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Darcy Permeability of Hollow Fiber Bundles Used in Blood Oxygenation Devices

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Abstract

Many industrial and biomedical devices (e.g. blood oxygenators and artificial lungs) use bundles of hollow fiber membranes for separation processes. Analyses of flow and mass transport within the shell-side of the fiber bundles most often model the bundle for simplicity as a packed bed or porous media, using a Darcy permeability coefficient estimated from the Blake-Kozeny equation to account for viscous drag from the fibers. In this study, we developed a simple method for measuring the Darcy permeability of hollow fiber membrane bundles and evaluated how well the Blake-Kozeny (BK) equation predicted the Darcy permeability for these bundles. Fiber bundles were fabricated from commercially available Celgard® ×30-240 fiber fabric (300 μm outer diameter fibers @ 35 and 54 fibers/inch) and from a fiber fabric with 193 μm fibers (61 fibers/inch). The fiber bundles were mounted to the bottom of an acrylic tube and Darcy permeability was determined by measuring the elapsed time for a column of glycerol solution to flow through a fiber bundle. The ratio of the measured Darcy permeability to that predicted from the BK equation varied from 1.09 to 0.56. A comprehensive literature review suggested a modified BK equation with the “constant” correlated to porosity. This modification improved the predictions of the BK equation, with the ratio of measured to predicted permeability varying from 1.13 to 0.84.

Keywords

Artificial Lungs; Respiratory Assist Devices; Porous Media; Darcy's Law; Blake-Kozeny Equation; Ergun Equation

Introduction

Hollow fiber membrane (HFM) modules arise in numerous important industrial and biomedical separation processes including membrane distillation, membrane microfiltration and ultrafiltration, organic pervaporation of aqueous media, and gas separation or adsorption [1-3]. In the biomedical arena, HFM modules form the exchange elements of the blood oxygenators used in cardiopulmonary bypass circuits during cardiac surgery, in next-

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generation respiratory assist devices (artificial lungs) being developed for patients with failing lungs [4, 5]. In blood purification, HFM modules are also used for commercial hemodialyzers and hemofilters for plasmapheresis. The performance of a given membrane module depends on the flow characteristics through the tube (intraluminal) and shell (extraluminal) sides of the module. The intraluminal compartment reflects flow through tubes in parallel, and design features can be analyzed relatively easily using engineering principles for flow through pipes [6]. The flow through the shell side of HFM modules is more difficult to analyze. Modeling the microscale flow occurring within the interstitial space between hollow fibers is computationally difficult, even intractable, because membrane modules can be composed of thousands of individual fibers. A more commonly-used and accepted approach involves modeling the HFM bundle as an effective packed bed or porous medium. The individual HFMs are not resolved but their average effect on local fluid drag can be incorporated through phenomenological coefficients such as the Darcy permeability of the fiber bundle.

For fluid flow through porous media, Darcy's Law states that the viscous drag force per unit volume, $\bar{F}_v$, is proportional to fluid velocity [7]:

$$\bar{F}_v = -\frac{\mu}{k} \bar{V}_0 \quad (1)$$

where μ is the fluid viscosity, k is the Darcy permeability of the porous media, and $\bar{V}_0$ the *superficial* fluid velocity vector within the media. If fluid inertial and gravitational forces are negligible, an equation of motion incorporating Eqn.1 for momentum losses produces the more common form of Darcy's Law:

$$\bar{V}_0 = -\frac{k}{\mu} \nabla P \quad (2)$$

where ∇P is the pressure field within the porous media [6]. Simpler analyses of flow through blood oxygenators often assume uniform flow paths across the HFM bundle and employ integrated forms of Darcy's Law, with the permeability, k , implicitly incorporated into friction factors that are correlated to the inverse Reynolds Number [8, 9]. Increasingly, artificial lungs, blood oxygenators and other devices employing HFM bundles are designed *a-priori* and/or evaluated *a-posteriori* using CFD (computational fluid dynamics). These CFD analyses incorporate the differential form of Darcy's Law within differential momentum balances to enable simulations of non-uniform and complex flow paths through the HFM bundle that can arise, for example, due to unique HFM bundle geometry, the location of discrete inlets/outlets, and/or novel "active mixing" mechanisms that intentionally disrupt the macroscopic flow fields [10,11]. These approaches estimate the Darcy permeability of the HFM bundles using the empirical Blake-Kozeny equation, the frictional component of the Ergun equation used to estimate viscous losses for flow through packed bead columns [6].

