한국동력기계공학회지 제12권 제5호 pp.54~58 2008년 10월

Study on the Hydraulic and Thermal Characteristics of Metallic Porous Medium

다공성 금속의 수력 및 열 교환 특성에 관한 연구

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(received 7 May 2008, revised 11 September 2008, accepted 30 October 2008)

주요용어 : 발포다공성매체(Metallic Porous Media), 투과계수(Permeability), 내부계수(Inertial Coefficient), 유효전도율(Effective Conductivity)

요 약 : 최근 열교환기의 향상을 위해 발포다공성매체의 적용이 증가하고 있다. 열교환기의 적용에 있어서 발포다공성매체의 이점을 살펴보기 위해 본 연구에서는 2가지 실험을 수행하였다. 첫 번째는 수력의 관점에서 투과계수 및 내부계수를 결정하는 것이고, 두 번째는 열교환의 관점에서 다공성매체의 유효전도율을 측정하는 것이다. 본 실험에서는 기공도는 거의 같으나 기공의 크기가 각각 20 ppi와 40 ppi인 구리 다공성매체를 사용하였다. 실험의 결과는 40 ppi 크기의 다공성매체가 수력과 열교환, 두가지 관점 모두에서 보다 높은 저항 효율을 나타낸다는 것을 보여준다.

Nomenclature

α : coefficient for curve fit equations [kg/m^{3}s]
β : coefficient for curve fit equations [kg/m^4]
L : length of foam [m]
u : velocity [m/s]
μ : viscosity of air [m^2/s]
ρ : density of air [kg/m^3]
K : permeability [m^2]
f : inertial coefficient
k_e : effective conductivity [Wm^{-1}K^{-1}]
k_R : conductivity of copper [Wm^{-1}K^{-1}]
p : pressure [Pa]
t : temperature [°C]

1. Introduction

In Metal foam has been long used in industry field. Study on the character of metal foam is needed. Two kinds of copper foam used in the experiments are presented in Fig. 1. 20 PPI (pores per inch) has a little larger porosity 0.9699 than 40 PPI(porosity 0.9585), we can notice that the difference is very small. On the other side, from Fig. 1 we can see that the size of pores is quite different from each other. Fig.2 is the microscopic view of foam, and the notion for size of cell is illustrated in it. This paper presents a experimental investigation for the determination of permeability(K), inertial coefficient(f) and effective thermal conductivity(k_e) of two copper foam, which have almost the same high porosity but different cell size.

2. Determining Permeability (K) and inertial coefficient (f)

2.1 Experiment procedure

The Forchheimer extended Darcy's equation is accepted here for this homogeneous, uniform, and isotropic metallic foam(1) :

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$$-\frac{dp}{dx}=\frac{\mu u}{K}+\frac{\rho f}{\sqrt{K}}u^2 \qquad (1)$$

The experiments on the metal foam samples were conducted in a wind tunnel (Fig. 2). 12 copper foams size of D 50 mm, thickness 20 mm were inserted in the tube, 6 pressure sensors along the tube were used to measure pressure of air. (pressure sensor : digital manometer series 477)The tunnel is connected to a probe calibrator and a vacuum machine. when vacuum machine turn on, the air will flow through the tube, and we will get the pressure profile using pressure sensor. Airflow velocity trough the metal was set from 1.14 to 2.67 m/s. The pressure drop data collected during experiment were found to increase with the length.

