Determination of bulk and entrance contributions to the pressure drop in metallic foams

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ABSTRACT

Pressure drop in flow through systems (filters, catalysts, electrodes, etc.) is an important parameter to evaluate and optimize. Pressure drop can be calculated knowing the permeability, the specimen dimensions and geometry of the porous media as well as the viscosity, density and flow rates of the fluid. Different models have been proposed to describe pressure drop in porous medium. Most models show that the pressure drop is a function of the thickness of the porous medium and the velocity of the fluid.

The present study was carried out to have an understanding of the pressure drop in metallic foams of different pore size and thicknesses. The pressure drop was obtained for metallic foams having uniform structure and different thickness, density and pore size. Measurements were done at velocities up to 20 m/s. The Hazen-Dupuit-Darcy permeability model was not able to predict the experimental results. Indeed, for a given porous material and velocity, the pressure drop divided by the thickness does not give a single normalized pressure drop value. Experiments indicated that the pressure drop could be divided into two components: entrance and bulk pressure drops. Although the bulk contribution can be normalized by the thickness, the entrance effect contribution cannot. Results indicate that entrance of the porous media is a significant contributor to the pressure drop and its effect decreases with the pore size. Above a critical thickness, the contribution of the entrance effect on the total pressure drop becomes insignificant and classical models can be applied.

INTRODUCTION

Open cell metallic foams have a combination of attractive properties such as permeability, thermal and electrical conductivities, thermal and environmental stability, high stiffness and low specific weight. Resistance to fluid flow is an important parameter to optimize in many applications such as filters and heat exchangers. For that reason, understanding the pressure drop behavior through metallic foam is important when designing flow through systems.

BACKGROUND

Henry P.G.Darcy conducted column experiments in 1856 to describe fluid flow through sand beds and found that the pressure drop can be described as a function of the fluid velocity and a constant called the hydraulic conductivity (*k*). He described the pressure drop normalized by the thickness as follow:

$$\frac{\Delta p}{t} = \frac{1}{k} V \qquad (1)$$

where Δp is the pressure drop, t is the thickness of the porous medium, V is the fluid velocity and k is the hydraulic conductivity. Since his experiments were only done with water, Darcy did not make any reference to the fluid viscosity. Later, Hazen indirectly observed the effect of fluid viscosity by changing the temperature of the fluid flowing through a filter [1]. The fluid viscosity appeared in the modified Darcy's equation as:

$$\frac{\Delta p}{t} = \frac{\mu}{K} V \qquad (2)$$

The hydraulic conductivity k of the original Equation 1 was substituted by K/μ in Equation 2, where K is called the specific permeability, a hydraulic parameter independent of the fluid properties, and μ is the fluid dynamic viscosity. Equation 2 states that the pressure drop per unit length of porous medium is proportional to the product of velocity and the dynamic viscosity of the fluid [2].

Darcy's equation is only applicable when the velocity of the fluid is sufficiently small, which means that the Reynolds number of the flow is around unity or smaller [3]. As the velocity increases, the influences of inertia and turbulence become more significant and the results depart from this simple model. This departure eventually causes that the pressure-drop across a porous medium to be governed by the form drag, which depends on the fluid density ρ and quadratic velocity V^2. The physical phenomenon responsible for the quadratic term in Equation 3 is assumed to be the force imposed to the fluid by any solid surface obstructing the fluid flow path. I. Newton [4] proposed that this resistivity was proportional to the fluid density and the average fluid velocity square. The addition of this contribution gives the Hazen-Dupuit-Darcy equation:

$$\frac{\Delta p}{t} = \frac{\mu}{K} V + C \rho V^2 \qquad (3)$$

where C is a form coefficient related to the geometry of the porous media and ρ is the medium density.

EXPERIMENTAL SET-UP AND PROCEDURE

Experimental set-up

The experiments were conducted using the set-up described in Figure 1. The instrument was designed to measure the flow of compressed air and pressure drop across the specimens. Air was allowed to fill the pressure vessel at the pressure of about 1.25×10^5 Pa. The pressure was controlled by a manual pressure control-valve. Air filter was employed in line prior to the pressure vessel to absorb impurities and foreign particles. Air was then allowed to pass through the settling chamber by means of 50.8 mm steel pipe and then entered a 25.4 mm steel pipe to reach the specimens. The settling chamber was used to avoid turbulences in the gas flow. The length of the pipe was selected in order to have the air flow completely developed before entering the specimens for the entire velocity range.

