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Rodrigues, V. P.; Innocentini, M. D. M.; Lefebvre, L-P.; Baril, É.

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Gas Permeation through Perforated Metallic Foams

V.P. RODRIGUES, M.D.M. INNOCENTINI
Universidade de Ribeirão Preto, Curso de Engenharia Química, Av. Costábile Romano, 2201, 14096-900 Ribeirão Preto – SP, Brasil

L-P. LEFEBVRE, E. BARIL
National Research Council Canada/Institut des matériaux 75, de Mortagne, Boucherville, Québec, Canada, J4B 6Y4

ABSTRACT

Porous metals have attractive properties (good structural integrity, heat and electricity conductivity, thermal and chemical stability, high permeability and large specific surface area) for many flow-through applications. For those applications, control of the fluid flow resistance and gas diffusion are important parameters to optimize. Several characteristics of the porous material will have an impact on the permeability and gas flow and diffusion. Indeed, the effects of micro-scale characteristics (i.e. density, pore size, pore connectivity and tortuosity, etc.) on permeability of porous medium have already been reported. However, the shape and the design of the device (filter, electrode, heat exchanger) may also have significant impact on the gas flow and should be optimized.

This paper describes air flow characteristics through perforated copper foams. Perforations and diaphragms were used to evaluate gas diffusion into the foam. Perforations in the foams reduce the pressure drop and may be used to give access to the internal surface of the material.

INTRODUCTION

In many flow-through applications (heat exchanger, electrodes….), the performance of a device depends on the surface area, the convection at the surface, the pressure drop across the porous medium and accordingly the convection of the working fluid on the external and internal surfaces of the material. Porous metals and ceramics can be used in those applications because they have large surface area and their surface roughness help creating turbulence that increases convection and surface exchanges (thinner boundary layer). Creating turbulence gives, on one hand, access to the internal surface of the material but, on the other hand, increase the pressure drop. Accordingly, the optimization of flow-through devices generally requires compromises.

Solutions may sometimes come from the design. This has been successfully done in filtration for example, where accordion patterns were developed with cloth filters to increase significantly the area of the filter while minimizing pressure drop. Since little work has been done in this direction with metallic foams, there is a need to adapt such design solutions to foam specificity (possibility to produce bulk material with high tortuosity, good mechanical strength, electrical and thermal conductivity).

As an example, increased permeability and gas diffusion can be obtained using perforations in the foams. The diameter, the length and disposition of the perforation may all affect the fluid distribution, the pressure drop and surface exchange at the fluid/material interface. In order to optimize the design of the perforation network, the effect of perforations on the fluid flow in the porous material must be determined.

This paper presents pressure drop and gas diffusion in foams with and without perforations. Diaphragms (i.e. perforated plates) as well as rod and tube were used to control and evaluate the gas diffusion and the contribution of the perforation on the pressure drop. By comparing the results obtained on different foam configurations, the contributions of the different mechanisms were determined.

EXPERIMENTAL PROCEDURE

Copper foams cylinders (25.4 mm diameter and 15 mm thick) were produced with a powder metallurgy process described in [1]. The material had open porosity (95%) and was permeable. Figure 1 presents the structure of the material.

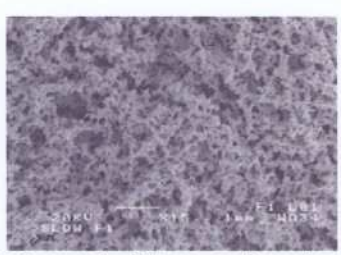

Figure 1: SEM micrograph of the copper foam characterized in this study.

The pressure drop was evaluated on foams with and without perforations (Figure 2). A series of diaphragms were used to control and evaluate the gas diffusion in the foams (Figure 3a). Tests were conducted with perforated 0.65 mm thick stainless steel plates having different orifice diameters (1.5 to 5 mm). Solid

rod (1.5 mm diameter) and ultra thin polyethylene tube (1.5 mm diameter, 150 µm wall thickness) were also inserted in the perforation of the foam to control and evaluate the contribution of the flow through the perforation and the diffusion into the foam.

