A Simple Apparatus for Determining the Permeability of Thin- Thickness Porous Materials by Pressure-Decay Technique

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A simple experimental set up, for the evaluation of the permeability of thin-thickness porous material, is presented. The proposed system makes use of a perpendicular fluid flux that at controlled pressure can permeate the medium. The permeability variables are estimated by measuring the relative pressure before and after the fluid permeates the sample. A special mortise holder was constructed to allow fixation of thin samples. Vitreous membranes with different volumetric porosities were tested validating the system. The permeability parameters were obtained by using Forchheimer equation by considering the porous structure as consolidate one.

Uma montagem simples, para a medida da permeabilidade em materiais porosos de espessura fina, é apresentada. O sistema proposto faz uso de uma câmara de permeação com fluxo perpendicular a amostra. As variáveis de permeabilidade são conseguidas pela medida da diferença de pressão antes e após o fluido permear o meio. Dispositivo especial de encaixe foi desenvolvido para fixação das amostras independente de sua espessura. Membranas vítreas com diferentes porosidades foram ensaiadas validando a montagem. Os parâmetros de permeabilidade foram obtidos pelas equações de Forchheimer considerando o meio poroso como uma estrutura consolidada.

I Introduction

Porosity and permeability are interchanged parameters that are of fundamental importance in porous systems characterization. All open-pore materials present degrees of permeability, which can, in a first instance, be understood as the facility of a fluid to flow through a medium. The correct evaluation of permeability is very important in a broad range of physics and engineering fields such as soil science, particulate systems, reactive reactor medium, fabrics, porous ceramic and filter processing and their applications.

The usual devices for permeability measurements essentially consist in a set up where a fluid is forced to pass through a define volume of the porous medium. The permeability determination is done by following the distribution of pressure along the sample length, as illustrated in Figure 1.

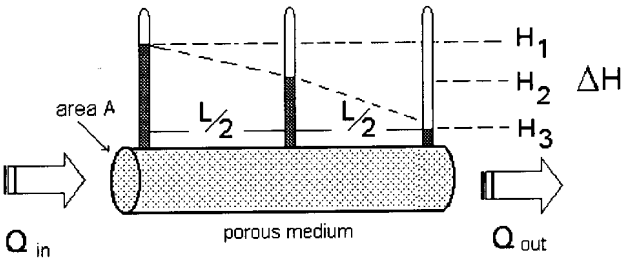

Figure 1. Permeameter measurement principle.

This methodology is well established and has been widely used for non-consolidated materials that can be packed into a column along of which manometers could be placed. This is not appropriate, however, for thin-thickness samples due to the difficulty to handle or to measure the pressure at specific positions.

In the literature, other techniques for permeability measurements suitable for thin samples as radiation incidence [1], image analysis and reconstruction

[2], electric conductivity measurements [4] and photoacustic methods[5] are reported. These methodologies however, need specific instrumental support, being rather sophisticated than the pressure-decay technique. In this work we present a simple experimental apparatus, based on the principle of pressure drop, which is suitable for thin-thickness sample permeability measurements.

II Experimental Details

The experimental set-up is based on the difference of pressure taken in one point before and one after a fluid (air or water) is inputted to the sample. The sample should be close to rectangular or to cylindrical form and having parallel faces. A jig was devised to enable the fixation of the sample in the holder without mechanical pressure. The holder is located in a middle distance between the pressure gauges that are fixed along the chamber, allowing measurements independent of specimens thickness. The working area could as well, be adjusted by using metallic mortise rings with different diameters. Small amount of silicon grease is necessary to fix the sample.

A long feeding tube connected to the sample holder attains the maintenance of a steady fluid flux condition during the measurements. This tube assures the reduction of the turbulence around the measuring points. Figure 2 schematized an overview of the assembled system and Figure 3 presents details of the developed sample holder. The metallic ring (5) in Figure 3 can assume several forms and lengths adapting to the sample's shape or thickness.

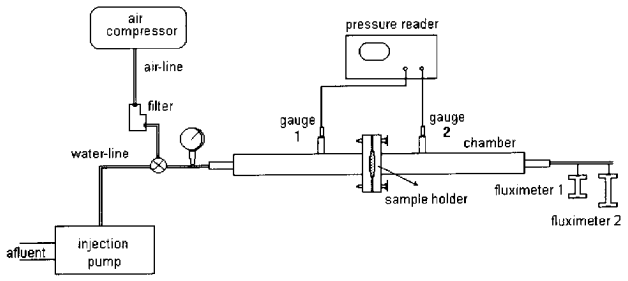

Figure 2. Sketch of the experimental set-up, out of scale.

