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Theory study on thermal performance of metal foam

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ABSTRACT: In many literatures the researchers pointed out that the using metal foam will significantly enhance the performance of heat exchanger. This paper focuses on theory study of metal foam, including calculation method of properties of foam (permeability K, inertial coefficient f, fiber diameter d_f, and effective conductivity k_e), model of pressure drop and model of heat transfer. Theory analysis on the performance of heat exchanger will be presented here. Finally the optimal material will be obtained from theory calculation.

Key words: Metal foam, Theory Study, Performance of heat exchanger

기 호 설 명

d_f : Fiber diameter
d_p : Pores diameter
f : Inertial coefficient
K : Permeability [m^{-2}]
k_e : Effective concudtivity [W/(mK)]
P : Pressure [Pa]
PPI : Pores per inch
Nu : Nusselt number
u : Dacian velocity [m/s]

그리스 문자

ε : Porosity
Θ : Dimentionless temperature

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1. Introduction

Metallic foams have a distinct but continuous and rigid solid phase, and a fluid phase. as showed in Fig. 1. They are typically available in high porosities, also have high thermal conductivity and large area per unit volume. Typically the properties of commercial available foam are measured by the manufacture, these properties include PPI (pores per inch), porosity, permeability, inertial coefficient, effective conductivity, etc. Many researchers developed models to obtain these by calculation. In case of heat exchanger, there is three kinds of heat transfer mechanisms, heat conduction in fibers, heat transfer by conduction in fluid phase, and internal heat change between solid and fluid phases. The following will discus all above in detail.

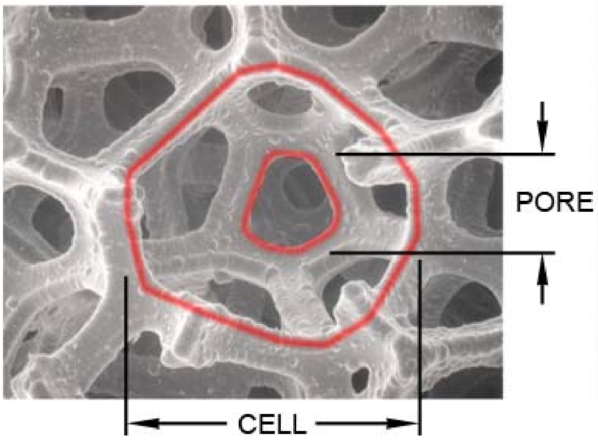

Fig. 1 Microscopic photo of foam

2. Properties of metal foam material

Typically, metal foam is charactered by foam material, PPI (the number of pores per inch), porosity (ε, the volume ratio of void space to total space), permeability(K), inertial coefficient (f), surface area density(a) and effective conductivity(k_e). Resent years some researchers have study on the calculative characteristics of metallic foam. Calmidi (1998) purposed a specific formulation for permeability base on the experiment data. Boomsma and Poulikakos (2001), Bhattacharya, Calmidi et al. (2002), Singh and Kasana (2004) developed models to calculate the effective conductivity of foams, respectively. (Lu, Zhao et al. (2006) presented a formulation to get area density a.

$$\frac{K}{d_p^2} = 0.00073(1-\varepsilon)^{-0.224}(d_f/d_p)^{-1.11} \qquad (1)$$

$$\text{where, } d_p = 0.0254/PPI \qquad (2)$$

$$\frac{d_f}{d_p} = 1.18\sqrt{\frac{(1-\varepsilon)}{3\pi}}\left(\frac{1}{1-e^{-((1-\varepsilon)/0.04)}}\right) \qquad (3)$$

