Permeability of metallic foams and its dependence on microstructure

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ABSTRACT

Metallic foams (MF) are relatively new materials with a combination of attractive properties (permeability, high surface area, thermal and chemical stability, etc.). They can be produced from different materials and can be manufactured using various processes. Due to their unique properties, they find applications in different sectors of engineering, such as energy absorption, filtration, heat dissipation, etc. For many applications, the permeability is an important parameter to characterize and optimize. Most of the recent literature on the subject studied the permeability in the low velocity range. The present study was carried out to have a better understanding of permeability for greater velocity ranges. An equipment was designed and built for this purpose. Pressure drop measurements were made across the thickness of open-cell nickel foams. Pore and window sizes were measured by image analysis on SEM micrographs. The experimental results are in relatively good agreement with the Hazen-Dupuit-Darcy model (R^2>98%). The permeability is affected by pore size, porosity and the normalized projected area of the connecting pores (i.e. windows).

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INTRODUCTION

In many applications, the pressure drop observed when a fluid passes through a permeable material is of critical importance. A large amount of work has been done on the determination of the pressure drop across porous media and various analytical models have been proposed. Some research has been done to link the pressure drop with the material structure, mainly the pore size and the density or porosity. Due to the complexity of the structures of most existing porous media, no universal model has succeeded in describing analytically the behavior of fluids through these materials. Recent results obtained for metallic foams indicated that their behavior as permeable materials could not be adequately described by the existing models [1]. The aim of the present work was to get some hints on the discrepancy observed and get a better understanding of the effect of foam structure on permeability.

BACKGROUND

Pressure drop across a homogeneous porous medium for steady fluid flow is given by the Hazen-Dupuit-Darcy model:

$$\frac{dp}{dx} = \frac{\mu}{K}V + \rho.C.V^2 \tag{1}$$

where dx represents the thickness (or length) of the porous medium, dp is the pressure drop across dx, V is the fluid flow velocity, ρ is the fluid density, μ is the fluid viscosity, K is the permeability and C is a coefficient related to the geometry of the solid permeable medium. In equation 1, the first term represents the viscous drag and the quadratic term (ρCV^2) accounts for the drag imposed by the solid porous matrix on the flowing media [2]. Several researchers adopted Erguns-like models to explain and fit their experimental results [3,4]. Bhattacharya *et al.* [5] mentioned that their experimental results best fitted the equation:

$$\frac{dp}{dx} = \frac{\mu}{K}V + \frac{\rho f}{\sqrt{K}}V^2 \tag{2}$$

where f is the inertial coefficient, also known as Ergun coefficient, K is the permeability and V is the fluid velocity. The model is widely accepted for steady state unidirectional pressure drop in a homogeneous, uniform and isotropic porous medium, fully saturated with incompressible Newtonian fluid. K and f are strongly related to the structure of the medium. However, Lage [2] showed that the permeability could be related to the effective surface area of the solid porous matrix. The coefficient C does not depend on the extent of the surface but on the structure of the solid matrix (which is related to the variation of the cross section area of the solid matrix).

Several researchers [5-7] reported experimental and theoretical correlations between porosity and permeability. Du Plessis *et al.* [8,9] stated that they could model

pressure gradients in flow through metallic foam using rectangular representative unit cells. Paek *et al.* [10] expressed that Du Plessis model was only valid for porosities higher than 97% and modeled an inertial coefficient, which depends on tortuosity of the porous medium. Recently Tadrist and Miscevic [3] presented a correlation with inertial effects due to the porosity ε of the medium and to the average pore diameter d using the following equation:

$$\frac{dp}{dx} = A\frac{(1-\varepsilon)^2}{\varepsilon^3 d^2}\mu V + B\frac{(1-\varepsilon)}{\varepsilon^3 d}\rho V^2 \quad (3)$$

where A and B are constants. Although the parameter A is clearly quantified for granular media, difficulties arise with metallic foams. In those models, the structure is most often assumed to be a web-like cellular structure made of solid filaments connected in a three dimensional network that has a corresponding pore diameter [11]. Unfortunately, porous structures are most of the time much more complicated and the models proposed are not suitable for all materials, structures and properties. Tadrist and Miscevic [3] recently concluded that there is no clear correlation between porosity ε and permeability K or inertial coefficient, f, while Paek *et al.* [10] demonstrated that the permeability of metal foam increases as the cell size d increases for fixed porosity ε.