In this study, we developed a simple apparatus and method to experimentally measure the Darcy permeability coefficient of several HFM materials commonly used in bundles of artificial lungs and blood oxygenator devices. One of the principal purposes of the study was to evaluate how well the Darcy permeability of these bundles could be estimated using the Blake-Kozeny equation. Our results should be of special interest to the growing number of investigations using CFD analyses and porous media approximations in the design and development of industrial or biomedical devices incorporating HFM bundles.

Experimental Methods and Data Analysis

Hollow Fiber Membrane Material

All hollow fiber membrane (HFM) materials were made from Celgard® microporous polypropylene oxygenator fibers manufactured by Membrana GmbH® (Wuppertal, Germany). The HFM material was supplied as fabric fiber mats in which nylon weft threads held the fibers at constant spacing. Two different fiber sizes were used: a) Celgard® x30-240 with 300 μm outer diameter (OD) and 240 μm inner diameter (ID) and b) a custom Celgard® fiber with 193 μm OD and 139 μm ID. The Celgard® x30-240 mat was tested at hollow fiber densities of 35 and 54 fibers per inch, while the custom Celgard® mat was tested at a fiber density of 61 fibers per inch.

The HFM material to be tested was cut into 3.02 cm diameter circular pieces and stacked together to form simple bundles. The first layer of fiber was glued to a circular ring of polystyrene (3.81 cm outer diameter and 2.54 cm inner diameter) using five minute epoxy (P/N 14270, Devcon, Glenview, IL). Successive fiber layers were glued with five minute epoxy onto their subjacent layers, with fiber layers being aligned parallel, perpendicular, or angled to each other, until the desired number of layers were stacked. The angled bundle fibers were arranged at an angle of 36° to one another to mimic fiber arrangements in a blood oxygenator. In pilot studies we determined that the measured permeability did not significantly depend on whether 5 or 10 layers of fiber were used. Subsequently we fabricated all fiber bundles using 10 layers of fiber. The parallel fiber layers were laid on top of each other so that they formed a staggered arrangement. The staggered arrangements in parallel fiber layers were allowed to lie on each other by their natural physical contact, as would occur similarly when a complete fiber bundle is made by wrapping fiber mat in concentric annular layers. The stacked fiber bundles were allowed to dry overnight. Two fiber bundles were created for each combination of different fiber fabric type, number of fiber layers, and fiber orientation.

After a fiber bundle was used for a permeability measurement (as described in the following section), the bundle was cut in half. The cutting of the fiber bundle did not impact the integrity of the fiber bundle visually or by physical measurement because the epoxy used to pot the fiber bundle constrained the assembly and the fibers remained undisturbed. The bundle thickness was measured using a flat blade digital caliper (Tesa Dura-Cal Digital Caliper, Switzerland) to minimize the effects of distortion (compression) at contact points that can be caused by the rotating anvil of micrometers. Thickness measurements were performed at five distinct points along the chord and averaged. The coefficient of variation in thickness of this measurement was typically less than 5%. All measurements were performed by a trained journey instrument maker in our institute's manufacturing core.

Permeability Apparatus and Measurement

The permeability fixture consisted of a 2.54 cm (1 inch) inner diameter acrylic tube ten centimeters high with increments marked every centimeter (**Figure 1**). The polystyrene ring supporting a stacked fiber bundle was glued to the bottom of the acrylic tube. The potting used to hold fiber layers into the fiber bundle (as described above) formed a complete circumferential seal around the bundle and the inner diameter of the potting corresponded to the inner diameter of the polystyrene ring and the acrylic tube. The permeability fixture was suspended above an overflow beaker using a ring stand.

