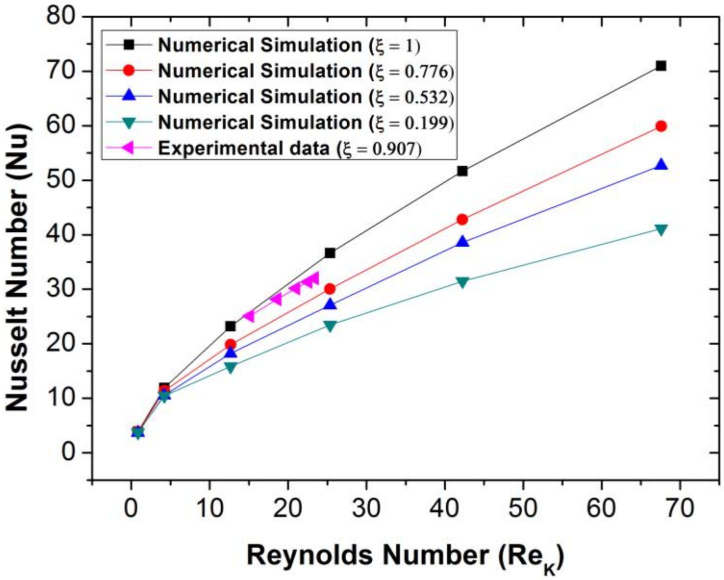


Fig. 6. Nusselt number (Nu) versus Reynolds Number (Re_K) of simulation and experimental result.

6. Conclusion

Heat transfer characteristic according to variation of ligament thickness is verified. A numerical simulation and experiment is conducted and validated for heat transfer of filled and hollow ligaments. The used metal foam in experiment is 40PPI and Weaire-Phelan model is applied to metal foam geometry for numerical simulation. A new parameter, filling ratio (ξ) was defined and the result showed that hollow parts of metal foam ligament gives an important influence to heat transfer characteristics in the range of Nusselt number (Nu).

Acknowledgements

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