Experimental Analysis of Fibrous Porous Media Permeability

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Porous media play a significant role in numerous industrial applications. One type of porous medium is composed of fibers or fiberlike particles (such as polymer chains in solution, fiber glass, filters, insulating materials, and reticuled ceramics). Jackson and James (1986) conducted a bibliographic study of the experimental results and theoretical models for the evaluation of the permeability of porous media. Experimental results are available for 25 different fibrous media with fiber diameters ranging from 10 Å to 10 mm. The deduced permeability values are quite specific to each experiment, since the geometry of the media are not clearly defined (such as filter and fiberglass).

In the present work the flow laws and permeability were determined for porous medium composed of randomly-packed monodispersed fibers. This medium has been characterized in terms of its fiber aspect ratio by Rahli et al. (1993) and Milewski (1986). These authors experimentally determined the relationship between porosity and aspect ratio for randomly packed monodispersed fibers. The porosity ranges from 0.35 to 0.90 for an aspect ratio between 4 and 70, compared to randomly packed spherical particles (porosity between 0.36 and 0.40).

In the present work, an experimental approach was developed to determine the flow laws in such porous media. The following paragraphs explain how pressure drop laws were obtained as a function of the fluid's superficial velocity. We studied the influence of porosity on the permeability of the fibrous porous medium. Analysis and discussion of the experimental results are presented and compared to the earlier models. Most of them deal with cylinders (with an infinite aspect ratio) in a simple array with a flow either parallel or perpendicular to the axis of cylinders.

Experimental Setup

The fibers were made from a bundle of metal wire (bronze, copper) of 150 μm in diameter. An electronic device controlled a stepping motor and a wire cutter. This system allows the wire to be drawn and cut to a chosen length. Several wires can be cut simultaneously. The rigid fibers were stacked randomly in a measuring cell by progressively packing and vibrating the cell. The porosity was then determined by weighing the fibers. The porosity values were identical when this operation was repeated for a given fiber aspect ratio, and this operation was carried out for each fiber aspect ratio (Rahli et al., 1993). Figure 1 shows a representation of the experimental device that was used to determine the flow law for a fluid moving through a fibrous medium. The enclosure C holding the fibers is composed of two stabilization tanks. Filters formed of sintered bronze spheres (60 μm in diameter) hold the fibers inside the measuring cell. The cell is made of Plexiglas, since this material is easy to work and it is transparent (35 mm dia. and 70 mm height). Two pressure tubes are placed inside the fibrous medium, near the filters. The enclosure (C) is placed between two identical and interconnected reservoirs (A, B). Two overflow outlets ensure that the level of the liquid remains constant in these reservoirs. The excess liquid is recovered in reservoir (E). The pump (P) takes the water from tank (E) to reservoir (A).

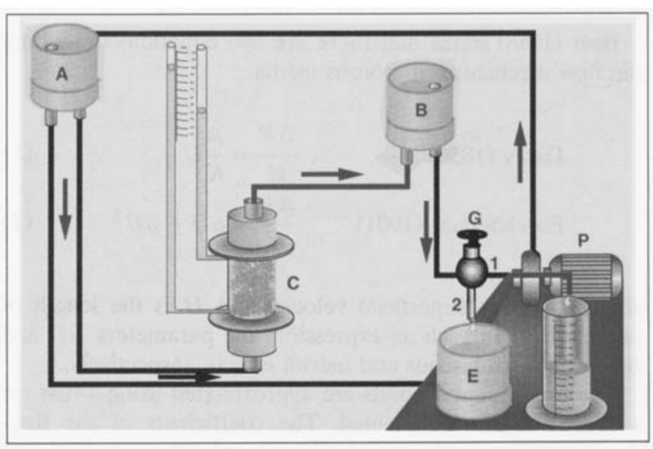

Figure 1. Experimental apparatus used to determine pressure drop in relation to the superficial velocity.

(C) Fibrous bed test section; 35-mm-dia cylindrical tube (70 mm length); (A) (B) (E) reservoirs; (P) peristaltic pump; (G) gate.