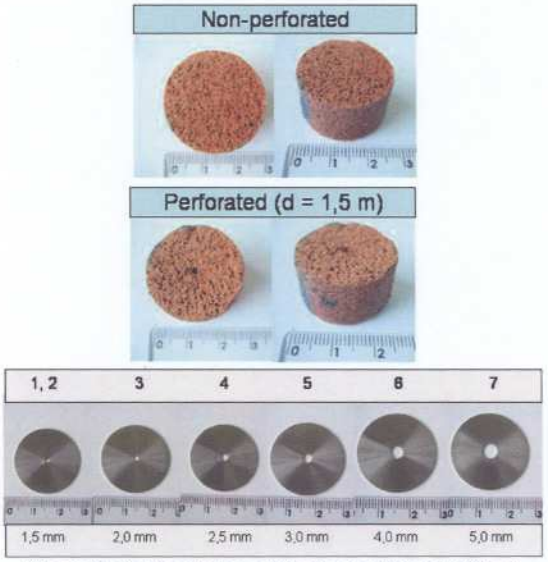

Figure 2: a) Description of the foam with and without perforation and b) diaphragms used to control the gas diffusion in the foams (1 and 2 were identical).

Samples were subjected to flow tests with compressed air. Experimental evaluation of pressure drop consisted of tests in which air was forced to flow through the porous sample under a stationary regime. The samples were sealed between two chambers and the absolute fluid pressure at the inlet (P_i) and outlet (P_o) were measured and recorded as a function of flow rate (Q) or fluid velocity ($v_s = Q/A$) (Figure 3). Table I summarizes the operational conditions used in the tests.

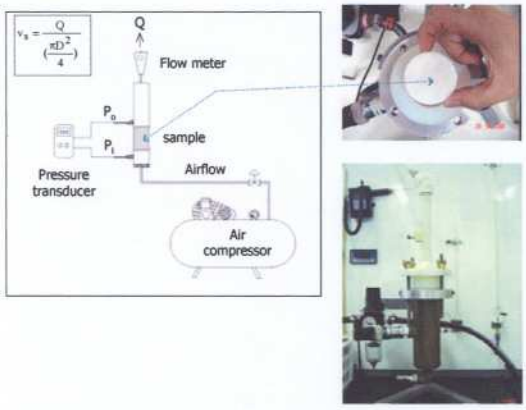

Figure 3: Details of the experimental set up.

TABLE I. Operational conditions for the permeation tests.

Fluid	Compressed air
Temperature (T)	25 to 31°C
Ambient pressure ($P_{atm} = P_o$)	712 to 716 mmHg
Air density (ρ)	~1.09 kg/m^3
Air viscosity (µ)	~1.88×10^{-5} Pa.s
Applied inlet pressure (P_i)	up to 2 bar
Superficial air velocity (v_s)	up to ~ 6 m/s
Useful sample flow diameter (D)	15 mm
Useful flow area (A)	177 mm^2
Number of acquired points	> 15
Fluid	Compressed air

The collected data were fitted with Forchheimer's equation for flow of compressible fluids [2-5]:

$$\frac{P_i^2 - P_o^2}{2P_oL} = \frac{\mu}{k_1} v_s + \frac{\rho}{k_2} v_s^2 \qquad (1)$$

The least-square method was used to fit the parabolic model and calculate the permeability constants k_1 and k_2.

RESULTS

Initially, the permeation behavior of copper foams and orifice plates was evaluated individually. Figure 4 presents the pressure drop curve for a copper foam specimen. Forchheimer's equation could be reasonably fitted to experimental data and k_1 and k_2 constants were found typical of metallic and ceramic foams described in the literature. The contribution of the inertial term $[\rho v_s^2/k_2]$ on the total pressure drop was 50% higher for air velocity of 2.2 m/s.

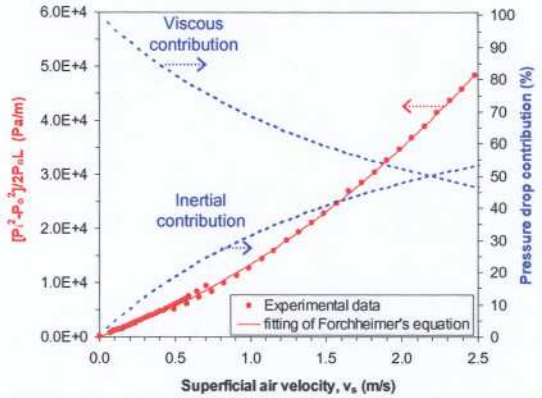

Figure 4: Pressure drop curve of copper foam characterized in this study. Lines refer to the fitting of Forchheimer's equation.

