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EXPERIMENTAL AND THEORETICAL ANALYSIS OF THE PERMEABILITY FOR HIGHLY COMPRESSIBLE POROUS LAYERS

C. S. POPESCU*, V. MARIAN, M. D. PASCOVICI

Department of Machine Elements and Tribology, Politehnica University of Bucharest, Bucharest, Romania
E-mail: popescu@ontr.pub.ro

ABSTRACT

During the last 10–15 years a new lubrication mechanism applicable to highly compressible porous layers acting as self-sustained films has been developed. This type of lubrication is strongly dependent on porosity variation and consequently on permeability hence the name ex-poro-hydrodynamic-XPHD lubrication was proposed. The objective of the present paper is to analyse theoretically and experimentally the permeability of a highly compressible porous layer. The experimental part consists in measuring the flow rate of water which passes through a porous material trapped between two rigid surfaces. By measuring the flow rate through the material at different heights, the permeability of the material as a function of its compacticity can be determined. A comparison between the experimetal results and the theoretical variation of the permeability using the Kozeny–Carman law is realised.

Keywords: porous and compressible materials, permeability, CFD, lubrication.

AIMS AND BACKGROUND

During the last 10–15 years a new lubrication mechanism applicable to highly compressible porous layers acting as self-sustained films has been developed. This lubrication process was observed and analysed independently at the Politehnica University of Bucharest[1,2] and at the City University of New York[3].

This type of lubrication is strongly dependent on porosity variation and consequently on permeability hence the name ex-poro-hydrodynamic-XPHD lubrication was proposed[2].

* For correspondence.

The applications foreseen until present referred to: viscosity pumps[1], thrust bearings[2], red cells lubrication[2,3] for narrow capillary circulation.

Both in technology, as well as in the living world, there are a lot of examples of structures which lead to creating such layers: textile unwoven materials such as felt or rags, fresh snow, goose down, articular cartilage, etc.

The permeability of the porous material has an important role in this type of lubrication, and its variation with the compacticity has to be determined experimentally in order to validate the theoretical models.

The permeability of porous materials was also determined using axial flow and transverse flow experiments[4].

The objective of the present paper is to analyse theoretically and experimentally the permeability of a highly compressible porous layer using a radial flow.

EXPERIMENTAL

Test rig. The experimental test-rig is presented in Fig. 1. Water flows pressure-driven through a porous material trapped between two rigid surfaces. Varying the thickness of the compressed porous layer h, different material porosities are obtained. Fluid pressure was also varied by changing the height level H_L of the water reservoir. The flow rate is measured using a graduated water collector. Two types of unwoven porous materials were used for the experiment. We call them M1 and M2 for further reference.

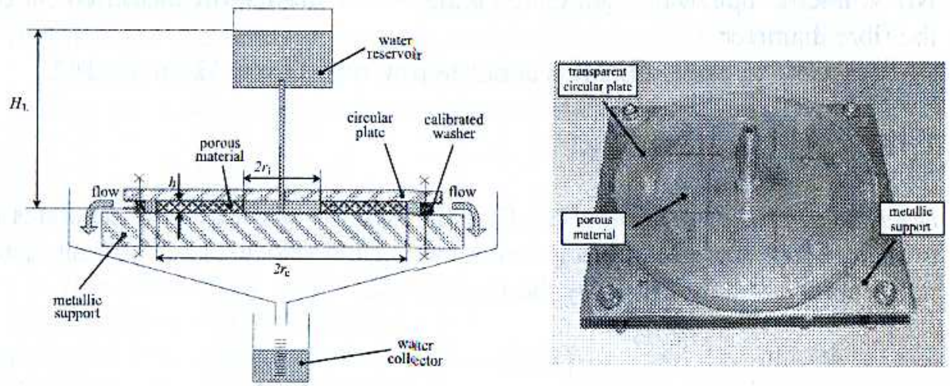

Fig. 1. Test-rig to measure the flow rate through a porous material

Description of porous materials. Material M1 has cellulose and cotton in its composition, which differs from the structure of material M2 that has only synthetic fibres. The main difference is that the cotton and cellulose fibres of M1 imbibed with water change their dimensions significantly, while for M2 the wa-

