2017

Darcy's Law-Based Model for Predicting Wicking of Liquids in Glass-Fiber Wicks

Mohammad Amin Faghihi Zarandi
University of Wisconsin - Milwaukee, faghihi2@uwm.edu

Krishna M. Pillai
University of Wisconsin - Milwaukee, krishna@uwm.edu

Adam Kimmel

Darcy's Law-Based Model for Predicting Wicking of Liquids in Glass-Fiber Wicks

UNIVERSITY of WISCONSIN
UWMILWAUKEE

Laboratory for Flow and Transport Studies in Porous Media

†M. Amin F. Zarandi*, Krishna M Pillai⁒ and Adam Kimmel
Department of Mechanical Engineering, PhD student *
Department of Mechanical Engineering, Associate Professor ⁒
Lamplight Company, Product Development Engineer †

TIKI Paradise In Your Backyard
LAMPLIGHT WCBRADLEYCO

ABSTRACT

Spontaneous imbibition of liquids in glass-fiber wicks, where a liquid-front progresses during the wicking process, is investigated experimentally and modeled using the concepts of single-phase flow in porous media. In order to have an accurate validation of the proposed model, a well-characterized glass-fiber wick and a wicking liquid are used to plot the liquid-front of absorbed liquid as a function of time. The experimental outcomes are compared with predictions by the proposed analytical solution obtained by combining Darcy's law with the continuity equation and a capillary (suction) pressure formula imposed on the liquid-front. The theoretical permeability and capillary-pressure formula used in the model are obtained by treating the wick as a bundle of parallel fibers. All properties of the wicking liquid and wick used in the experiments, including the porosity, permeability, viscosity, surface tension and contact angle, are measured independently. The proposed theoretical model is found to compare favorably with experiments without the use of any fitting parameters. Though more experiments are being done to further test the analytical model, by all indications, it has potential of becoming a powerful practical tool to predict wicking in industrial wicks manufactured from parallel tows of glass fibers.

BACKGROUND

Washburn equation $h_f = \left(\frac{R_h \gamma \cos(\theta)}{2\tau^2 \mu}\right)^{1/2} \sqrt{t}$

The modified Washburn equation can be used to predict the liquid front hf as a function of time. In the most wicking applications, the this equation is used when the inertial and gravitational energies can be neglected. Although the Washburn equation has been widely used for the modeling wicking in porous media, it has some limitations. In this equation the porous structure is assumed to be as a bundle of capillary tubes. Hence, It can predict only one-dimensional (1D) imbibitions of fluids along the direction of capillary tubes, and due to the unidirectional nature of fluid flow model of this equation, it cannot predict the three-dimensional (3D) flows in wicks which have complicated shapes. Furthermore, due to the complicated flow paths of liquids in real porous media are replaced by straight and hypothetical flow paths through cylindrical tubes,it will always have a parameter, such as the hydraulic radius, which due to its origin in the pipe flow physics, is physically irrelevant and is often used as a fitting parameter.

ASSUMPTIONS

- The wick below the rising liquid-front is fully saturated
- The Capillary pressure created at the front
- The wick treats as a bank of semi-radius fibers
- Inertial energy is neglected

THEORY

Single-Phase Darcy's Law Based Model

Darcy's Law $v = -\frac{K}{\mu} \nabla P$

Equation of Continuity $\frac{dv}{dh} = 0$

Predicting Model

$$p_s \ln\left|\frac{p_s}{p_s - \rho g h_f}\right| - \rho g h_f = \frac{\rho^2 g^2 K}{\varepsilon \mu} t \qquad h_f = \frac{p_s}{\rho g}\left[1 + W\left(-e^{-1-\frac{\rho^2 g^2 K}{\varepsilon \mu p_s} t}\right)\right]$$

Capillary Pressure

$$p_c = \frac{2(1-\varepsilon)\gamma \cos\theta}{\varepsilon r_{fb}}$$

EXPERIMENTAL PROCEDURE

Porosity (ε)

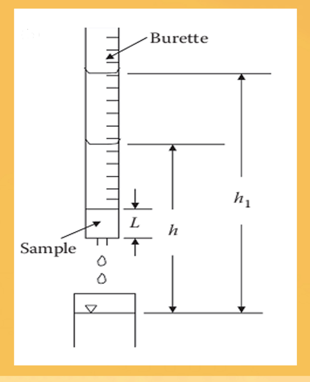
$$\varepsilon = 1 - \frac{V_{fr}}{V}$$

1-Dipping Method

2-Using Micrographs

Permeability (K)

