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Experimental hydrodynamic study of flow through metallic foams: Flow regime transitions and surface roughness influence

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ABSTRACT

The aim of the present work is to study the hydrodynamic behavior of the single phase water flow through three metallic foam samples (i.e. Copper, NiFeAlC, and Inconel) in a plate heat exchanger. These samples have a same pore diameter (1200 μm) and grade (20 PPI), however, the Microscopic images show that the ligament diameter and the surface roughness are different. The effect of the metallic foam surface roughness and the ligament diameter on the pressure drop behavior is analyzed, and the regime transitions from pre-Darcy to turbulent are identified. It is found that more, the metallic foam surface is rough, more the pressure drop is important and the turbulent regime is reached rapidly. The Permeability and Forchheimer parameters were calculated for each flow regime. It is noticed that each fluid regime can exhibit different permeability and Forchheimer coefficient for the same foam sample. The present data were confronted to those available in the literature and a good qualitative and quantitative agreement was obtained.

1. Introduction

Researchers in the thermal engineering field have always looked to enhance the heat transfer using several methods, among them: fins and porous medium, in particle the open-cell metallic foam which are known by their high porosity (in general $\geq 90\%$). Boomsma et al. (2003) investigated experimentally the metal foams as compact performance for heat exchangers. They found that the insert of this kind of material decreases the thermal resistance by nearly the half compared to that in a plain heat exchangers.

However, all these devices used to improve the heat transfer cause an increase in the pressure drop trough the heat exchangers. Indeed, a conceptual study of heat exchangers is, in reality, an optimization work which ensures: the highest heat transfer possible versus the smallest pressure drop. Several studies show that the pressure drop in the metallic foam can be influenced by various parameters. Boomsma and Poulikakos (2002), Dukhan et al. (2014), Hamadouche et al. (2016), Mancin et al. (2010) have experimentally investigated the pressure drop in the aluminum foam. Boomsma et al. (Boomsma and Poulikakos, 2002) studied the effects of compression and pore size variation. They found that an increase in the compression factor causes a decrease in the permeability and the latter becomes more sensitive to the change in the porosity as it increases. Dukhan et al. (2014) investigated experimentally the pressure drop and the flow regime transitions. Their results show that the metallic foam can exhibit different Permeability and Forchheimer coefficient in each flow regime. Hamadouche et al. (2016) demonstrated that metallic foam baffles create lower pressure drop and best heat transfer compared to the solid baffles due to their high permeability and thermal conductivity. The experiences of Mancin et al. (2010) show that the pressure drop increases with the decrease of the relative density (defined as the density of the foam divided by the density of the metal). For other metallic foam materials, the studies of XianbingJi et al. (Ji and Xu, 2012) and Gerbaux et al. (2009) exhibit the influence of the grade (PPI) on the friction factor, where the friction factor increases fast in the lower grade for the same porosity values. In the standard literature, the static pressure is measured only at the inlet and the outlet of the channel. However, Madani et al. (2007) have measured the static pressure along the channel using multiple pressure sensors. This technique allows the elimination of the channel inlet and outlet effects. The study of Zhao et al. (2001) compared two types of materials, Copper and FeCrAlY. They found that the pressure drop in the copper metallic foam is much higher than that in the FeCrAlY one for the same PPI and relative density.

The theoretical studies are rare in this field (Bai and Chung, 2011; Fourie and Du Plessis, 2002; Kopanidis et al., 2010); Mo Bai et al. (Bai and Chung, 2011) investigated a direct numerical

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Table 1
State of the art on pressure drop in single phase flow through a metallic foam.