An aqueous glycerol solution with a nominal viscosity of $4.6 \pm 0.9 \text{ g/cm}^3\text{s}$ was used in the permeability fixture as the fluid medium. The kinematic viscosity of the solution was measured prior to each test using a capillary viscometer (P/N 9721-Y77, Calibrated Cannon-

Manning Semi-micro, Size 450 C181, Cannon Instrument Company, State College, PA). The permeability fixture was flushed through with approximately 20 mL of the aqueous glycerol solution prior to data collection to ensure that no air bubbles were trapped in the fiber bundle. The overflow beaker was also filled with the same solution to the point where it overflowed into a collection beaker placed underneath the apparatus. The permeability fixture was then adjusted so that the bottom of the fiber bundle just touched the top of the aqueous glycerol solution in the overflow beaker. This was done to eliminate any pressure deviations from atmospheric pressure at the bottom of the bundle due to surface tension of drops that would form otherwise. The permeability fixture was filled with the aqueous glycerol solution to just above the desired starting height mark of either 3, 6, or 9 cm. Elapsed time for the glycerol/water solution to pass from the starting height (h_i) to the ending height ($h_f = 2$ cm above the fiber bundle) was recorded. Measurements were repeated two times at each height. In several tests the aqueous glycerol solution that was in the collection beaker at the end of a test run on a given bundle was sampled to ensure that its kinematic viscosity was the same as that at the beginning of the test run. A high viscosity glycerol solution was used to generate easily measured time intervals and also to ensure that viscous effects dominated over inertial effects in the flow through the bundle, as Darcy's Law and the Blake-Kozeny equation only account for viscous effects.

Darcy's Law integrated over the fiber bundle in the vertical direction yields:

$$V_0 = \frac{k P_0}{\mu \delta} \quad (3)$$

where V_0 is the superficial velocity, given by $V_0 = Q/A$ (flow rate or flux, Q , and tube area A) and δ is the thickness of the fiber bundle. The gage pressure at the bottom of the tube, P_0 , depends on the fluid height, $h(t)$, in the column:

$$P_0 = \rho g h(t) \quad (4)$$

where ρ is the fluid density, and g is gravitational acceleration. Eqns 3 and 4 can be combined through the conservation of mass statement, $V_0 = -dh/dt$, and integrated to yield:

$$\Delta t = \frac{\nu \delta}{g k} \ln h_i/h_f \quad (5)$$

where Δt is the time interval to span the initial and final heights and $\nu = \mu/\rho$ is the kinematic viscosity.

Values of Δt versus $\ln h_i/h_f$ were averaged over two runs for each height ratio, and a linear regression used to determine k from Eqn 5 using the measured values for fiber bundle thickness, and kinematic viscosity. The mean and standard deviation of the permeability values for each pair of identical fiber bundles were then computed.

Estimating Darcy Permeability

The Darcy permeability of the hollow fiber bundles was estimated from the Blake-Kozeny equation relating pressure drop to flow through packed bed columns of length, L [6]

$$\frac{\Delta P}{L} = 150 \left(\frac{\mu V_0}{D_p^2} \right) \frac{(1 - \epsilon)^2}{\epsilon^3} \quad (6)$$

where ϵ is the medium porosity and D_p is the effective particle diameter, estimated as $D_p = 6/a_v$, in which a_v is the total particle surface area per volume of particles in the medium (a_v

is 4 divided by fiber diameter for this application). The Darcy permeability estimated from the Blake-Kozeny equation for packed bed columns is:

$$k = \frac{1}{150} \frac{\epsilon^3 D_f^2}{(1 - \epsilon)^2} \quad (7)$$

Permeability values were estimated for the three different fiber fabrics stacked in parallel or perpendicular layers, as well as the 35 fibers per inch fabric stacked in angled layers. For each bundle, the porosity was calculated using as a basis an arbitrary 1 cm by 1 cm square of bundle with a total volume given by $V_T = \delta(1 \text{ cm}^2)$, where δ is the measured average thickness of the bundle. The volume of fibers in that total volume is given by