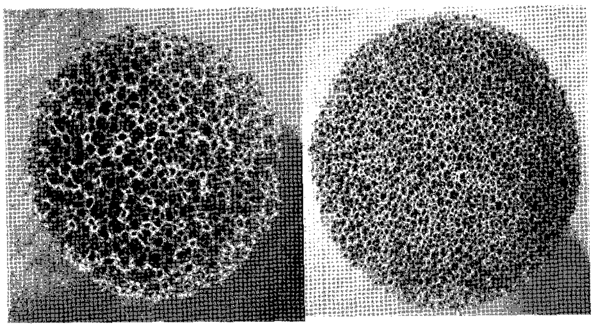

Fig.1 Copper foam (left one 20 PPI, right one 40 PPI)

2.2 Result

The momentum equation can be written as:

$$\frac{\Delta p}{L}=\alpha u+\beta u^2 \qquad (2)$$

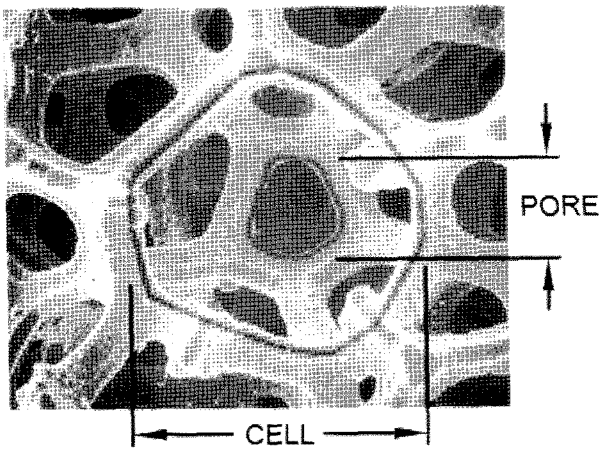

Fig. 2 microscopic photo of foam

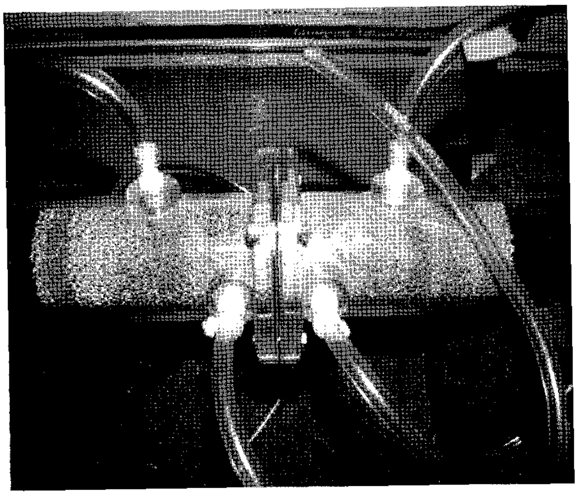

Fig. 3 Pressure drop measurement device

with the technic of curve fitting, the value of α and β can be determined. Comparing Eq. (1) and Eq. (2), the value of K and f are:

$$K=\frac{\mu}{\alpha},\quad f=\frac{\beta\sqrt{K}}{\rho}.$$

These K and f are listed in Table 1. The result shows that although the porosities (the fraction of void volume) are almost same (0.9699 and 0.9585, respectively), the 40 PPI metallic foam shows a higher resistance influence in hydraulic aspect than 20 PPI foam due to the small size of pores.

Table 1 Characteristics of the copper foam used for pressure drop experiments.

Model	PPI	porosity	$K(\times 10^7\ m^2)$	f
1	20	0.9699	2.7	0.0175
2	40	0.9585	0.95	0.0243

3. Effective conductivity

3.1 Experiment procedure

The effective thermal conductivity depends on various characteristics of the material, such as structure of metal frame, thermal radiation effect, natural convection effect, and cell size effect.[1] The study on modelling effective thermal conductivity have been done by several researchers. Our experiment result will be compared to the theory result from both Boomsma[3] and Ramvir Singh[5].