Falling Head Method for permeability estimation $K = \frac{\mu a L}{\rho g A t_{exp}} \ln\frac{h_1}{h_2}$



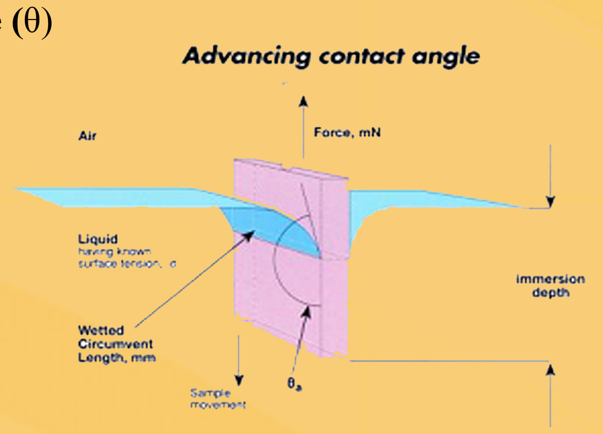
Surface Tension (γ)

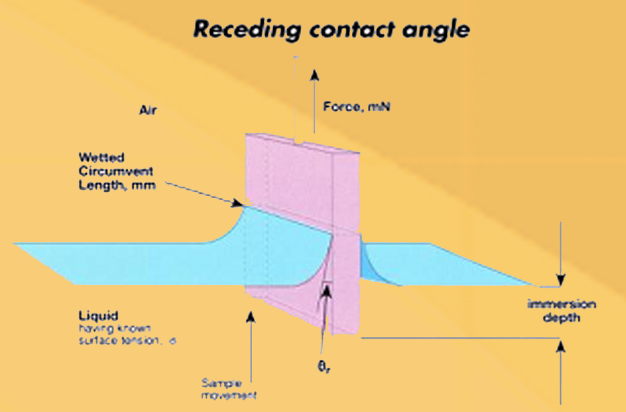
F=γ.p.cosθ

Tensio Meter

Wilhelmy Plat

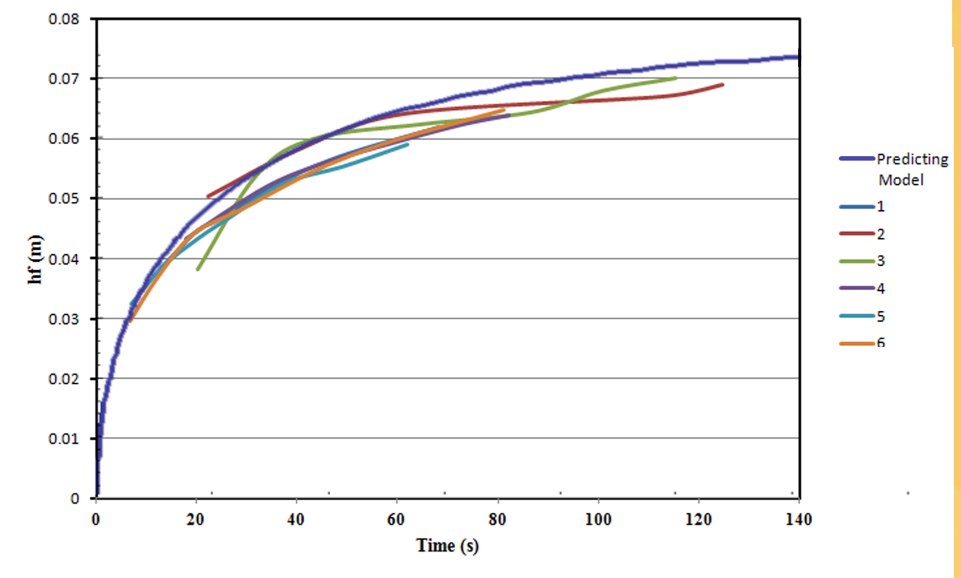
Contact Angle (θ)