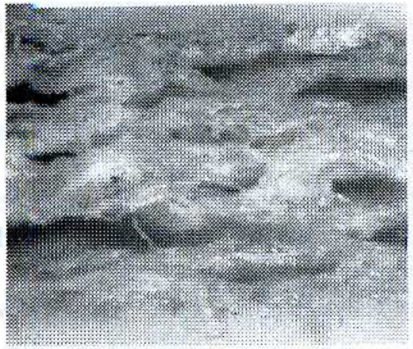

Fig. 2. Porous structure of M1

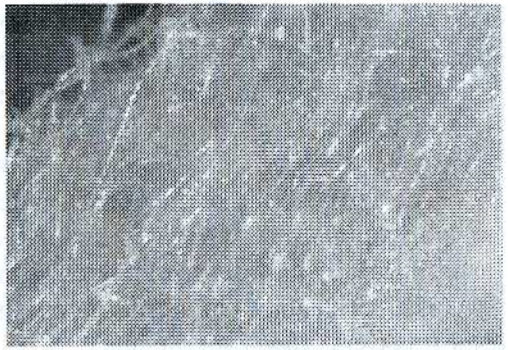

Fig. 3. Porous structure of M2

ter remains only inside the pores. Therefore, M2 keeps it height constant when imbibed with water and M1 suffers a radical change in height when imbibed. It is worth to be mentioned that the uncompressed height of M2 is greater than that of M1 in a dry state.

The structures of both materials are presented in Figs 2 and 3.

Determination of compacticity. The initial compacticity is defined as the ratio between the volume of the solid part and the total volume. By introducing the porous sample in a graduated glass tube, the volume of the solid part is determined. The total volume at a certain film height h is $\pi h(r_e - r_i)^2$.

Measurement of the fibre diameter. The fibre diameter was measured using a Nikon microscope, with a graduated scale, which allowed the measurement of the fibre diameter.

The fibre diameter for M1 is about 18 μm, respectively 12 μm for M2.

THEORETICAL MODEL

Determination of permeability. The flow through the porous media generates a pressure drop, expressed as function of mean fluid velocity, fluid viscosity and permeability, best described by the Darcy's law:

$$\nabla p = -\frac{\eta u_m}{\phi}. \tag{1}$$

Considering the flow rate through the porous structure in radial coordinates as $Q = 2\pi r u_m h$, one can determine that:

$$Q = -2\pi r \frac{\phi h}{\eta} \frac{dp}{dr}. \tag{2}$$

From this relation the permeability can be obtained:

$$\phi = \frac{Q}{p_H} \frac{\eta}{2\pi h} \ln\left(\frac{r_e}{r_i}\right). \tag{3}$$

The flow rate being experimentally measured, we can compute the permeability values.

Analytical pressure distribution. The generalised 1D Reynolds equation of fluid flow through the porous media can be determined considering flow conservation:

$$\frac{d}{dx}\left(\phi h \frac{dp}{dx}\right) = \eta\left(U \frac{d(h\varepsilon)}{dx} - V\varepsilon\right). \tag{4}$$

This analytical model requires the following assumptions:

- Newtonian fluid is considered, in laminar and isothermal flow;
- constant pressure across the thickness of the porous layer;
- solid structure is conserved throughout the layer deformation process[5].

The fluid flow in the experiment has only the Poiseuille component, so without normal or tangential velocities, with constant permeability, the axisymmetric analytical model in polar coordinates is stated:

$$\frac{d}{dr}\left(r \frac{dp}{dr}\right) = 0. \tag{5}$$

The pressure drop between $r = 0$ and $r = r_i$ is neglected, so we will assume that the inlet pressure at r_i is $p_i = p_H$ and at r_e the pressure is null.

Applying the boundary conditions and computing the constants of integration, one can express the pressure variation as follows:

$$p = \frac{p_H}{\ln\left(\frac{r_i}{r_e}\right)} (\ln r - \ln r_e). \tag{6}$$

It is worth to be noticed that this analytically determined function does not take into consideration the constant permeability of the material and thus the compacticity.