$V_F = N_L N_f (1 - \text{cm}) \pi \left(\frac{D_f}{2}\right)^2 (1 - \text{cm})$, where N_L is the number of fiber layers, N_f is fiber density of the fiber fabric, and D_f is the fiber diameter. Porosity is then given by $\epsilon = (V_T - V_F)/V_T$. The weft threads used to make the fiber fabric were not accounted for in the porosity calculation, as their volume was negligible compared to fiber volume and pilot tests indicated that removing every other weft thread from the fabric had a negligible effect on the measured permeability.

Results

Darcy permeability values were measured for all samples of hollow fiber membrane (HFM) bundles by measuring the elapsed time (Δt) for an aqueous glycerol solution to drain through the bundle from an initial column height (h_i) to final column height (h_f) of the permeability apparatus shown in Figure 1. **Figure 2** displays a typical plot showing the linear relation between Δt and $\ln h_i/h_f$ for parallel fiber bundles made from the 300 μm outer diameter HFM fabric at 35 fibers/inch (fpi) and 54 fpi. For each fiber bundle, the standard deviation shown for each elapsed time is that based on two measurements at each height. The slopes obtained from linear regression of these data yielded the Darcy permeability values, k , from Eqn 5. The Darcy permeability of the 54 fpi HFM fabric was substantially lower than that of the 35 fpi HFM fabric ($k = 5.36 \times 10^{-6} \text{ cm}^2$ versus $k = 9.53 \times 10^{-6} \text{ cm}^2$). The linear regressions of Δt versus $\ln h_i/h_f$ for all HFM bundles studied here had R^2 values similar to those in Figure 2.

Table 1 summarizes the measured Darcy permeability values for all the hollow fiber bundles studied. For each fiber bundle type, the measured permeability indicates the standard deviation and coefficient of variation (CV) for two different fiber bundles constructed for that particular fiber type. For fiber bundles made from the 300 μm OD fiber, the measured Darcy permeability with perpendicular fiber stacking was greater than that with parallel fiber stacking. The permeability value of the angled fiber bundles made from the 300 μm OD fiber fabric falls between the permeability values of the parallel and perpendicular bundles of that fiber fabric. Table 1 also compares the measured Darcy permeability to that estimated from the Blake-Kozeny equation (Eqn 7). For the fiber bundles made from the 300 μm OD fiber fabric, the Blake-Kozeny equation predicted the measured Darcy permeability within 10% for the parallel stacked layers, and within 40% for the perpendicular stacked layers. For both parallel and perpendicular stacking, the Blake-Kozeny equation was less predictive of the measured Darcy permeability for the fiber bundles made from the 193 μm OD fiber fabric. The deviation between measured and predicted permeability will be further discussed below.

Discussion

The design and evaluation of industrial and biomedical devices composed of bundles of hollow fiber membranes often involves using CFD (computational fluid dynamics) to predict flow patterns through the shell-side of the hollow fiber bundle. Hollow fiber bundles like those used in blood oxygenators can incorporate thousands of individual hollow fibers. Accordingly CFD analyses most often model the effects of the fibers on fluid drag using a packed bed or porous media approach rather than resolving individual fibers and imposing the no-slip boundary condition on each of them. The porous media model for hollow fiber bundles uses Darcy's Law to model the fiber effects on fluid drag and a Darcy permeability coefficient estimated from the Blake-Kozeny equation. In this study, we measured the Darcy permeability of bundles made from hollow fiber fabric commonly used in blood oxygenators and artificial lungs, and we assessed how well the Blake-Kozeny equation could predict bundle permeability. For the commonly-used commercial Celgard x30-240 hollow fiber fabric (300 μm outer diameter and either 35 or 54 fibers per inch), the Blake-Kozeny estimate was within 9% of the actual Darcy permeability of the fiber bundle when the fiber layers were stacked in parallel arrangement, as would occur with typical fabrication of an annular fiber bundle for an oxygenator or artificial lung device.