The following is the Boomsma's model

$$k_e = \frac{\sqrt{2}}{2(R_A + R_B + R_C + R_D)} \qquad (4)$$

where

$$R_A = \frac{4\lambda}{(2e^2+\pi\lambda(1-e))k_s + (4-2e^2-\pi\lambda(1-e))k_f} \qquad (5)$$

$$R_B = \frac{(e-2\lambda)^2}{(e-2\lambda)e^2k_s + (2e-4\lambda-(e-2\lambda)e^2)k_f} \qquad (6)$$

$$R_c = \frac{(\sqrt{2}-2e)^2}{2\pi\lambda^2(1-2e\sqrt{2})k_s + 2(\sqrt{2}-2e-\pi\lambda^2(1-2e\sqrt{2}))k_f} \qquad (7)$$

$$R_D = \frac{2e}{e^2k_s + (4-e^2)k_f} \qquad (8)$$

$$\lambda = \sqrt{\frac{\sqrt{2}(2-(5/8)e^3\sqrt{2}-2\varepsilon)}{\pi(3-4e\sqrt{2}-e)}} \qquad (9)$$

where, $e = 0.339$

There is also one formula to describe the area density:

$$a = \frac{3\pi d_f(1-e^{-((1-\varepsilon)/0.04)})}{(0.59d_p)^2} \qquad (10)$$

3.Pressure drop and heat transfer

Consider a rectangular block of open-cell metal foam and heated from above with constant heat flux q, and the other three faces is thermal insulated. The block has a length L (19.5 cm) in the flow direction, Width W (14 cm) and height H (7 cm), as shown in Fig. 2. The air flows through the channel getting heat away from heating plate at velocity u m/s. The properties such as PPI, porosity, permeability, inertial coefficient, effective conductivity, fiber diameter, pore size, area

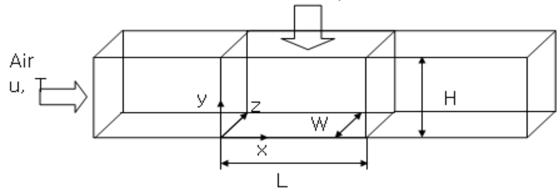

Fig. 2 Schemic of problem

Table. 1 Properties of Aluminium foam

	PPI	porosity	$Kx10^7$ (m^2)	f	kse (W/mK)	$dfx10^5$ (m)	$dpx10^5$ (m)	a (m2)
A1	5	0.973	2.70	0.097	2.48	50	402	415.42
A2	5	0.912	1.80	0.085	6.46	55	380	917.55
A3	10	0.949	1.20	0.097	4.10	40	313	799.63
A4	20	0.955	1.30	0.093	3.71	30	270	756.07
A5	20	0.901	0.90	0.088	7.19	35	258	1305.1
A6	40	0.927	0.61	0.089	5.48	25	202	1390.1
A7	40	0.913	0.53	0.084	6.37	25	180	1850.6

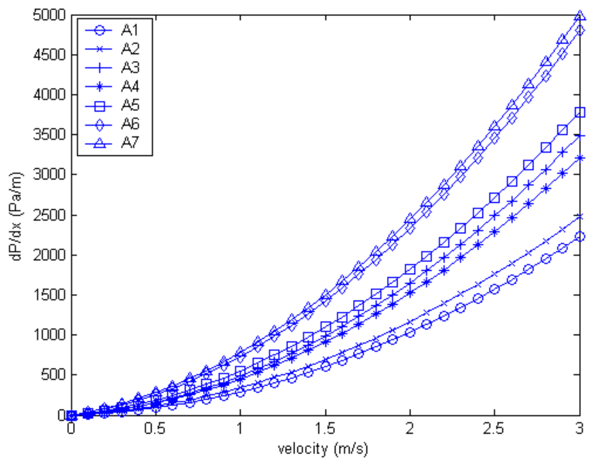

Fig. 3 Unit pressure drop in A foams

ratio are listed in Table 1. The analysis on pressure drop and thermal performance will be described in the following.

3.1 Pressure drop

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

$$-\frac{dp}{dx}=\frac{\mu u}{K}+\frac{\rho f}{K}u^2 \qquad (11)$$

Fig. 3 shows the unit pressure drop when the air velocity ranges from 0m/s to 3 m/s in Aluminium foam. In our problem definition, the length of foam is 0.195 m along the air flow direction. Generally, high PPI leads higher pressure loss, the pressure drop in 40 PPI foam is almost 3 ~ 4 times of that in 20 PPI foam. At a fixed porosity (for example A2 and A7, porosities of them are almost the same at the value of 0.912), decreasing the cell size increased the surface area to volume ratio which therefore increased the flow resistance by lowering the permeability and increasing the pressure drop. (Paek, Kang et al. 2000) did experimental work with aluminium foams, the work result agree with our analysis.