In open-cell foams, the main bottleneck to the flow is the windows that connect one pore to the other. Despois and Mortensen [12] used the similarity between the shape of pores in these foams and that of sintered spherical particles in a dry powder compact. The permeability of such porous material as a function of the average surface area of the windows between the pores is:

$$K = \frac{2[a/\pi]^{3/2}\varepsilon}{\pi d} \quad (4)$$

The average window area (equal to the average contact area at the necks between two particles) is:

$$a = \frac{\pi}{12}\left(\frac{\varepsilon-\varepsilon_0}{1-\varepsilon_0}\right)d^2 \quad (5)$$

where ε_0 is the initial packing density of the spherical particles (ε_0=0.64 for random dense packing of monosized spheres). Despois and Mortensen [12] predicted, with the derived expression of K, the permeability of open-cell aluminium foams with porosities between 60% and 90% and two different pores sizes (75 and 400 μm). This prediction was done in Darcian flow regime and, therefore, drag forces were negligible.

EXPERIMENTAL PROCEDURE

The experiments were conducted using the instrument shown in Figure 1. The instrument consists of a middle flange assembly, a pressure transducer, a velocity meter, a pressure vessel and a settling chamber. The instrument was designed to obtain accurate

determination of the flow of compressed air and pressure drop across the sample. The pressure was controlled using a manual pressure control-valve. An air filter was employed in line prior to the pressure vessel so that impurities or foreign particles could be removed. Air was then allowed to pass through a settling chamber by means of a 2-inch steel pipe. The settling chamber was used to avoid turbulence in the upstream gas flow source.

The metallic foam specimens were securely assembled in the middle flange. The mid-flange assembly was placed in a 1-inch steel pipe and was held by two end flanges. Teflon tape was used to insulate the specimens and to fit them well within the mid-flange and prevent air by-pass.

Pressure taps were drilled in the pipe as close as possible to the sample and one-way valves were used to prevent air flow from the hole. Downstream pressure was confirmed to be atmospheric pressure by measurement. Upstream pressure was measured using an OMEGA 0-25 psi gauge range pressure transducer (±0.1% full scale accuracy). Flow velocity was measured using an OMEGA 0-1000 ft/min velocity meter (±1% full scale accuracy). The acquisition of signals from the velocity meter sensor and pressure transducer was done with a data acquisition device connected to a PC.

The set-up was tested for leaks. To minimize the error, 100 measurements were collected for each experiment and mean values were used to plot the graphs.

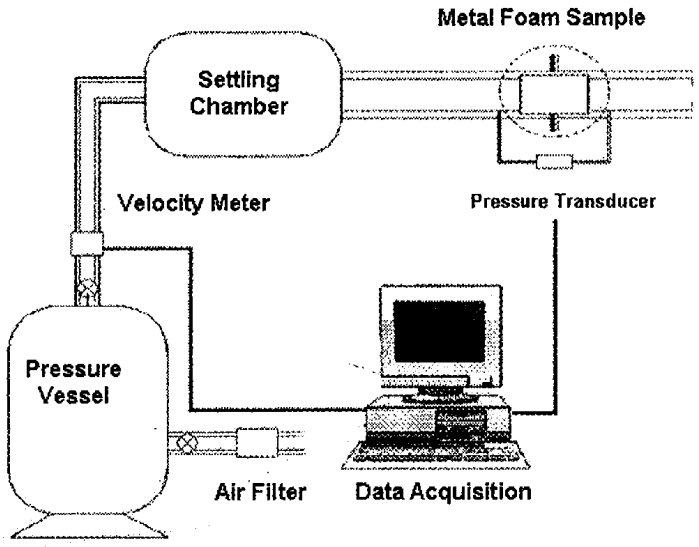


Figure 1 – Experimental Setup

The materials characterized were open-cell nickel foams produced using a process described in [13]. Figure 2 presents a typical microstructure of the foam characterized in this study. The material has a complex network of connecting pores. The

microstructure can be roughly defined by the pores (or cells) and the openings between pores (windows).

Specimen dimensions and weight were used to determine the specimen density and porosity. Open porosity was measured using a gas pycnometer (Micromeritics 1305). Pore and window sizes were measured on digitalized SEM micrographs. The pore size was evaluated by encircling the pores on the digitalized micrographs and calculating the diameter of circular pores of equivalent area. The window sizes were determined by drawing the longest lines through the windows to determine the equivalent window diameter and its equivalent projected area (the windows were approximated as circles).