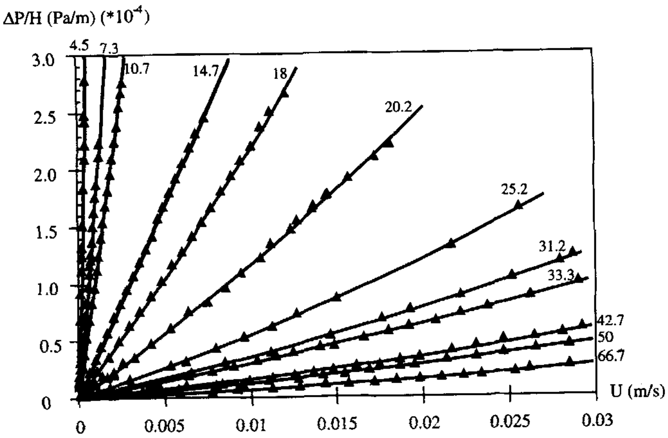

Figure 2. Variation in pressure drop in relation to the apparent velocity for all aspect ratios studied.

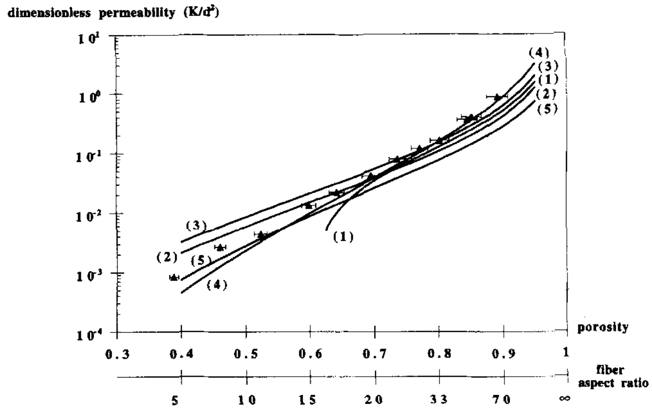

Figure 3. Variation of the permeability in relation to the fibrous medium's porosity ϵ and the fiber aspect ratio.

▲ Our experimental results; (1) Jackson and James model (1986); (2) Happel and Brenner model (1962) (perpendicular); (3) Happel and Brenner model (1962) (parallel); (4) Kyan et al. model (1970); (5) Sahraoui and Kaviany model (1992).

The operating principle consists in imposing a fixed height difference between the level of the liquids in the two reservoirs (i.e., A and B). The liquid then flows through the porous medium. All residual air is removed from the medium by circulating the liquid for several hours prior to each measurement. The variation in pressure drop ΔH is determined systematically according to the superficial velocity. The piezometric load is measured between the inlet and the outlet of the fibrous medium. A graduated test tube and a stopwatch are used to measure the flow Q at outlet -1- of reservoir (B), thus allowing the superficial velocity to be deduced. The experimental procedure consisted in measuring both the flow rate Q through the fibrous medium with a predetermined section A (thus $U = Q/A$), and the corresponding pressure drop $\Delta P = \rho g \Delta H$ at a predetermined distance H. After the Q and ΔH values are acquired, the flow rate is increased and the system is allowed to stabilize. The next set of data is then acquired to determine the characteristic flow resistance for the medium.

Experimental Results and Analysis

Bear (1988) states that there are two equations describing the flow mechanism in porous media

Darcy (1856) $$\frac{\Delta P}{H} = \frac{\mu}{K} U \quad (1)$$

Forchheimer (1901) $$\frac{\Delta P}{H} = \alpha U + \beta U^2 \quad (2)$$

where U is the superficial velocity and H is the length of particle bed. In such an expression, the parameters αU and βU^2 vary with viscous and inertia effects, respectively.

The experimental points are approximated using a first- or a second-degree polynomial. The coefficients of the first-degree polynomial were initially determined using the least-squares method. Before introducing a second-degree term into the regression polynomial, the statistical Snedecor test was applied. This approach is used to test whether the improvement associated with the introduction of a second term is significant (Neuilly and Cetama, 1993). Second-degree polynomial regression is used only if the improvement is found to be significant. The coefficients of this polynomial are then determined using the least-squares method. Figure 2 shows the variations in pressure drop in relation to the superficial velocity fluid for all aspect ratios studied. The friction losses related to the superficial velocity are inversely proportional to the fiber aspect ratio. For low aspect ratios, the variation law is nearly linear. No inertia effects were observed given the low velocities. When the aspect ratio (and thus the porosity) increases, inertia effects become considerable. The permeability values deduced from the experimental results vary in relation to the porosity of the medium (Figure 3). This variation increases in proportion to the porosity value. The permeability varies from 20 to 20,000 Darcy, for porosity ranging between 35 and 90%. The error for porosity values is due essentially to the imprecision (estimated at ± 0.5 mm) in measuring the bed height. This figure also shows the fiber aspect ratio plotted on the abscissa. The error for fiber length did not exceed to 2.5% taking into account the errors introduced by the fiber extremities and the imprecision in measuring their length. The permeability was found to vary according to the porosity, especially for high porosity values.