3.2 Heat transfer

it is acceptable to use thermal equilibrium model to our case. Following single governing equation for the heat transfer inside the metal foam developed by Dukhan and Chen (2007) is presented here.

$$\Theta(X,Y)=\alpha X+\frac{1}{2}Y^2-\frac{1}{6}-2\sum_{n=1}^{\infty}\frac{(-1)^n}{\Lambda_n^2}e^{-\alpha\Lambda_{nn}^2X}\cos(\Lambda_n Y) \qquad (12)$$

$$\Theta(X,Y)=\frac{T-T_\infty}{q_w H/k_{s,eff}} \qquad (13)$$

where, $X=x/H, Y=y/H$

$$\alpha=\frac{k_e}{\varepsilon\rho C_p uH} \qquad (14)$$

and, $\Lambda=\lambda_n H=n\pi,\ n=1,2,3...$

Using Eq. (12) at u=2m/s, we can get the temperature inside the foam samples. X means the direction of air flows, here we set X=1.0, 1.5, 2.0, 2.5. Fig. 4 shows Aluminium foam Temperature profile. To compare the thermal

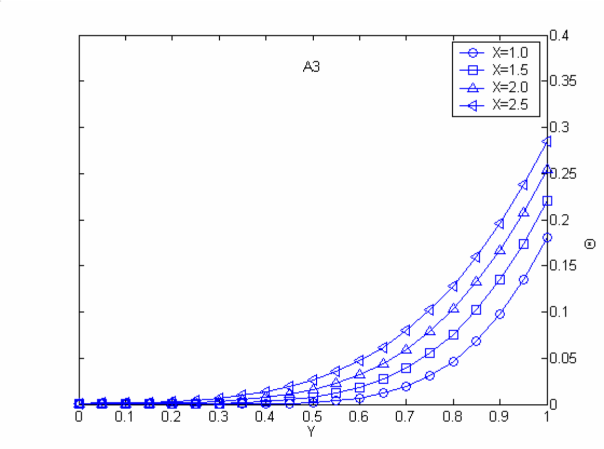

Fig. 4 Dimensionless temperature profile in A3

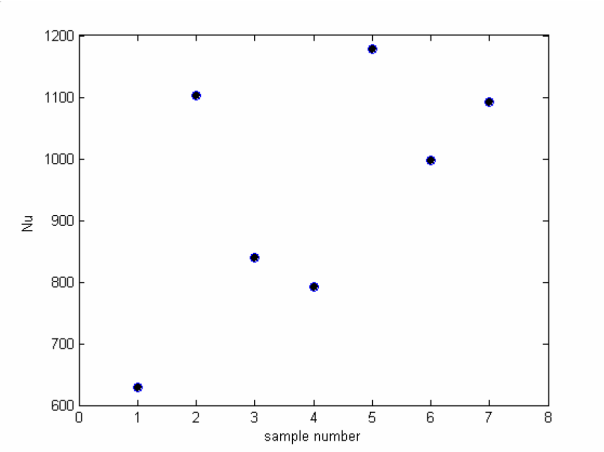

Fig. 5 Nu in 7 foams at u=2m/s

performance of all of 7 foams, we compare their Nu number at the same velocity, u=2 m/s shown in Fig. 5. We can see that not like the hydraulic performance(pressure drop), thermal performance do not simply have the same trend with PPI, it is influenced by the effective conductivity. At the same u, higher effective conductivity leads to higher Nu number.

4 Conclusion

This paper summarized the main formulas on thermal issue of metal foam. As a special material (specific geometry of fiber inside), metal foam is characterized by some value, porosity, PPI, fiber diameter, specific area, effective conductivity. In the application of heat exchanger case, one thermal equation is acceptable, and both pressure drop and thermal performance are discussed here using mathematical model.

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