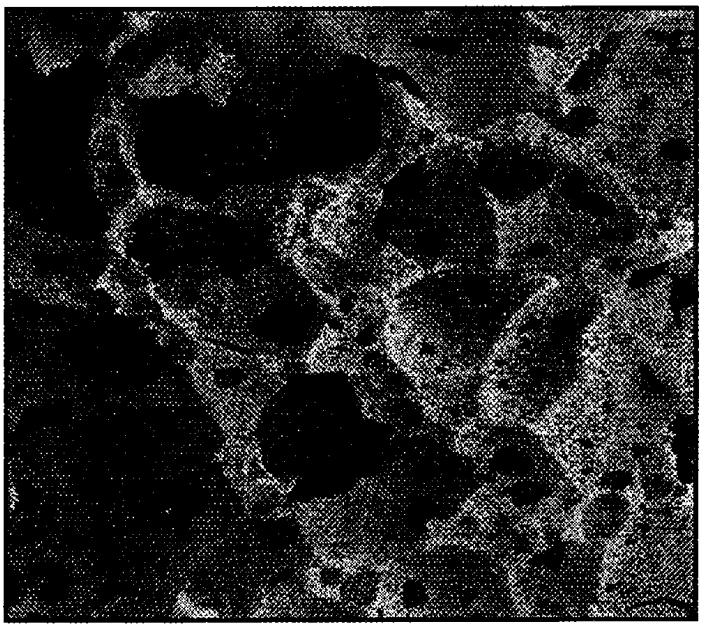


Figure 2 – Microstructure of the Ni foam characterized in this study

Table 1 presents the characteristics of the different foams.

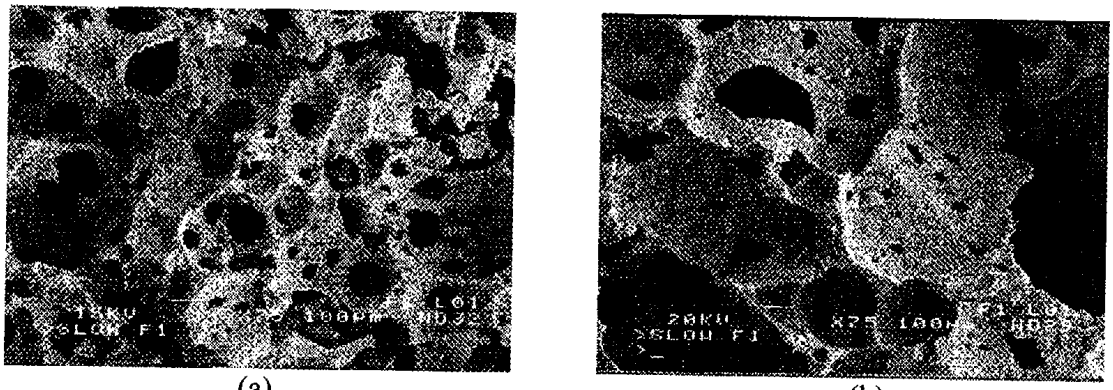
Table I – Structural Characteristics of IMI Metal Foam

Sample	Porosity (vol.%)			Pore diameter		Window diameter	
	Open	Total	Standard Deviation	µm	Standard Deviation	µm	Standard Deviation
Ni70-1A3	89.88	91.65	0.05	485.7	17.35	57.0	2.42
Ni70-1A4	90.46	92.22	0.04	461.5	26.39	57.2	2.38
Ni70-1A5	90.55	92.23	0.02	512.4	19.93	55.4	2.17
Ni60-1A2	92.72	94.30	0.08	307.6	21.41	54.0	3.52
Ni60-1A3	91.18	93.87	0.22	309.8	29.86	67.9	0.44
Ni60-1A4	92.28	94.53	0.06	273.2	24.34	56.3	1.32

RESULTS AND DISCUSSION

The pore size, window size and porosity of the Ni70 and Ni60 foams are significantly different (Table 1). Visual comparison of the microstructure of the two foams shows the obvious difference between their respective pore size (Figure 3). However, the average window size is not significantly different between the two foams.

The pressure drop experiments were done in a non-Darcian flow regime (Figure 4). Indeed, the normalized pressure drop (*-dP/dx*) plots are not linear suggesting a strong contribution of the quadratic term. Significant difference in normalized pressure drop is also observed between Ni70 and Ni60 foams. Ni70 specimens cause higher pressure drops than Ni60 specimens.