Metallic foam samples were securely assembled using different middle flanges and held in place by means of two standard flanges (25.4x107.95 mm). Three middle flanges were used; one 13 mm thick and two others 25 mm thick. Four different spacers with thicknesses of 3, 8, 10, and 21 mm were used to fill up the gaps between the samples and the standard flanges when the specimens are placed inside the middle flanges. This combination of different flanges and spacers gave the flexibility to test specimens with different thicknesses ranging from 2 to 63 mm. The diameter of the specimens was 47 mm.

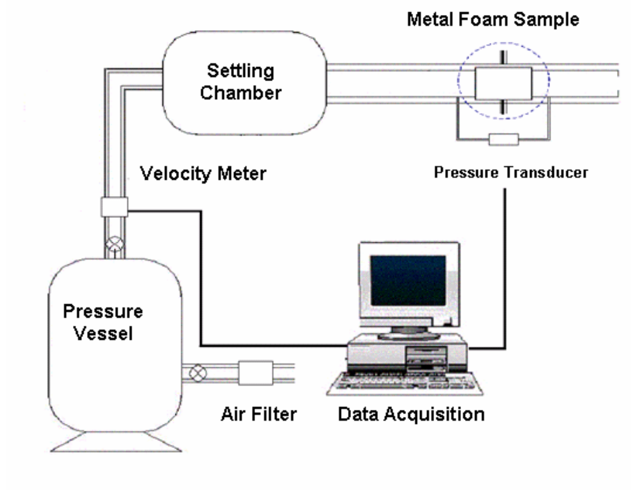

Figure 1. Experimental set-up.

The pressure was measured using an OMEGA pressure transducer (pressure range of 0-1.7237×10^5 Pa with ±0.1% full scale accuracy). A pressure tap was drilled into the pipe, 80 mm from the specimens. A one way valve was used to prevent air leakage. The downstream pressure was measured as atmospheric. Flow velocity was measured using an OMEGA velocity meter (flow velocity range of 0.0508-5.08 m/s with a ±1% full scale accuracy). The velocity meter was calibrated and placed into the pipe at correct position using a flow meter. The flow was steady-state, unidirectional and fully developed before entering the specimens. To minimize the experimental errors, 100 data points were collected at every 2 seconds after the flow became stabilized and the average was used to plot the graphs for each condition.

Specimens

Nickel-chromium open cell foams from Recemat were used in the experiments. Table 1 and Figure 2 present the characteristics and structure of the foams used in this study. Specimen thicknesses ranging between 2 to 20 mm were used to produce stacks from 2 mm to 63 mm using 47 mm diameter discs cut by wire EDM.

Grade	**Pore Size** (mm)	**Average Porosity** (%)
NC 4753	0.4	0.87
NC 2733	0.6	0.89
NCX 1723	0.9	0.88
NCX 1116	1.4	0.89

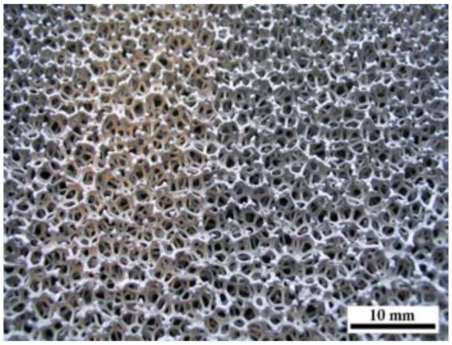

Figure 2. Photograph of a foam characterized in this study (NC610).

RESULTS AND DISCUSSION

In order to verify the effect of stacking the foam on the pressure drop, the pressure drop through a 10 mm sample was compared to that measured on a stack of two 5 mm discs of the same grade. Figure 3 shows that the results are similar and stacking can be used to reproduce the pressure drop in thicker foams.