The principle of the measurement is shown in Fig. 4. There are total 10 temperature sensors along the copper bar. Letter A stands for the group of sensor. Letter B stands for the column that is using to keep balance of device. C stands for tap water inlet, and D is water outlet. Constant heat flux through thecopper bar was kept by heating top part of the device with constant temperature hot water tank and cooling the bottom of device with uniform cold water flow(tap water flows from C to D). For this device there is a formula to calculate the conductivity of sample pieces.

$$k_e = \frac{(L_b - L_a)}{\frac{\Delta t_b L_R}{k_R \Delta t_R} - \frac{\Delta t_a L_R}{k_R \Delta t_R}} \qquad (3)$$

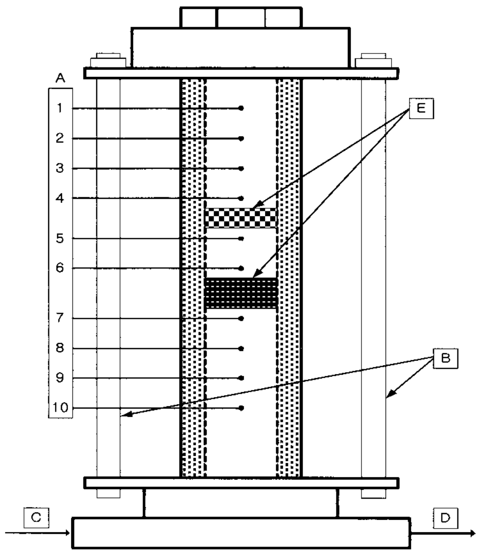

Fig. 4 Device for determination of effective conductivity(E indicates copper foams)

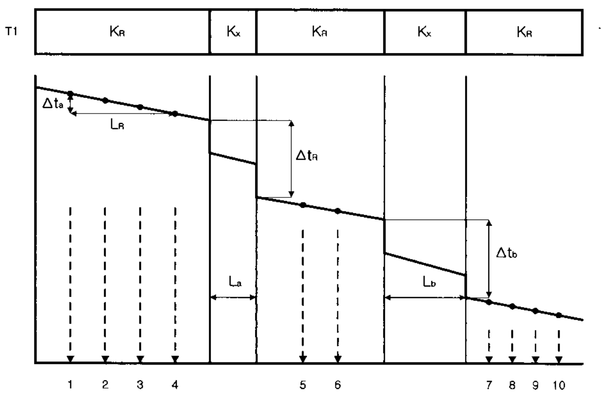

Fig. 5 Scheme of temperature profile along copper bar

where, as Fig 5 shows, a and b symbolize two piece of foam with different thickness (20mm and 10 mm, respectively), R symbolize copper bar.

3.2 Result and anylysis on thermal conductivity

The study on modelling effective thermal conductivity have been done by several researchers. Boomsma and Poulikakos[3] developped a three dimensional model using metal foam structure as tetrakaidecahedron cells with cubic nodes at the intersection of two fibers. Bhattacharya et al.[4] presented a one dimensional heat conduction model considering the porous structure as a two dimensional array of hexagonal cells. Ramvir Singh[5] summarized the experiment data from Bhattacharya[3] and developed a compuion. C.Y. Zhao's[1] result shows that the effective conductivity with convection can be more than twice that at vacuum(which means there is no convection happen). All of these research did not take convection and radiation phenomenon into consideration.

The Boomsma's model is

$$k_e = \frac{1}{\sqrt{2}\,(c+d+q+w)} \qquad (4)$$

where,

$$c = \frac{4F}{[2e^2 + \pi F(1-e)]\lambda_s + [4 - 2e^2 - \pi F(1-e)]\lambda_f}$$

$$d = \frac{(e-2F)^2}{(e-2F)e^2\lambda_s + [2e - 4F - (e-2F)e^2]\lambda_f}$$

$$q = \frac{(1-\sqrt{2}\,e)^2}{\pi F^2(1-2\sqrt{2}\,e)\lambda_s + [\sqrt{2} - 2e - \pi F^2(1-2\sqrt{2}\,e)]\lambda_f}$$

$$w = \frac{2e}{e^2\lambda_s + (4-e^2)\lambda_f}$$

$$F = \sqrt{\frac{\sqrt{2}\,(2 - 0.625\sqrt{2}\,e^3 - 2\phi)}{\pi(3 - 4\sqrt{2}\,e - e)}}$$

$e = 0.339$

Ramvir Singh's formula is

$$k_e = k^F k'^{(1-F)} \qquad (5)$$

where.