(a) (b)

Figure 3 – Micrographs of selected metal foams a) Ni60-1A2 and b) Ni70-1A5

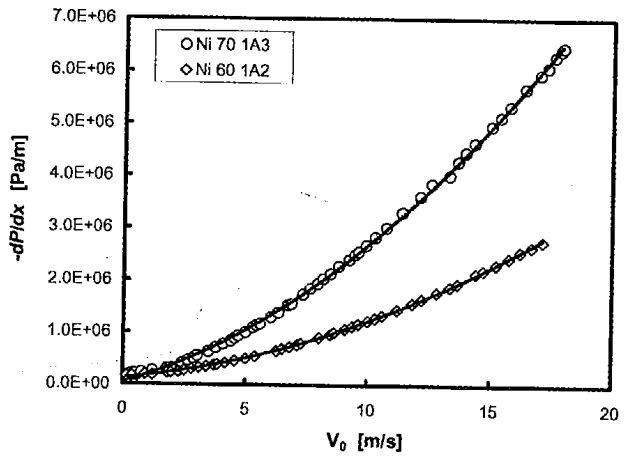
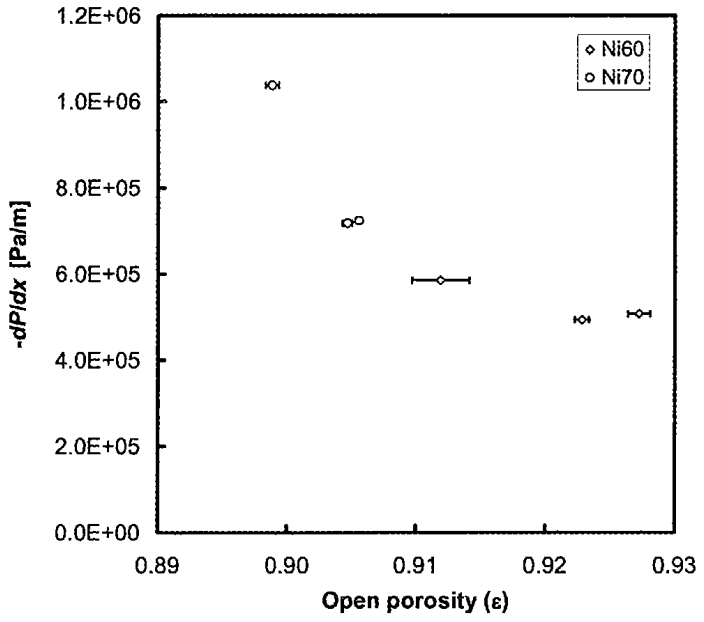


Figure 4 – Unit Pressure Drop Versus Velocity for Ni70-1A3 and Ni60-1A2 Specimens

Plots of the measured normalized pressure drop as a function of the characteristics of the foams are given in Figure 5. As expected, the pressure drop decreases when porosity increases. However, the pressure drop seems to increase when the average pore size increases. This is contradictory with results reported by Tadrist and Miscevic (equation 3 and reference [3]), Bhattacharya Mahajan [5] , Paek *et al.* [10] and Despois and Mortensen [12]. However, the effect of pore size cannot be evaluated independently since both the porosity and the pore size vary from sample Ni70 and Ni60. A more detailed analysis of the data suggests that the observed trend is linked to two factors. The first one is the area of the connecting pores. Figure 6 shows the relationship observed between the pressure drop and the normalized area of connecting pores (windows). As the open area decreases, the flow resistance increases. The number of windows per unit area was significantly different for the two foams and the effect of the windows can be better estimated using the specific surface area of the windows. The overall surface of windows was significantly higher for the Ni60 foams.



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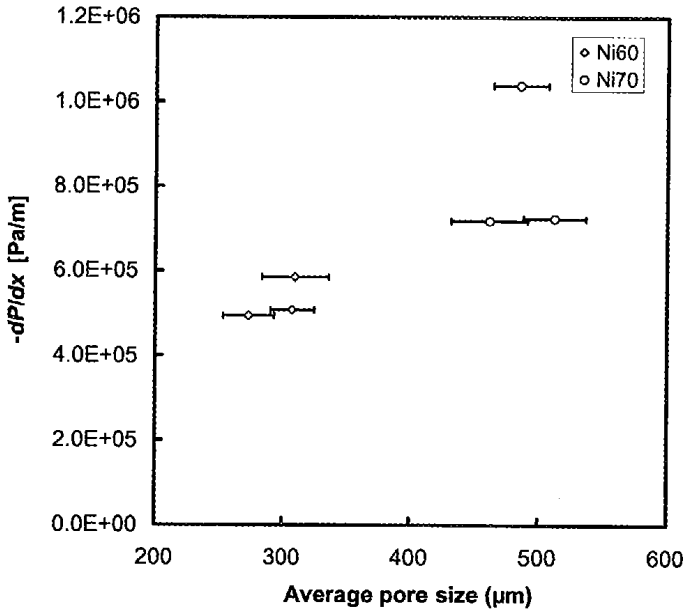