The pressure drop curves for all orifice plates are shown in Figures 5. Data were plotted in logarithmic scale due to the large variation in pressure drop caused by the increase in the orifice

diameter. Forchheimer's equation was not well fitted for data in the low superficial velocity range, where the viscous term [$\mu v_s/k_1$] should prevail. This is because the velocity is much higher in the perforations and the pressure drop in orifice plates is purely related to kinetic (inertial) losses. In Fig. 5b, the differences among curves were significantly reduced when pressure drop data was plotted against the orifice velocity, $v_{orifice}$, as defined by:

$$v_{orifice} = v_s \frac{D_{tube}^2}{D_{orifice}^2} \qquad (2)$$

In this case, all data could be adequately fitted according the power-law equation $y = 1481.8x^{1.9934}$, which confirms the quadratic dependence of orifice velocity on the plate pressure drop.

Figure 6 shows that the mathematical sum of pressure drops in the orifice plate and non-perforated copper foam is not equivalent to the actual pressure drop measured in the orifice plate + non-perforated foam bonded together. When an orifice plate is placed in front of the foam, the local fluid velocity increases at the entrance of the foam and the fluid flow cross section is significantly reduced (99% at the entrance), both contributing to the higher pressure drop measured.

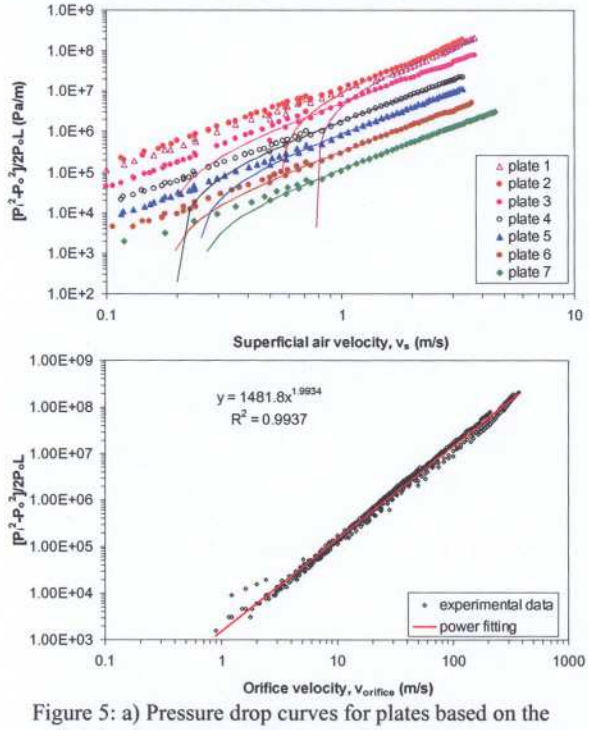

Figure 5: a) Pressure drop curves for plates based on the superficial velocity (lines refer to the fitting of Forchheimer's equation) and b) pressure drop curves for plates based on the orifice velocity.

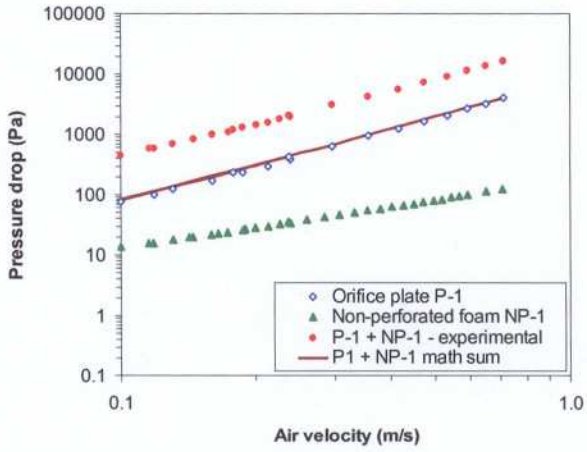

Figure 6: Pressure drop curve of individual plate and foam and also the composite plate + foam.

Pressure drop curves for non-perforated copper foam coupled with orifice plates on the inlet and outlet faces of the foam are shown in Figure 7. The results show that the orifice diameter at the outlet had an important impact on the pressure drop. The impact of the outlet diaphragm decreases in importance as the orifice diameter gets larger. The curve obtained with the 5 mm outlet plate (curve f) is very similar to the curve without the plate at the outlet (curve g). This means that after the fluid has passed through the 1.5 mm inlet plate, it spreads to a maximum of 5 mm on the outlet face of the copper foam. The constriction effect became important when the outlet orifice diameter was smaller than 4 mm (i.e. 25% pressure drop increases compared with no outlet diaphragm). When there is a 1.5 mm diaphragm at the outlet (curve a), the pressure drop is almost 4 times larger compared to no diaphragm at the outlet (curve g).