Authors	*Samples Dimensions (mm)*	*Material*	*Grade (PPI)*	*ε (%)*	*Dp (mm)*	*V (m/s)*	*Fluid*	*Approach*
Boomsma et al. (Boomsma and Poulikakos 2002)	40×40×2	Aluminum	10, 20,40	92–92.8	2.3–6.9	0–1.042	Water	Exp
Dukhan et al. (2014)	D = 50.8	Aluminum	20	87.6	–	0 - 0.6	Water	Exp
Hamadouche et al. (2016)	100×(16,20)×6.35	Aluminum	40	93	–	1–5	Air	Exp
S.Mancin et al. (2010)	100×100× 40	Aluminum	5,10,20,40	90.3, 95.6	0.634–2.36	2–5	Air	Exp
Xianbing Ji et al. (Ji and Xu, 2012)	52×8×3	Copper	30,60,90	88	2.76,1.19,0.69	0.03–0.2	Di-ionized Water	Exp
Gerbaux et al. (2009)	–	Nickel	48–52	92.7	0.4	0.05 – 1.4	Air	Exp
Madani et al. (2007)	10×50×100	Copper	36	96	0.745	0–0.2	n-Pentane	Exp
Zhao et al. (2001)	127×127×12	FeCrAlY Copper	10, 30, 60	84.5, 94.5	0.554–3.131	03–14	Air	Exp
Fourie et al. (Fourie and Du Plessis, 2002)	–	–	10,20, 30	93.6, 93.1, 91.5	–	0.2–4.6	Newtonian fluid	Semi-Emp
Kopanidis et al. (2010)	9.61×9.61×19.852.82×2.82×5.82		10, 40	97	2.1, 6.9	1–6		Num
Mo Bai et al. (Bai and Chung, 2011)	114×22.5×1	Aluminum	5,10,20,40	–	1.5, 2.70, 3.10, 3.13	1–9	Air	Num
Present work	50×25×5	Inconel Copper NiFeAlCr	20	92 93 92	1.2	0.015–0.5	Water	Exp

Nomenclature

a, b	Correlation parameters
D	Channel diameter (m)
Exp	Experimental
Emp	Emperical
F	Forchheimer coefficient
f	Friction factor based on permeability
K	Permeability (m^2)
L	Channel length (m)
Re	Reynolds number based on permeability
P	Static pressure (Pa)
P	Pore per inch
v	Inlet velocity (m/s)
G	Mass velocity (Kg/sm^2)
μ	Dynamic viscosity (Pa s)
ρ	Fluid density (kg/m^3)
λ	Friction factor
ε	Porosity (%)
Δ	Differential

Subscripts

p	Pore
li	Ligament

simulation method using the Fluent CFD to evaluate the pressure drop in metal foams. The model is based on a structure of sphere-centered open-cell tetrakaidecahedron. The results were compared with available experimental data and excellent agreements have been found. Fourie et al. (Fourie and Du Plessis, 2002) used a theoretical model based on the rigorous assumption of the plane Poiseuille flow and a simplistic geometric model for the prediction of pressure drop in the metallic foam. Kopanidis et al. (2010) Presented a 3D numerical simulation methodology for flow at the pore scale level. The numerical model of the geometry was discretized using a tetrahedral volume mesh for both its void and solid phases. The results indicate that it can be considered a valid approach and may be used for better understanding of foam pore scale flow.

The main parameters used in the aforementioned studies are given in Table 1.

The current study presents the influence of the surface roughness and the ligament diameter on pressure drop, which were determined using Scanning Electron Microscopy, during single phase water flow through plate channel considered as plate heat exchanger (Kouidri et al., 2015; Kouidri et al., 2015) . In the other hand, the flow-regime transitions boundaries from pre-Darcy regime to turbulent one were identified.

2. Flow and methods

The flow through any porous media presents several flow regimes, depending on the flow conditions. Overall, there are four flow regimes:

2.1. Pre-Darcy regime

In the literature concerning the flow in porous media, Bear et al. (Bear and Corapcioglu, 1984) determined a threshold value for Re, below which Darcy's law does not hold. The flow in this lowest range of Re is defined as "pre-Darcy flow". The fluid in this regime may exhibit a non-Newtonian behavior and the streaming potential generated by the flow produces small countercurrents on the pore walls in opposite direction of the main flow (Bear and Corapcioglu, 1984). Thus, the study of the pre-Darcy regime needs instrumentations with high sensitivity to be able to measure the extremely low pressure gradients and velocities (Fand et al., 1987). Kececioglu and Jiang (1994) stated that the reduced pressure drop seems to be inversely proportional to Reynolds number.

2.2. Darcy regime

A century and half ago, Darcy (1856) established his law on flow in the porous medium (Eq. 1):

$$\frac{\Delta P}{L} = \frac{\mu}{K} V \tag{1}$$

Where ΔP is the static pressure, L is the length of the porous medium following the flow direction, μ is the fluid viscosity, V is the Darcian velocity based on the cross-section dimensions of the channel, and K is the porous medium permeability.