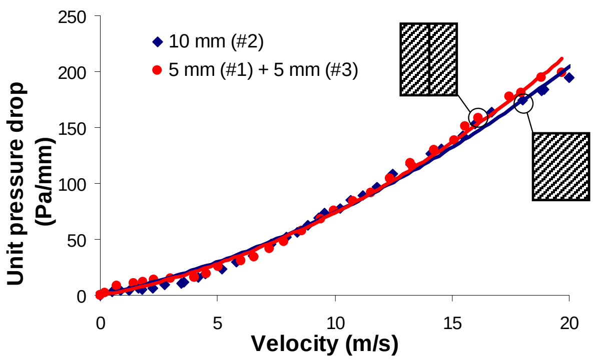

Figure 3. Unit pressure drop for single 10 mm discs and stack of two 5 mm discs for NCX1723 (Pore size: d=0.9 mm).

The total pressure drop was measured for stacks of metallic foams having various thicknesses. The unit pressure drop curve was obtained by dividing the total pressure drop by the specimen thickness. Equation 3 was used for curve fitting.

Figure 4 shows that as expected, the total pressure drop increases when the thickness increases. However, this increase is not linear with the sample thickness. Indeed, Figure 5 shows that the unit pressure drop curves for specimens with different thicknesses do not all fall on a single curve. Therefore, for each different thickness, different *K* and *C* are obtained using the Hazen-Dupuit-Darcy model. This is contrary to what is expected from the model. In fact, based on this model, the permeability coefficients should be independent of the specimen geometry and thickness.

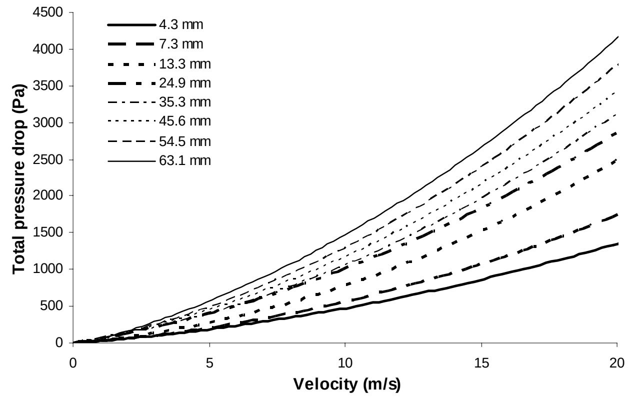

Figure 4. Total pressure drop for NCX1723 foams of different thicknesses.

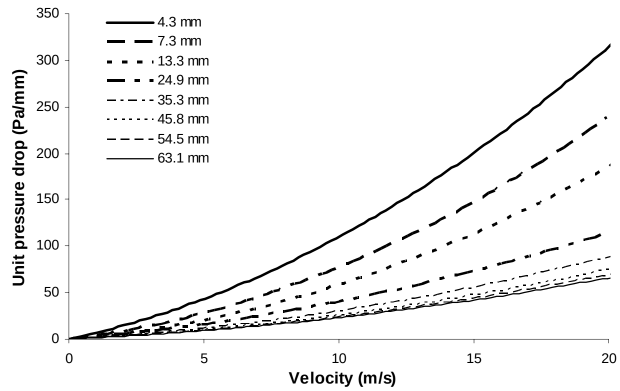

Figure 5. Unit pressure drop for NCX1723 foams of different thicknesses.

Figure 5 shows that the unit pressure drop curves are closer to each other when the thickness of the foam increases. As shown in Figure 6, the unit pressure drop decreases when the thickness increases and this reduction becomes very small when the thickness gets larger. From this figure, the critical thickness to get a constant unit pressure drop for foams with pore size of 1.4 mm is around 60 mm.

This behavior suggests that there is a parameter in the expression of the pressure drop that becomes negligible at higher thicknesses. The effect could be assimilated to an entrance effect that depends on variations of local permeability and flow regime. This effect depends on the pore size (see Table 1 and Figure 7). When pressure drop is normalized by the thickness of the foam, the entrance contribution becomes insignificant, especially at high thicknesses.