Discussion and Comparison with Models

To our knowledge, there is no general relationship that defines permeability as a function of porosity for porous media made of randomly-stacked monodispersed fibers. The experimental results are compared to the models described in earlier works. These comparisons are strictly qualitative, since the models were developed for an ideal array of infinite length cylinders.

There are relatively few empirical or semiempirical correlations dealing with the permeability of a porous fibrous media. Jackson and James (1986) proposed a model that gives permeability in relation to porosity. Using this model, the permeability of randomly-packed fibers is expressed in relation to the porosity. These authors point out that this law is only valid for high porosity values ($\epsilon > 0.7$).

Happel and Brenner (1962) developed analytical solutions of the Navier-Stokes equation for parallel and normal flows around a cylinder of a given diameter. By using a unit cell model, these authors analyzed the flow parallel and perpendicular to an array of cylinders. To determine K for a random array of cylinders with high aspect ratio $(L/d \to \infty)$, Happel and Brenner (1962) proposed a linear combination of the permeability calculated for parallel and perpendicular flow.

Numerical solutions of Navier-Stokes equations have been studied by Sahraoui and Kaviany (1992) using a finite-difference method for a two-dimensional flow through an array of cylinders. The variation law for permeability vs. porosity, deduced from this approach, is as follows

$$\frac{K}{d^2} = 0.0606\frac{\pi}{4}\frac{\epsilon^{5.1}}{(1-\epsilon)} \qquad 0.4 \le \epsilon \le 0.8 \tag{3}$$

Kyan et al. (1970) have noted the existence of a surprisingly large friction loss, despite the porosity of the layer. Using a geometric model of the fibrous bed, they assumed that the fluid was not flowing through a significant portion of the pore space. They postulated that the total pressure drop across the bed is equal to the sum of the pressure drop values associated with viscous loss, drag, and fiber deflection.

The permeability values deduced from these models are compared to our experimental results in Figure 3. This comparison is limited to the applicable porosity range for each model.

For porosity values greater than 0.7, the permeability values deduced from the model of Jackson and James (1986) are smaller than those in the present work. The variation law proposed by these authors differs considerably from the present experimental results for all porosity values studied.

The laws deduced from the models of Happel and Brenner (1962) are similar in behavior to our results, although the values vary considerably for different porosities. For porosity values lower than 0.6, the models tend to overestimate the permeability. When the permeability is greater than 0:7, the results obtained using these approaches are lower than the experimental values.

The numerical results obtained by Sahraoui and Kaviany (1992) were systematically lower than our experimental results. This difference increases with the porosity. Good agreement is observed between the experimental results and those deduced from the Kyan et al. (1970) model for the porosities between 0.7 and 0.9 where the curves overlap. For porosity values less than 0.7, a significant deviation is observed.

These comparisons indicate that the models based on fibers arranged in simple, ordered patterns do not accurately predict the permeability of the randomly-packed monodispersed rigid fibers. Such models do not take into account the fiber aspect ratio r and the contribution of the fiber-extremity surface. This contribution falls below 2% for r values greater than 25, but it is quite significant for low aspect ratios.

Conclusion

In this work, experimental studies were carried out on fluid flowing through porous media formed of randomly-packed monodispersed fibers. A systematic study was conducted for different porosity values $\epsilon(L/d)$. The variations of the permeability values plotted against the porosity of the medium are determined using experimental flow laws and Darcy's law. The comparison of experimental results and models for simple arrays of cylinders does not prove satisfactory for all approaches. It therefore seems that a model will need to be developed to take into account the aspect ratio of the randomly-stacked fibers.

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