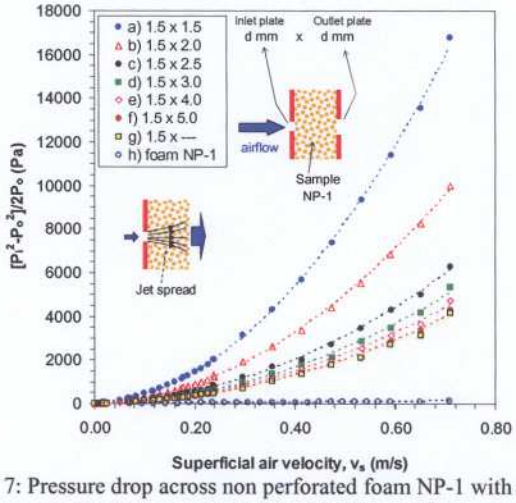

Figure 7: Pressure drop across non perforated foam NP-1 with orifice plates at the entrance and exit of the gas flow.

Figure 8 presents the pressure drop curves for the perforated foam with and without the perforation filled with a solid core to block the perforation. The foam is highly permeable and the cross section of the perforation represents only 1% of the cross section

of the foam exposed to the gas flow. However, reduction in permeability constants were considerable (37.3% for k_1 and 9.6% in k_2) for the sample with blocked perforation, which means that the perforation had important contribution on airflow though the foam. This contribution can become even more important if the surface density of perforations is increased or if the permeability of the material is low.

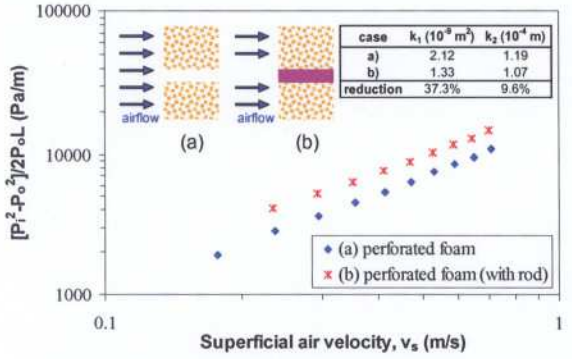

Figure 8: Pressure drop across the perforated foam FP-1 (1.5 mm diameter) with and without a solid rod to block the perforation.

A set of experiments was also carried out with the perforated foam, orifice plates and a thin plastic tube to control and evaluate gas diffusion in the perforated foams (Figure 9).

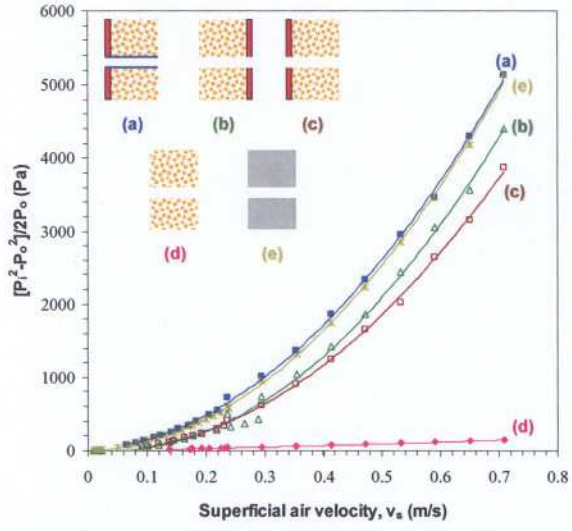

Figure 9. Normalized pressure drop curves for different perforated foam configurations (1.5 mm diameter).

The much lower pressure drop level observed in Figure 9 without the diaphragm (curve d) compared to with inlet diaphragm (curve c) shows that flow through the foam is important and not only located in the perforation. When a plastic tube is inserted in the perforation to impede gas diffusion into the foam (curve a), the pressure drop also increases. Comparison of curves b) and c) reveals that pressure drop is slightly higher when a diaphragm is placed on the outlet surface, probably preventing the spreading of the gas flow inside the foam. This spreading reduces fluid velocity and consequently the pressure drop.

The higher pressure drop level of curve e) compared with curve c) reveals that even when flow is constricted on the inlet surface by the orifice plate, it spreads through the foam bulk along the perforation, i.e., the perforation is not the only flow path in the copper foam.

CONCLUSIONS

The effect of perforations and gas diffusion in highly porous copper foams (porosity of 95%) was evaluated. Single perforation did affect the pressure drop in the foam. This effect could be significantly more important if the effective cross section of the perforations was higher or if the permeability of the material was lower. The results indicate that gas diffusion occurs within the foam, as well as within the perforated foam. This may be important if perforations are used to reduce pressure drop while giving access to the internal surface of the material for applications where surface exchange are critical, such as in electrodes, catalysts or heat exchangers.

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