The fiber bundle made from the parallel arrangement of 300 μm fibers at 35 fpi had a measured porosity that was significantly less than the theoretical porosity assuming distinct layers of fiber fabric lying on top of one another (0.53 versus 0.67). All other fiber bundles had measured permeabilities close to their theoretical values. A lower porosity than theoretical indicates a staggered array of parallel fibers with intrusion of one layer into another. Even in the other parallel fiber bundles, we observed that the fibers naturally assumed a staggered configuration in their distinct layers because of the weft thread knots at the fiber-weft junctions. One concern would be if such a staggered arrangement produces fibers touching one another, significant local blockage of flow, and permeability values that differ from one fabricated bundle to another of the same fiber fabric. This could be of special concern for the 300 μm fibers at 54 fpi because the space between fibers is only 170 μm , less than the fiber diameter. For this reason, we fabricated two different fiber bundles for each fiber fabric and orientation. The coefficient of variation (CV) of permeability values between two fiber bundles of the same type was less than 6% for all but one type, which had a CV of 10%. The fiber bundles of 300 μm fibers at 54 fpi had a CV of 5.8% for its two different fiber bundles. This suggests that gross fiber blockage in the parallel fiber arrangement was not a significant problem.

MacDonald et al. [12] reviewed the ability of the Ergun equation to predict pressure drops through packed beds made from a variety of different solid packings, effective particle diameters, and bed porosities reported from measurements in the literature. Several of these measurement sets involved observations on flow through packed beds of cylindrical particles. Their review across a large data set indicated that the empirical constant used in the Blake-Kozeny (BK) relation, Eq. 7, is better selected as $A = 180$ rather than $A = 150$ so that the measured permeability lies within $\pm 50\%$ of the estimated permeability over the entire data set examined in their review. Using $A = 180$ in Eq. 7, the ratio of measured to estimated permeability for the hollow fiber bundles in Table 1 ranges from 1.31 to 0.67, and thus the measured permeability lies within $\pm 33\%$ of the estimated permeability.

The analysis of MacDonald et al can also be used to further refine the constant A in the BK relation. Their analysis indicated that A was dependent on particle shape, equivalent particle size, D_p , and porosity, ϵ . We can ignore the linear correlation with D_p because our D_p range is only 1% of the range over which A was correlated to D_p in their study. Table 1 suggests, however, that a correlation with porosity may be important. Accordingly, we calculated A in

Eq. 7 using the measured permeability in Table 1 and correlated A with the porosity of the fiber bundle, as shown in Figure 3. A good linear correlation existed and was given by

$$A = 542 \epsilon - 128 \quad (8)$$

with an R^2 value of 0.82. Using this correlation and Eq. 6, the estimated permeabilities were recomputed and compared to measured permeabilities (Table 2). Table 2 indicates that after accounting for the correlation between the BK constant and porosity, the measured permeability lies within $\pm 16\%$ of the estimated permeability.

Hollow fiber bundles would best be modeled as an anisotropic porous medium. The Darcy permeability for flow perpendicular to the fibers (as studied here) would be expected to be different (lower) than that for flow parallel to the fibers, leading to a Darcy permeability tensor. This study focused solely on the Darcy permeability of fiber bundles with flow perpendicular to the fibers. In practice, blood oxygenators and artificial lung devices are designed to promote perpendicular flow across the fiber bundle over parallel flow because of substantial mass transfer advantages. Furthermore, the CFD analyses of these devices have limited their approach to isotropic porous media models characterized by a single Darcy permeability. From a practical standpoint, measuring the Darcy permeability for flow parallel to fibers using a simple apparatus like that developed here would be difficult, but could be done by modifying the apparatus and approach. If CFD analyses of flow and mass transfer in devices composed of hollow fiber bundles advance to incorporate a Darcy permeability tensor, then our study should logically be extended to evaluate the Darcy permeability for both perpendicular flow and parallel flow.