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Figure 5 – Pressure Gradient (*-dP/dx*) Measured at 5 m/s as a Function of the (a) Open Porosity (ε) of the Metal Foam and (b) the Average Pore Size

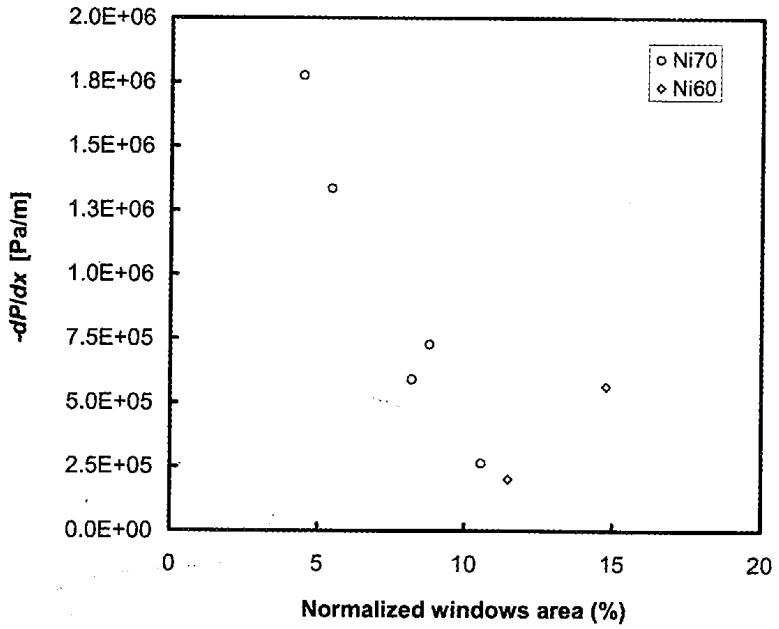
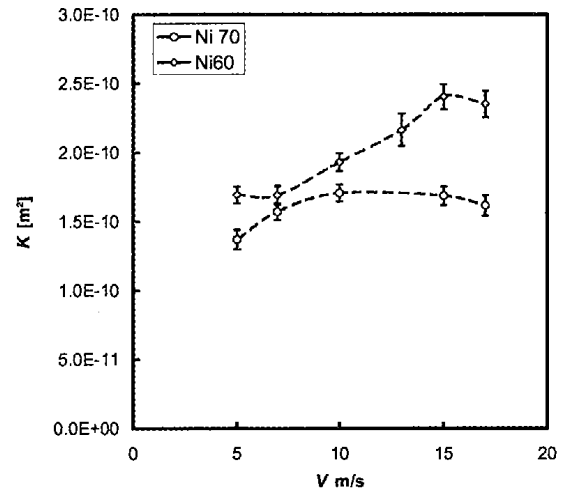


Figure 6 – Pressure Gradient (*-dP/dx*) Measured at 5 m/s as a Function of the Normalized Windows Area (the Total Area of the Windows Divided by the Examined Area 8.24 mm^2)

Although it may appear obvious that the interconnecting pores or windows per unit area control the permeability, this parameter is usually not considered in most analytical models linking the permeability to the structure of porous media. In those studies, the normalized window area was varying the same way as the porosity or pore size and its contribution was somehow included in the correlation between these values. This may explain the discrepancy in the models and the complexity of determining general analytical models that can adequately describe fluid flow behavior in porous materials having different structures. Indeed, in most natural and synthetic materials, the structure of the material changes significantly with density and pore size. A detailed characterization of the structure must then be done to link the permeability with structural parameters.