In Fig. 4 is presented the axisymmetric Poiseuille flow through the porous material between two parallel circular surfaces.

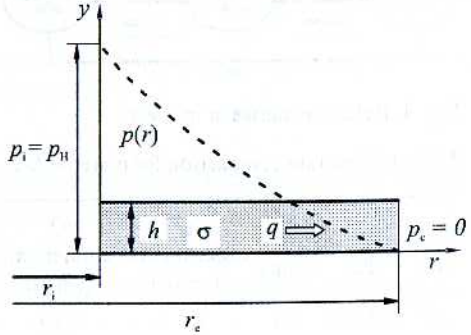

Fig. 4. Axisymmetric analytical model

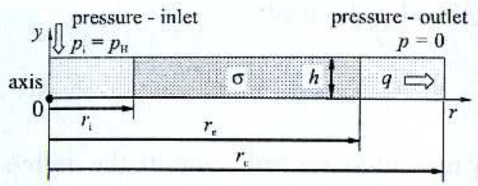

Fig. 5. Axisymmetric numerical model

Numerical model. A validation of a numerical model, from both sides, experimental and theoretical, insures us for further analyses of more complex approaches as dynamic 3D problems.

In this numerical study we used Fluent, a commercial CFD program, capable of analysing the flow through deformable porous media. Solving the Navier–Stokes equations by finite volume method (FVM), this program generates a more complex approach than equations usually used in numerical lubrication applications.

In order to comply with the analytical model and the experiment, the variation of permeability, according to the Kozeny–Carman relation, was modelled.

For the 2D Fluent axisymmetric model the 'segregated' solver was used, with laminar flow in a steady state. The boundary conditions used are presented in Fig. 5.

RESULTS

In order to better explain the relations between the used models and their comparisons, we present the diagram from Fig. 6.

We used as variation of permeability the Kozeny–Carman relation:

$$\phi = \frac{D(1-\sigma)^3}{\eta^2} \qquad (7)$$

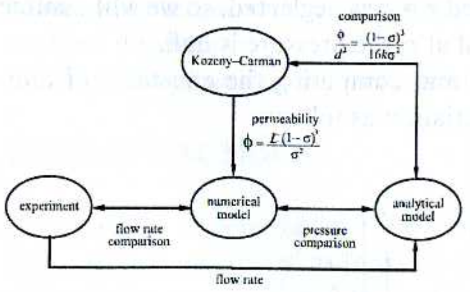

Fig. 6. Relations between models

where $D = d^2/16k$, with d – the fibre diameter and k – material characteristic.

The flow rate determined in the experiment was used to obtain the permeability by analytical means with equation (3). As a comparison between the experiment and the numerical model, we have presented in Table 1 the flow rates when material M2 was used, at three different inlet pressures, with h = 0.6 mm.

Table 1. Flow rate comparison for material M2

H_L (m)	p (Pa)	h (mm)	Q experimental (cm³/s)	Q numerical (cm³/s)
1.5	14710.5	0.6	1	9.84
1	9807	0.6	1.85	1.82
0.5	4903.5	0.6	2.94	2.87

For the same cases, another comparison was made, between numerical and analytical results of the pressure (Fig. 7).

A Fluent 2D case with pressure results is presented in Fig. 8.

In the correlation of experimental data with the Kozeny–Carman relation, shown in Fig. 9, we have added another variation that better suites our materials.