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Research Highlights

- The Darcy permeability of hollow fiber membranes was measured for use in the viscous dissipation term of CFD models of flow through artificial lung devices.
- The Darcy permeability ranged from 5.36×10^{-6} to 2.48×10^{-5} cm₂ for various bundles.
- The modified Blake-Kozeny equation predicted the measured permeability to within $\pm 33\%$.
- Predictions improved to within $\pm 16\%$ by accounting for the empirical correlation between the Blake-Kozeny constant and bundle porosity.

Figure 1.

Experimental setup for measuring the Darcy permeability of bundles of hollow fiber bundles. Fiber bundles were glued to the bottom of an acrylic tube. A glycerol solution placed in the tube flowed through the bundle and the elapsed time was measured for top of the solution to drop from an initial height (h_i) to final height (h_f).

Figure 2.

The elapsed time (Δt) followed the predicted linear relationship with $\ln h_i/h_f$ for all fiber bundles tested (each data point shown is the average of two trials for the respective parallel fiber bundle). The slope of the relationship was used to determine the Darcy permeability using Eqn 5.

Figure 3.
Correlation of Blake-Kozeny constant, A , to fiber bundle porosity, ϵ .

Table 1

Estimated Versus Measured Darcy Permeability

Fibers Per Inch	Outer Diameter (μm)	Porosity, ϵ	k (cm ²) measured	k (cm ²) estimated	Ratio Measured/Predicted
<i>Parallel Stacking of 10 Fiber Layers</i>					
35	300	0.53±.018	9.53 ± 0.92 × 10 ⁻⁶ CV=9.7%	8.82 × 10 ⁻⁶	1.08
54	300	0.47±.0043	5.36 ± 0.31 × 10 ⁻⁶ CV=5.8%	4.93 × 10 ⁻⁶	1.09
61	193	0.65±.0020	8.91 ± 0.42 × 10 ⁻⁶ CV=4.7%	1.21 × 10 ⁻⁵	0.74
<i>Perpendicular Stacking of 10 Fiber Layers</i>					
35	300	0.66±.0067	2.48 ± 0.14 × 10 ⁻⁵ CV=5.6%	3.44 × 10 ⁻⁵	0.72
54	300	0.50±.0089	6.59 ± 0.22 × 10 ⁻⁶ CV=3.3%	6.40 × 10 ⁻⁶	1.03
61	193	0.67±.00024	7.41 ± 0.20 × 10 ⁻⁶ CV=2.7%	1.33 × 10 ⁻⁵	0.56
<i>Angled Stacking of 10 Fiber Layers</i>					
35	300	.63±.0061	1.81 ± 0.04 × 10 ⁻⁵ CV=2.0%	2.73 × 10 ⁻⁵	0.66

Table 2

Modified Estimated Versus Measured Darcy Permeability

Fibers Per Inch	Outer Diameter (μm)	Porosity, ϵ	k (cm^2) measured	k (cm^2) estimated	Ratio Measured/Predicted
<i>Parallel Stacking of 10 Fiber Layers</i>					
35	300	0.53 $\pm$.018	9.53×10^{-6}	8.40×10^{-6}	1.13
54	300	0.47 $\pm$.0043	5.36×10^{-6}	5.86×10^{-6}	0.91
61	193	0.65 $\pm$.0020	8.91×10^{-6}	8.22×10^{-6}	1.08
<i>Perpendicular Stacking of 10 Fiber Layers</i>					
35	300	0.66 $\pm$.0067	2.48×10^{-5}	2.24×10^{-5}	1.11
54	300	0.50 $\pm$.0089	6.59×10^{-6}	6.85×10^{-6}	0.96
61	193	0.67 $\pm$.00024	7.41×10^{-6}	8.81×10^{-6}	0.84
<i>Angled Stacking of 10 Fiber Layers</i>					
35	300	.63 $\pm$.0061	1.81×10^{-5}	1.87×10^{-5}	0.97