In order to differentiate the contribution of viscous forces and the drag related to the structure of the porous material, the normalized pressure drop curves (Figure 4) were fitted with the Hazen-Dupuit-Darcy model (equation 1). From this fitting, permeability (K) and the coefficient (C) were evaluated. Figure 7 illustrates the evolution of the permeability and the C-coefficient as a function of fluid velocity for both types of Ni foams. As Antohe *et al.* [14] also suggest, K and C are velocity dependent. The effect of velocity of the flowing media had less impact on the values of K, which varies from 1.47 to $1.74X10^{-10}$ m^2 for Ni70 and from 1.72 to $2.38X10^{-10}m^2$ for Ni60. However, the non-Darcian coefficient (C) increases significantly with the increase in fluid velocity. Higher K values for Ni60 samples indicate that they were more permeable and that their pressure loss due to the quadratic term of equation (1) was less dominant when compared to Ni70 samples. As explained by Diedericks *et al.* [16], coefficient C is important and becomes



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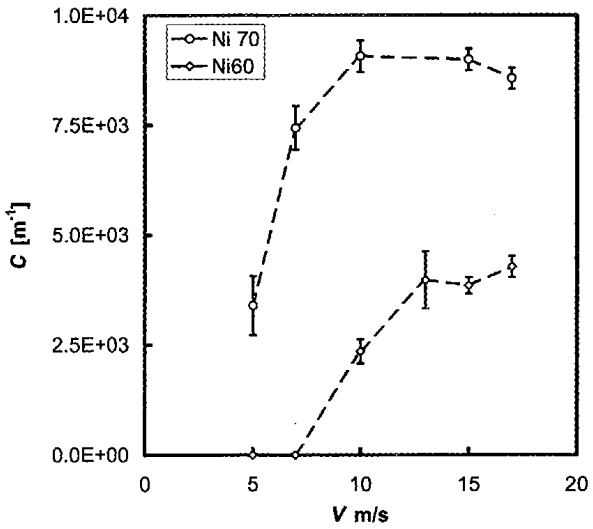


(b)

Figure 7 – Effect of the Velocity (V) on the Parameters of the Hazen-Dupuit-Darcy Model (a) Permeability (K) and (b) Drag force Coefficient (C) for Both Ni70 and Ni60 Samples

significant as the flow velocity increases. When flowing media velocity increases, the energy losses will be mainly linked to the kinetic energy as explained by Innocentini *et al.* [15]. Thus, at higher fluid velocities, this term becomes more prevalent and must be considered for an accurate description of the pressure-drop.

As proposed by Lage [2], the transition from linear (viscosity-dominated flow) to quadratic (inertia-dominated flow) regime is medium-specific. Indeed, as shown in Figure 7b, Ni60 is in a Darcian flow regime at 5 m/s while Ni70 imposes a significant drag related to the geometry of the porous medium. The effect is better illustrated by Figure 8 where the relative contribution of the drag force term (ρCV^2 of equation 1) is shown as a function of fluid velocity. The contribution of the drag term increases with increased fluid velocity. For Ni70, the contribution of the drag term is larger than that of Ni60 foam and seems to reach a constant value above 15 m/s. The balance between viscous and drag force contributions is related to the balance between: (1) the effective surface area and (2) the structure of the solid porous matrix (tortuosity). Therefore, the relative contribution of viscous force and drag force must depend on the internal geometry of the porous material.

The effects of porosity and pore size area on the permeability (K) and drag force (C) at 15 m/s are compared in Figure 9. As expected, the permeability increases and the drag force decreases with increasing porosity.