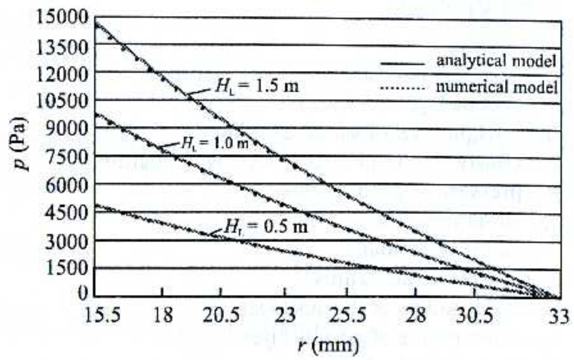

Fig. 7. Pressure comparison between the analytical and numerical models for M_2

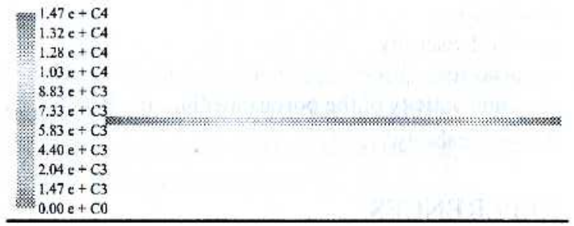

Fig. 8. Pressure contours from numerical model

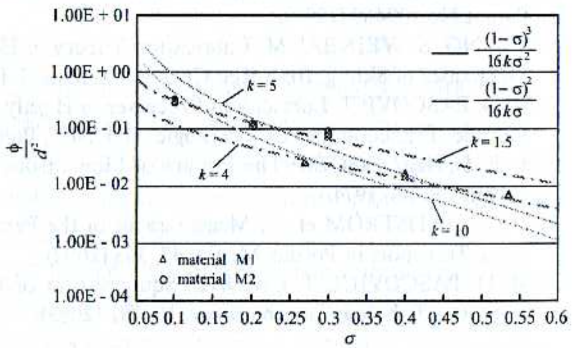

Fig. 9. Permeability related at fibre diameter as a function of compacticity

CONCLUSIONS

We can remark that both materials obey the same variation law, each one, inside a certain range of compacticity (0.25–0.55 for M_1 and 0.1–0.35 for M_2).

It is found that the law that interpolates the experimental points for this kind of materials should have the following expression:

$$\phi = \frac{D(1-\sigma)^2}{\sigma}. \qquad (8)$$

We can also observe that the experimental results are situated in the range of the Kozeny–Carman theoretical curves, k being between 2 and 12. Therefore, a certain value of k can be found, in order to approximate the points (using the least square method or other approximation method). This method should lead to greater error between the Kozeny–Carman curve and the experimental points.

Based on this steady state approach, dynamical experiments and theoretical studies will be developed.

NOTATIONS

D – complex constant of porous medium
h – porous layer thickness
H_L – height level of water reservoir
k – constant in the Kozeny–Carman equation
p – pressure of porous layer
p_H – inlet pressure
r – radial coordinate
r_c – circular plate radius
r_e – outer radius of porous layer
r_i – inner radius of porous layer
u_m – mean fluid velocity
U – tangential velocity
V – normal velocity
Q – flow rate
η – fluid viscosity
ε – porosity
σ – compacticity of the porous medium $\sigma = 1 - \varepsilon$
ϕ – permeability.

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Lubrication

CHARACTERISATION OF HYDRAULIC OILS BY SHEAR STABILITY AND EXTREME PRESSURE TESTS

M. RIPA*, C. SPANU, S. CIORTAN

University 'Dunarea de Jos' of Galati, 800 008 Galati, Romania
E-mail: Ripa.Minodora@ugal.ro

ABSTRACT

The paper presents shear stability and extreme pressure test results in order to characterise hydraulic oils. This comparative study is used to establish the way that the mechanical solicitations during service life of the oils affect the viscosity modification and thus the quality of oils performance.

Keywords: hydraulic oil, shear stability.

AIMS AND BACKGROUND

One of the basic characteristics of oils is the viscosity decreasing rate during service life. Knowing that the viscosity is influenced mainly by temperature variations, the most important goal is to obtain oils with as constant as is possible viscosity index overall functioning thermal domain. For that purpose some polymeric materials are used as oil additives[1].

The main problem encountered in polymer added oils is the loss of viscosity due to long polymeric chains fracture during the oil life cycle[2]. The establishing of viscosity loss in such cases is compulsive for a long oils' service life.

Anti-wear and extreme pressure are also important properties of oils. These properties become very important when oil is used in transmissions. The tests could be made on the four-ball tribotester. The four-ball machine was proposed for the first time by Boerlage[3] in order to determine some lubricant properties. Due to its design simplicity and a relatively simple geometry, it is widely used in research and industrial laboratories[4–10].

The tests were performed in the Technical Fluid Testing Laboratory – LubriTEST (University 'Dunarea de Jos' of Galati, Romania) on two hydraulic

* For correspondence.