The entrance effect can be observed when the pressure drop of a stack of two discs and the mathematical addition of the individual pressure drop curves of both discs are compared. Figure 8 shows that the mathematical addition of the individual pressure drops is larger than the pressure drop of the stack of the two discs. This observation is related to the mathematical addition of the entrance effect

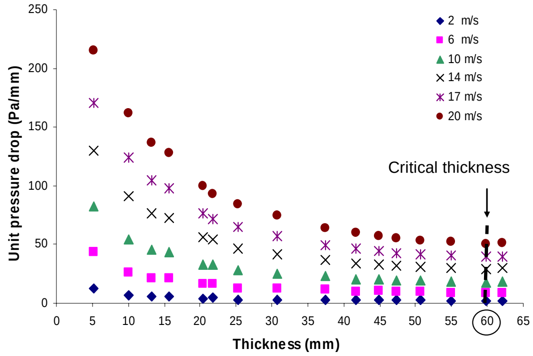

Figure 6. Unit pressure drop vs. thickness at different velocities, NCX1116 (d=1.4 mm).

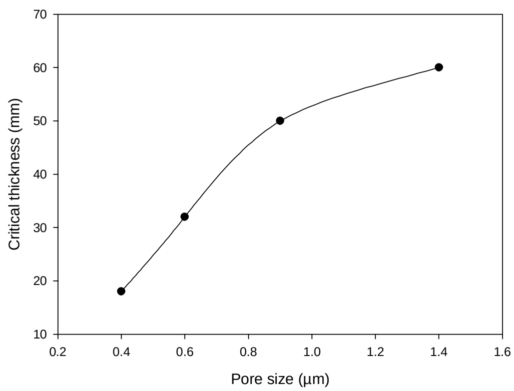

Figure 7. Critical thickness as a function of the pore size.

of both individual discs that is not experimentally measured on the stack where only one entrance effect is present.

The entrance effect is also illustrated in Figure 9 by comparing the effect of the entrance surface on stacks produced with foams of different grades (0.6 and 0.9 mm pore size). The pressure drop was higher when the flow enters the 0.6 mm pore size foam than when it enters the 0.9 mm pore size foam. This figure shows that the difference is more important at high velocities (>6 m/s). This indicates that classical models are applicable at low fluid velocities where the entrance effect seems insignificant. It is believed that the entrance effect is mostly inertial.

CONCLUSIONS

Pressure drop in metallic foams of different thicknesses was evaluated. The validity of Hazen-Dupuit-Darcy equation at high fluid velocity over a range of thicknesses of nickel-chromium metallic foams was evaluated. The results show that the unit pressure drop can only be normalized by the foam thickness above a determined critical thickness. The critical thickness was directly related to the foam pore size. Experiments showed that the entrance of the foam or the transition from medium of different permeability is a significant contributor to the pressure drop. This means that the total pressure normalized by the medium thickness as a function of fluid velocity can not be described with classical models. This also suggests that this effect must be taken into consideration during the measurement of the permeability to make sure the permeability is thickness independent and this characteristic is only affected by the structure of the foam.

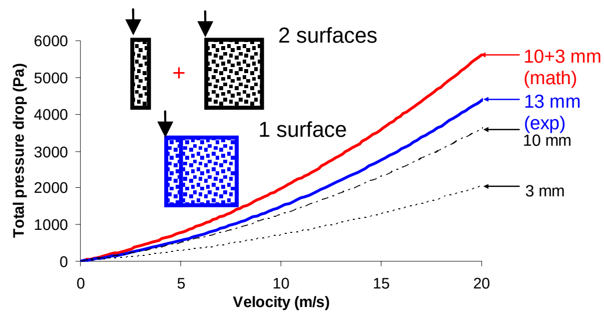

Figure 8. Individual, experimental and mathematical additions of pressure drop curves for NC2733 (d=0.6 mm).

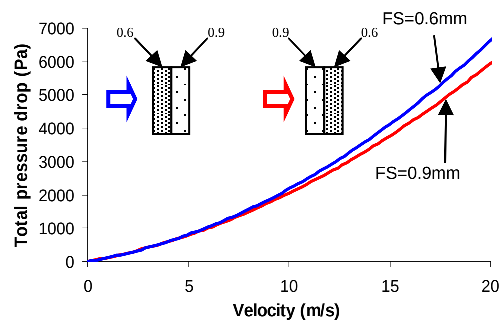

Figure 9. Effect of the pore size of the facing surface (FS) on the pressure drop in a stack of two foams of different grades (0.6 and 0.9 mm pore size). The thickness of each foam is 33 mm.

ACKNOWLEDGMENTS

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