Published in final edited form as:

ASAIO J. 2016 ; 62(3): 329–331. doi:10.1097/MAT.0000000000000348.

Darcy permeability of hollow fiber membrane bundles made from Membrana® Polymethylpentene (PMP) fibers used in respiratory assist devices

Shalv. P. Madhani^{a,b}, Brandon. D. D'Aloiso^{a,b}, Brian. Frankowski^{a,b}, and William. J. Federspiel^{a,b,c,d}

^aMcGowan Institute for Regenerative Medicine, University of Pittsburgh, 3025 East Carson Street, Pittsburgh, PA 15203, USA

^bDepartment of Bioengineering, University of Pittsburgh, Pittsburgh, PA

^cDepartment of Chemical and Petroleum Engineering, University of Pittsburgh, Pittsburgh, PA

^dDepartment of Critical Care Medicine, University of Pittsburgh Medical Center, Pittsburgh, PA

Abstract

Hollow fiber membranes (HFMs) are used in blood oxygenators for cardiopulmonary bypass or in next generation artificial lungs. Flow analyses of these devices is typically done using computational fluid dynamics (CFD) modeling HFM bundles as porous media, using a Darcy permeability coefficient estimated from the Blake – Kozeny (BK) equation to account for viscous drag from fibers. We recently published how well this approach can predict Darcy permeability for fiber bundles made from polypropylene HFMs, showing the prediction can be significantly improved using an experimentally derived correlation between the BK constant (A) and bundle porosity (ϵ). In this study, we assessed how well our correlation for A worked for predicting the Darcy permeability of fiber bundles made from Membrana® polymethylpentene (PMP) HFMs, which are increasingly being used clinically. Swatches in the porosity range of 0.4 to 0.8 were assessed in which sheets of fiber were stacked in parallel, perpendicular and angled configurations. Our previously published correlation predicted Darcy within $\pm 8\%$. A new correlation based on current and past measured permeability was determined: $A = 497\epsilon - 103$; using this correlation measured Darcy permeability was within $\pm 6\%$. This correlation varied from 8% to -3.5% of our prior correlation over the tested porosity range.

Keywords

Artificial Lungs; Respiratory Assist Devices; Porous Media; Darcy's Law; Blake–Kozeny equation; Ergun Equation; Polymethyl Pentene (PMP) Hollow Fiber Membrane

1. Introduction

HFM bundles are incorporated into devices used as blood oxygenators for cardiopulmonary bypass for cardiac surgery and in next generation respiratory assist devices used as artificial lungs for patients with failing lungs.^{1–5} Computational fluid dynamics (CFD) is often used as a tool to design these devices.^{6–11} Modeling the flow at the fiber level of the bundle can be computationally difficult as the bundles are composed of thousands of individual fibers. Instead modeling approaches typically treat the fiber bundle as a packed bed or porous medium in which the effect of local fluid drag from the individual fibers is incorporated using a Darcy permeability coefficient for the fiber bundle.^{11–14} The Darcy permeability, k , is estimated using the empirical Blake – Kozeny equation:

$$k = \frac{1}{150} \frac{\varepsilon^3 D_p^2}{(1-\varepsilon)^2} \quad (1)$$

in which ε is the bundle porosity and D_p^2 is the effective fiber diameter.¹⁵

We recently published a study assessing how well the Darcy permeability of hollow fiber bundles can be predicted using the Blake-Kozeny equation. We determined that the prediction of Darcy permeability can be significantly improved if the constant in Equation (1),¹⁵ $A=150$, is empirically correlated to fiber bundle porosity using $A=542\varepsilon - 128$. These studies were done using seven different fiber bundles constructed from Celgard® microporous polypropylene hollow fiber membrane mats with several different fiber sizes, fiber spacing in the mats, and fiber orientation between adjacent fiber mat layers within the fiber bundle. Increasingly, HFM bundles used in clinical blood oxygenators and in respiratory assist devices under development are using Membrana® polymethylpentene (PMP) hollow fiber mats.^{1–3,16–18} The Membrana® PMP fiber has an asymmetric membrane wall with closed surface pores, rather than a microporous membrane wall, to prevent blood plasma wetting, which can adversely affect gas exchange and device function.^{19,20} The Membrana® fiber mat has larger fibers than the largest Celgard® fiber used in our previous study (380 μm versus 300 μm outer diameter) and a different fiber density (44 versus 51 fibers per inch). As these differences due to fiber arrangement may affect flow at the fiber level, we wanted to assess how well our empirical correction to the Blake – Kozeny constant could predict the Darcy permeability of fiber bundles made from the Membrana® PMP fiber mats. This brief report summarizes the findings of our study.