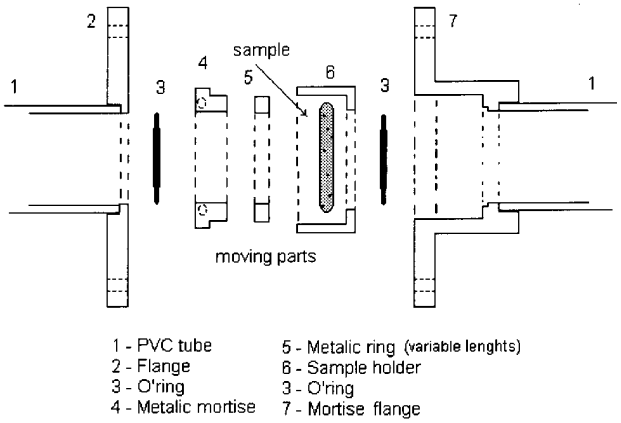

Figure 2. Diagram representative of the sample holder.

For testing the system we make use of sintered porous glass membranes processed in the Embrapa Instrumentation Center [6]. The samples have disk shape with 35×1 mm. Membranes with different volumetric porosities, previously characterized by mercury penetration, had their permeability evaluated. Permeability constants were obtained by fitting Forchheimer's equation to experimental values of ΔP, measured using electronic extensor gauges (1 and 2 in Fig. 2), versus the fluid surface velocity. The permeameter was assembled to allow working both in air or water. In the present work we use compressed air at room temperature. The air density was taken as $\rho = 1.079$ kg/m^3 and the viscosity $\mu = 1.83 \times 10^{-5}$ Pa.s. Tests were carried in duplicate to guarantee the data repeatability. Comparisons of experimental and theoretical permeability parameters were also performed.

III The Forchheimer's Equation

Several theoretical approaches have been used to describe and predict the permeability of a medium [7,8]. The Forchheimer's equation is the result of a model that has been successfully employed to quantify the permeability of non-consolidated granular porous media [9-11]. Such model states that for an uncompressible fluid the pressure drops through rigid and homogeneous medium is given by:

$$\frac{\Delta P}{L} = \frac{\mu}{k_1}\nu_s + \frac{\rho}{k_2}\nu_s^2 \qquad (1)$$

where ν_s is the fluid velocity, L is the medium thickness, μ and ρ are the fluid viscosity and fluid density respectively, and k_1 and k_2 are constants only dependent on the medium properties, known respectively as Darcian and non-Darcian permeabilities. Ergun [12] proposed expressions to describe k_1 and k_2 for packed spheres as follows:

$$k_1 = \frac{\epsilon^3 d_p^2}{150(1-\epsilon)^2} \qquad (2)$$

$$k_2 = \frac{\epsilon^3 d_p}{1.75(1-\epsilon)} \quad (3)$$

and

$$d_p = \frac{1.5(1-\epsilon)}{\epsilon} d_0 \quad (4)$$

where ϵ is the porosity, d_p is the mean particle diameter of the granular medium and d_0 the medium porous size.

To apply these equations in consolidated materials, with configured cell structures such as ceramics, we should replace the particle diameter (d_p) in equations (2) and (3) to the average pore diameter. The porous medium can be considered as a mutually interconnected composed material, as the solid and void phases are both three- dimensionally connected in space [13,14]. By equation 4 is possible to relate the pore medium size as proportional to particle dimension that compose the medium. That has been proved as a useful approach in several media [15-16].

IV Results and Discussion

Figure 3 shows experimental pressure-velocity curves as result of the technique, considering the fluid compressibility. The permeability constants were obtained by fitting equation (1) to the data. Numerical results are summarized in Table 1.

The curves indicate reduction in ΔP as the volumetric porosity increases. In sample 3 and unexpected drop in ΔP was found for all air velocity. That feature was attributed to intrinsic characteristics of the material, where blind pores instead of open-pore structure essentially compose the volumetric porosity.