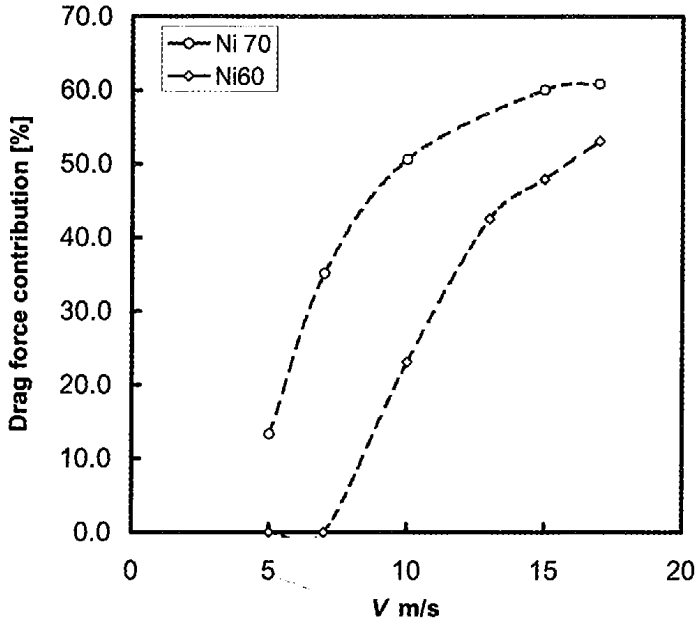
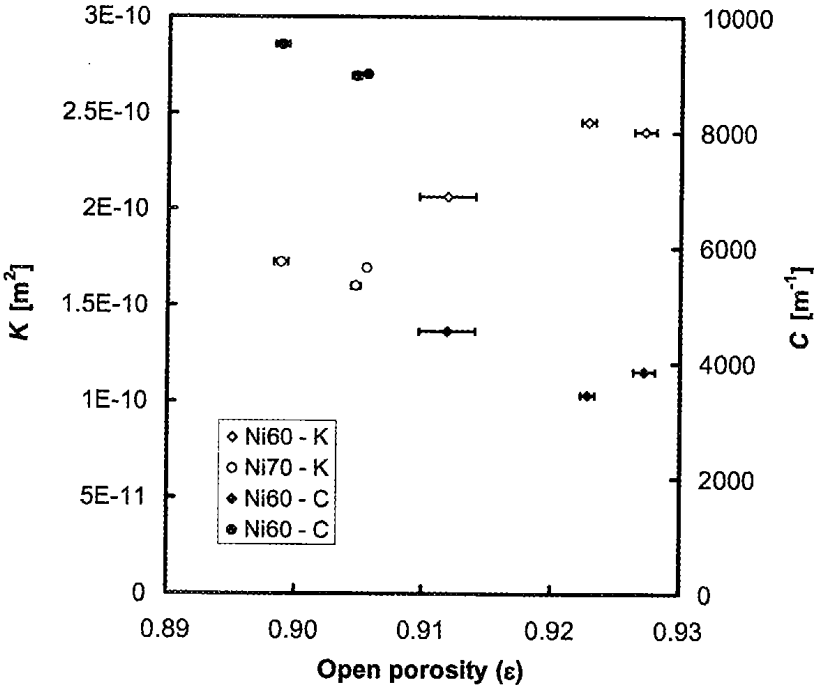


Figure 8 - Effect of the fluid velocity on the relative contribution of the drag force term (ρCV^2 of equation 1) on the normalized pressure drop ($-dP/dx$) measured on both Ni70 and Ni60 samples



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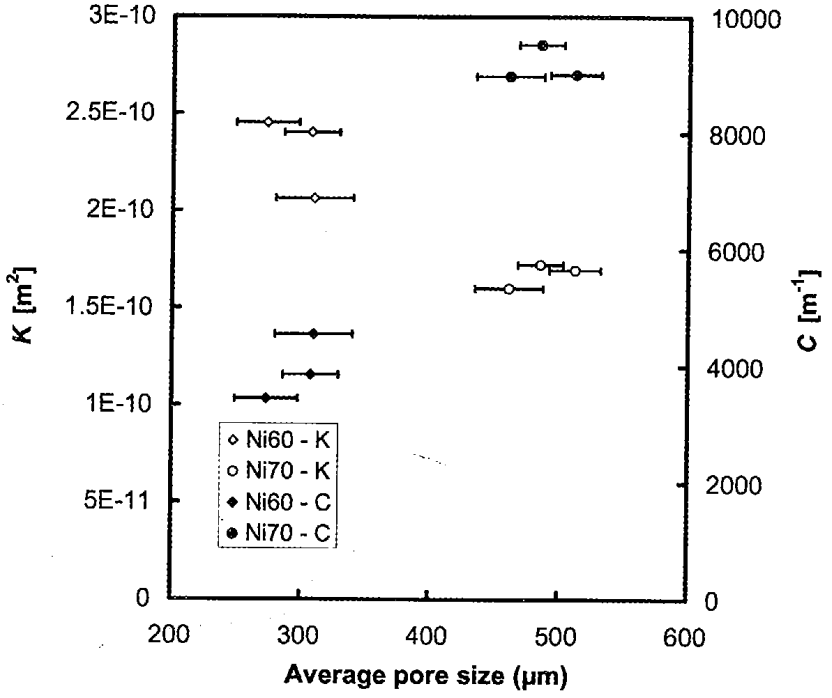

(b)

Figure 8 – Effects of (a) Porosity and (b) Pore Size on the Parameters of the Hazen-Dupuit-Darcy Model, Permeability (K) and Drag Force Coefficient (C), for Both Ni70 and Ni60 Samples at 15 m/s Fluid Velocity

However, one should note that the data is clustered into two groups. Ni60 shows higher permeability and lower drag force than Ni70. Within each group, there is slight variation of porosity and pore size. Therefore, it is impossible to draw a clear conclusion about the effect of these characteristics on the permeability and drag force of the foam.