$k = \phi k_f + (1-\phi)k_s$

$$k' = \frac{k_s k_f}{(1-\phi)k_f + \phi k_s}$$

$$F = (0.3031 + 0.0623\ln(\phi \frac{k_s}{k_f}))$$

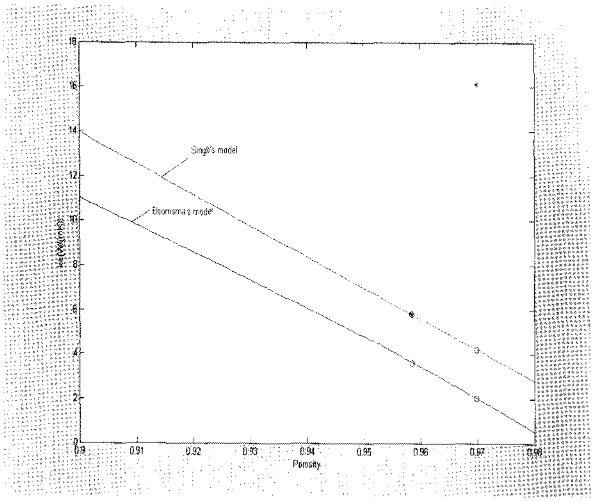

Fig. 6 Comparison between experiment and theory

Experimental result (using Eq. (3))and theory result(Boomsma and Ramvir Singh's model) were listed in Table 2 and Fig. 6. We can see that the effective conductivity of 40 PPI match well with the Ramvir Singh's theory, but the value of 20 PPI is much higher than predict. The difference between two model calculation result is quite small, due to the fact that two kinds of copper foam have almost same porosity (0.9699 and 0.9585), and we know that porosity is main factor in both of two model (as shown in Fig. 6). Since 20 PPI foam has much larger pore size than 40 PPI, the convection can therefore significantly enhance thermal transport as evidenced by the result shown in Table 2. In Fig. 6, we can also see that the experimental result of 20 PPI foam is higher than that of 40 PPI. This result agree with the conclusion of C.Y. Zhao's(2) research, which indicates that the effective conductivity with convection can be more than twice at vacuum. But detail enhancement in thermal conductivity due to convection is difficult to analysis, because the complicated structure and minuteness of foam.

Table 2 Comparison of conductivity between experiment and theory

PPI	Porosity	k_e(expt)	k_e(Boomsma)	k_e(Singh)
20	0.9699	16.05	2.02	4.21
40	0.9585	5.8	3.6	5.8

The thermal conductivity is in $Wm^{-1}K$

4. Summary

This paper focused on the hydraulic and thermal aspect study for two kinds of copper foam with almost same high porosity(0.9699 and 0.9585) but quite different pore size as shown in Fig. 1. Result indicated that 40 PPI copper foam show higher resistance influence both on fluid flow and heat transfer.

Acknowledgement

This research was financially supported by the Ministry of Commerce Industry and Energy (MOCIE) and Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Regional Innovation, and Second phase of Brain Korean 21 project.

Reference

1. P. Forchheimer, Wasserbewegung durch boden, 1901, VDIZ. 45 1782~1788.
2. Zhao, C. Y., T. J. Lu, et al. 2004, "The temperature dependence of effective thermal conductivity of open-celled steel alloy foams", Materials Science and Engineering A, Vol. 367, No.(1-2), pp. 123~131.
3. Boomsma, K. and D. Poulikakos, 2001, "On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam", International Journal of Heat and Mass Transfer, Vol. 44 No. 4, pp. 827~836.
4. Bhattacharya, A., V. V. Calmidi, et al, 2002, "Thermophysical properties of high porosity

metal foams", International Journal of Heat and Mass Transfer, Vol. 45, No. 5, pp. 1017~1031.
5. Singh, R. and H. S. Kasana, 2004, "Computational aspects of effective thermal conductivity of highly porous metal foams", Applied Thermal Engineering, Vol. 24, No. 13, pp. 1841~1849.