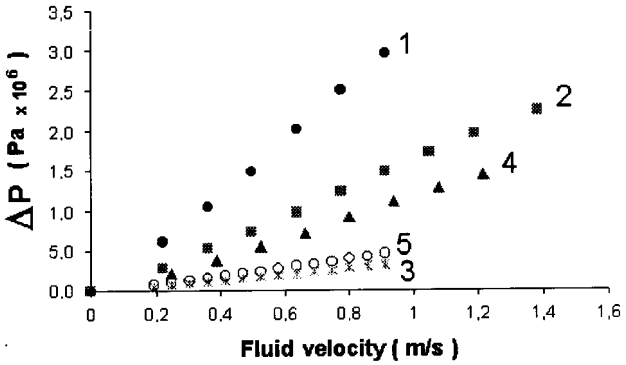

Figure 3. Plotted data of ΔP (pressure-drop measured between gauges) in function of fluid velocity for the samples tested. The numbers identify the samples as put in Table 1.

Table 1 - Permeability Constant for the tested samples with different volumetric porosity.

Sample	Volumetric Porosity (%)	Darcian Permeability, k_1 (m^2)	Non-Darcian Permeability k_2 (m)	k_1/k_2 (m)
1	24.53	6.36 E-12	1.38 E-6	4.64 E-6
2	26.58	7.02 E-11	1.06 E-5	6.62 E-6
3	29.40	1.3 E-11	6.12 E-6	2.12 E-6
4	32.89	2.021 E-11	4.47 E-6	4.52 E-6
5	34.27	5.1 E-11	6.19 E-6	8.24 E-6

In general, the results obtained in the system are coherent and data reflect different permeability levels as the volumetric porosity increases, as can be depicted from derivative values of k1 as presented in Figure 4. Similar behavior is found to k_2.

From equations (2) and (3) a graphic correlation between experimental and theoretical values can be done, validating the use of the system particularly defining the interval of permeability where the system is less sensitive. This correlation can be observed in Figure 5 to k_1. Similar plot is found to k_2.

These results indicate good concordance between values of k. The maximum deviation in the measurements, in the order of 30%, was found for high fluid velocity condition or for high permeability materials. These deviations point to the necessity of adapting the system for these types of measurements.

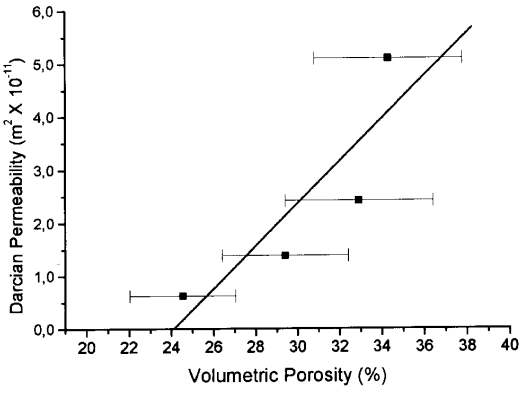

Figure 4. Darcian permeability in function of the membranes volumetric porosity.

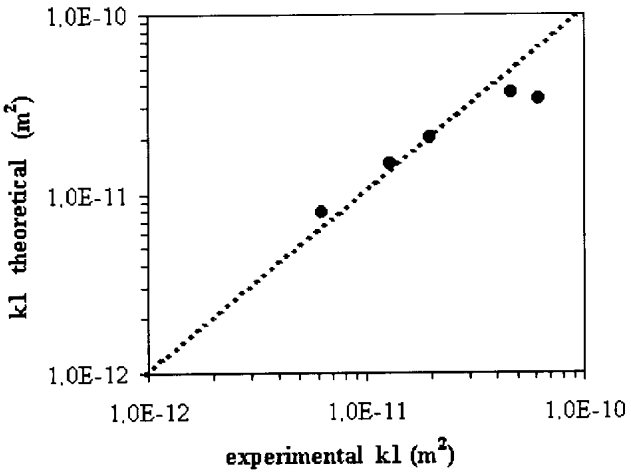

Figure 5. Correlation between theoretical and experimental k_1, measured in the system.

V Conclusions

The proposed set-up allows the determination of the permeability values of thin- thickness porous materials. In the tested examples, the results showed good concordance between increase of volumetric porosity and correspondent permeability. By using Forchheimer's model it was possible to define pressure or permeability range where the system works better.

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