2. Methods

All manufacturing and test methods were the same as previously reported¹⁵ with the exception that the circular fiber swatches used in our experimental apparatus were constructed from Membrana GmbH® (Wuppertal, Germany) Oxyplus® PMP hollow fiber mats (380 μm outer diameter, 44 fibers/inch density). High porosity swatches were created by increasing fiber spacing in the mats by removing every other fiber. The circular swatches were mounted at the bottom of a plastic tube and a pure glycerol solution (average nominal kinematic viscosity $\nu = 400$ cSt) was poured into the tube above the swatches. Measuring the

time interval, t , for the glycerol solution to flow from an initial height, h_i , to a final height, h_f in the tube provided the Darcy permeability of the fiber swatch using the relation:

$$\Delta t = \frac{\nu \delta}{gk} \ln \frac{h_i}{h_f} \quad (2)$$

derived previously, where δ is the thickness of the fiber bundle swatch, and g is gravitational acceleration.¹⁵ Values of t versus $\ln \frac{h_i}{h_f}$ were averaged over two runs for each height ratio used, and a linear regression to these data provided the Darcy permeability from Equation (2). This flow-through test is a controlled and simple test setup in which flow is driven by the force of gravity. The setup also works best for a very viscous fluid like glycerol, which ensures that the net pressure force per unit volume in the fiber swatch is predominantly overcoming viscous forces per unit volume has given by Darcy's law.

3. Results and Discussion

Darcy permeability values measured for each fiber swatch tested are shown in Table 1 along with their individual coefficients of variation (CV). CV values ranged from 3.1% to 15% with the maximum CV occurring in the parallel-arranged fiber bundles, consistent with the findings of Pacella et al.¹⁵ Darcy permeability values predicted based on Equation (1) and the BK constant given by $A = 542\varepsilon - 128$ are shown in Table 1 for comparison. The percent difference between measured and predicted Darcy permeability ranged from -8.3% to 6.7%.

The BK constant was determined for each of the fiber swatches in this study and a linear regression of these data versus porosity, combined with the data from Pacella et al. yielded the new correlation: $A = 497\varepsilon - 103$, which has an R^2 value of 0.9 compared to 0.8 in the Pacella paper.¹⁵ The percent difference between measured and predicted Darcy permeability using this new correlation ranged from -5.7% to 3.6%. Further, the percent difference between this new correlation and the Pacella correlation is shown in Figure 1 over a relevant range of porosity from 0.4 to 0.8. The percent difference ranged from 8.0% to -3.5%. Conceivably, our permeability correlation may not work as well if high porosities were achieved by removing alternating fiber layers from a swatch. We believe, however, that manufacturing devices of high porosities by removing fiber layers is challenging and we have not seen clinical or experimental devices created in this manner. Fiber spacing however is increased to increase porosity as mats with different fiber spacing are commercially available. Removing every other fiber in our experiment represents an extreme of this. Additionally, we would expect our correlation to predict permeability of commercial Membrana GmbH® Oxyphan® 50/280 type PP fiber membranes as well owing, to the small percentage difference between the old and new correlations.

One should note if blood was used instead of glycerol, permeability measured would be unchanged as long as the appropriate viscosity is used in Darcy's law, since permeability is a material property of a given porous medium.

4. Conclusion

The Darcy permeability of hollow fiber bundles made from commonly used commercial Membrana® PMP hollow fiber mats used in blood oxygenation devices can be predicted within $\pm 6\%$ if the constant in the Blake-Kozeny Equation (Eqn 1.), $A = 150$, is empirically correlated to fiber bundle porosity using $A = 497\varepsilon - 103$ with a larger R^2 value, as opposed to within $\pm 8\%$ using the previous correlation.

Acknowledgments

This publication was made possible by Grant Number 5R01HL117637-03 from the National Institutes of Health, National Heart, Lung and Blood Institute. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIH.