The effect of both pore size and porosity are summarized in Figure 10 and compared to the model of Despois and Mortensen [12]. The model predicts the relative trend but the absolute values are biased to high normalized permeabilities. The model of Despois and Mortensen is based on the average size of the windows and assumes that there is one "active window" per pore. The Ni60 and Ni70 foams contain more than one window in each pore. Despois and Mortensen observed similar discrepancies, which were related to the morphology of the foams with smaller windows. These windows were small perforations in cell membranes of closed-cell foams.

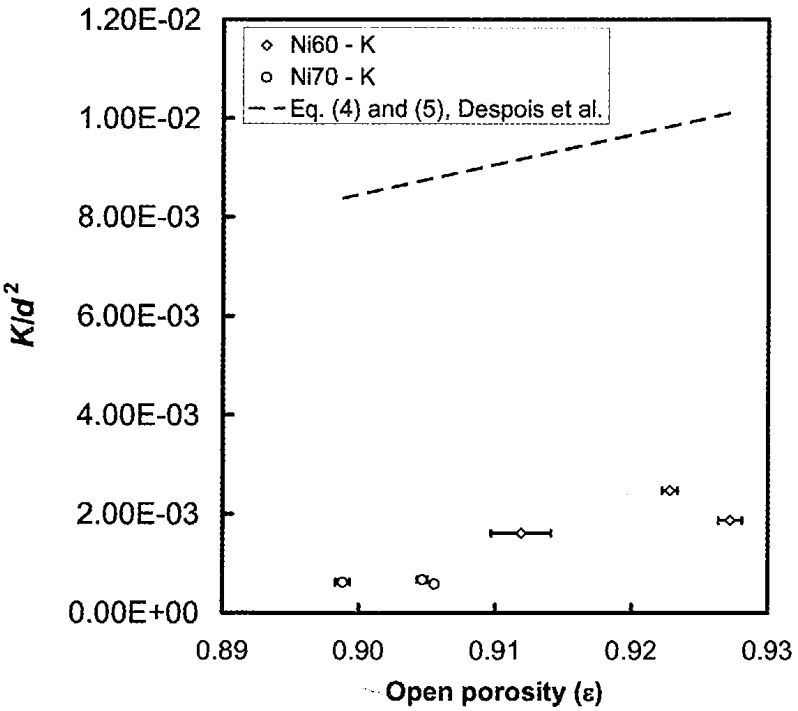

Figure 9 – Effects of the Foam Porosity on the Permeability (K) Normalized by the Pore Size Squared (d^2) Compared to the Model of Despois and Mortensen [12]

CONCLUSIONS

Due to the complexity of the structure of the nickel foams and to the intricacy of flowing fluid in tortuous media (especially in non-Darcian regime), it was not possible to find analytical models that could adequately describe pressure drop as a function of foam

characteristics. The experiments were performed with only two different sets of specimens in which several structural characteristics change simultaneously. This made the evaluation of the impact of a single parameter on foam permeability difficult.

Quantifying foam architecture may represent a technical challenge, especially in complex structures. Nevertheless, it is important to understand how structural parameters may affect fluid flow in porous media since it provides tools to optimize material structure and properties.

The main observations done in the present study are:

(i) Pressure drop in the metallic foams were found to fit a polynomial model of Hazen-Depuit-Darcy.
(ii) The pressure drop is due to a combined effect of K (permeability) and C (drag force).
(iii) The behavior of fluid flow can be very complex and does not only depend on the density and pore size, as proposed by most analytical models linking the permeability with the porous medium structure.
(iv) For the foams characterized in this study, the open cross-sectional area for the flow of air is found to be a critical factor. Thus, window sizes as well as the number of windows have to be considered for predicting the pressure drop.
(v) The permeability K is similar for the two types of foams while the quadratic term of the Hazen-Depuit-Darcy equation C is very different. Parameter C of Ni70 appears to be higher than that of Ni60.

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