References

1. Schewe RE, Khanafer KM, Arab A, Mitchell JA, Skoog DJ, Cook KE. Design and In Vitro Assessment of an Improved, Low-Resistance, Compliant Thoracic Artificial Lung. *ASAIO J.* 2012; 58:583–589. [PubMed: 23103694]
2. Zhang T, Wei X, Bianchi G, et al. A novel wearable pump-lung device: In vitro and acute in vivo study. *The Journal of Heart and Lung Transplantation.* 2012; 31:101–105. [PubMed: 22014451]
3. Haneya A, Philipp A, Foltan M, et al. First experience with the new portable extracorporeal membrane oxygenation system Cardiohelp for severe respiratory failure in adults. *Perfusion.* 2012; 27:150–155. [PubMed: 22249962]
4. Gabelman A, Hwang S-T. Hollow fiber membrane contactors. *Journal of Membrane Science.* 1999; 159:61–106.
5. Federspiel, WJ.; Svitek, RG. *Encyclopedia of Biomaterials and Biomedical Engineering.* Taylor & Francis; 2013. Lung, Artificial: Current Research and Future Directions; p. 922-931.
6. Fill B, Gartner M, Johnson G, Horner M, Ma J. Computational Fluid Flow and Mass Transfer of a Functionally Integrated Pediatric Pump-Oxygenator Configuration. *ASAIO Journal.* 2008; 54:214–219. [PubMed: 18356659]
7. Gartner MJ, Wilhelm CR, Gage KL, Fabrizio MC, Wagner WR. Modeling Flow Effects on Thrombotic Deposition in a Membrane Oxygenator. *Artificial Organs.* 2000; 24:29–36. [PubMed: 10677154]
8. Wu ZJ, Taskin ME, Zhang T, Fraser KH, Griffith BP. Computational Model-Based Design of a Wearable Artificial Pump-Lung for Cardiopulmonary/Respiratory Support. *Artificial Organs.* 2012; 36:387–399. [PubMed: 22145732]
9. Jeffries RG, Frankowski BJ, Burgreen GW, Federspiel WJ. Effect of Impeller Design and Spacing on Gas Exchange in a Percutaneous Respiratory Assist Catheter. *Artificial Organs.* 2014; 38:1007–1017. [PubMed: 24749994]
10. Akay B, Foucher JA, Camboni D, Koch KL, Kawatra A, Cook KE. Hemodynamic Design Requirements for In Series Thoracic Artificial Lung Attachment in a Model of Pulmonary Hypertension. *ASAIO J.* 2012; 58:426–431. [PubMed: 22581034]
11. Arens J, Schnöring H, Reisch F, Vázquez-Jiménez JF, Schmitz-Rode T, Steinseifer U. Development of a Miniaturized Heart-Lung Machine for Neonates With Congenital Heart Defect. *ASAIO Journal.* 2008; 54:509–513. [PubMed: 18812743]
12. Gage KL, Gartner MJ, Burgreen GW, Wagner WR. Predicting Membrane Oxygenator Pressure Drop Using Computational Fluid Dynamics. *Artificial Organs.* 2002; 26:600–607. [PubMed: 12081518]
13. Ergun S. Fluid flow through packed columns. *Chemical Engineering Progress.* 1952; 48:89.
14. Khanafer KM, Cook K, Marafie A. The role of porous media in modeling fluid flow within hollow fiber membranes of the total artificial lung. *Journal of porous media.* 2012; 15

15. Pacella H, Eash H, Frankowski B. Darcy permeability of hollow fiber bundles used in blood oxygenation devices. *J Memb Sci.* 2011; 382:238–242. [PubMed: 22927706]
16. Özyüksel A, Ersoy C, Akçevin A, et al. Cost-effective usage of membrane oxygenators in extracorporeal membrane oxygenation in infants. *Perfusion.* 2015; 30:239–242. [PubMed: 24965913]
17. Lequier L, Horton SB, McMullan DM, Bartlett RH. Extracorporeal Membrane Oxygenation Circuitry. *Pediatr Crit Care Med.* 2013; 14:S7–12. [PubMed: 23735989]
18. Lehle K, Philipp A, Hiller K-A, et al. Efficiency of gas transfer in venovenous extracorporeal membrane oxygenation: analysis of 317 cases with four different ECMO systems. *Intensive Care Med.* 2014; 40:1870–1877. [PubMed: 25323118]
19. Haneya A, Philipp A, Foltan M, et al. First experience with the new portable extracorporeal membrane oxygenation system Cardiohelp for severe respiratory failure in adults. *Perfusion.* 2012; 27:150–155. [PubMed: 22249962]
20. Strueber M. Artificial Lungs: Are We There yet? *Thoracic Surgery Clinics.* 2015; 25:107–113. [PubMed: 25430434]

Figure 1.
Percent difference in permeability prediction between new and old correlations.

Table 1

Measured Darcy permeability for PMP HFMs and predictions using the Pacella et. al. derived correlation

Bundle Stacking	Porosity, ϵ	Measured Permeability, k_m (cm ²)	Coefficient of Variation, CV	Predicted Permeability, k_p (cm ²)	% Difference between k_m and k_p
Parallel	0.45	$8.22E-06 \pm 1.24E-06$	15.04%	8.41E-06	-2.3 %
Perpendicular	0.49	$9.55E-06 \pm 2.94E-07$	3.08%	1.04E-05	-8.3%
Angled 14°	0.48	$1.00E-05 \pm 7.06E-07$	7.04%	9.97E-06	0.7%
Perpendicular	0.77	$1.09E-04 \pm 5.95E-06$	5.47%	1.02E-04	6.7%