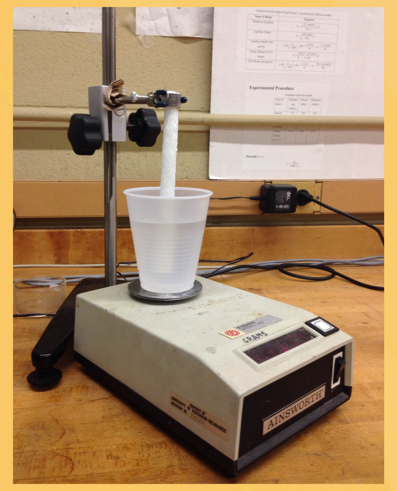


VALIDATION & RESULTS

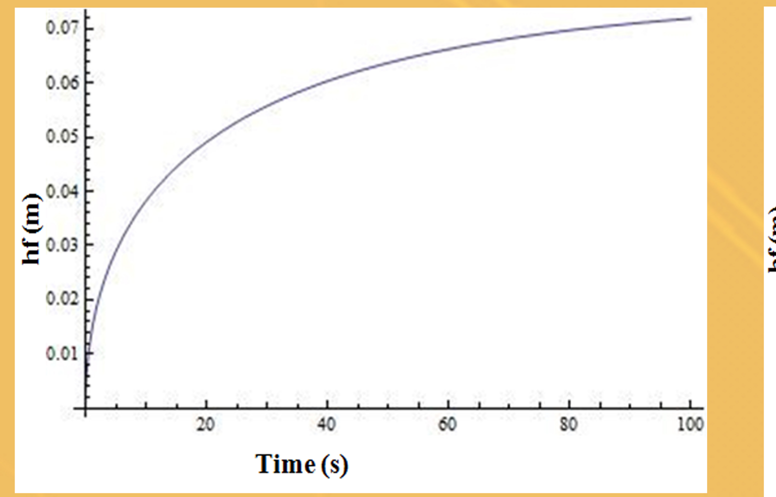
In order to validate our theoretical model, we set an experiment to measure rising of the liquid-front as a function of time. In this experiment, due to the linear relationship between liquid-front and the mass of absorbed liquid into the wick, we measured the absorbed mass during wicking phenomenon. In order to have an accurate data, we repeated our experiment for 6 wicks. Then we, according to mentioned linear relationship, plotted the liquid-front of absorbed liquid as a function of time.



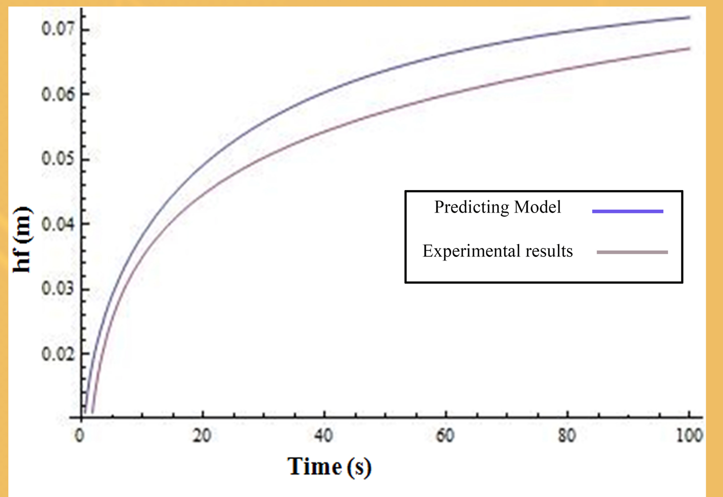
Comparison Between Liquid-front Vs. time based on predicting model and 6 different experimental results



Experimental setup for measuring the absorbed liquid as function of time



Liquid-front Vs. time based on predicting model



Comparison Between Liquid-front Vs. time based on predicting model and experimental results

SUMMARY & CONCLUSIONS

- We use single-phase Darcy's law to develop a simple powerful model to predict the absorption of a liquid into a wick made from lass fibres.
- For capillay pressure at the liquid front inside the wick, an expressionis formulated which depends on both the mean fiber radius and the porosity of the wick.
- One of important features of this work is the form of some new techniques that have been used to estimate the properties of fibers and liquid in the wicking models. For example, measurement of the wick permeability with the falling head method is a new methodin the science of wicking. Similarly, the using the wick micrographs to estimate the porosity is new to the field of wicking studies
- The theoretical model, which is as powerful as Washburn equation and considers the effects of gravity, has a satisfying correlation with the experimental results and not only can be used for one directional flow, but the presented model can also predict the wicking of liquids into porous media in two or three dimentional flows.

REFERENCES

[1] Vernet, N., Ruiz, E., Advani, S., Alms, J. B., Aubert, M., Barburski, M., Barari, B., Beraud, J., Berg, D. C., Correia, N., Danzi, M., Delavière, T., Dickert, M., Di Fratta, C., Endruweit, A., Ermanni, P., Francucci, G., Garcia, J. A., George, A., Hahn, C., Klunker, F., Lomov S. V., Long, A., Louis, B., Maldonado, J., Meier, R., Michaud, V., Perrin, H., Pillai K. M., Rodriguez, E., Trochu, F., Verheyden, S., Weitgrefe, M., Xiong, W., Zaremba, S., Ziegmann, G.: Experimental determination of the permeability of textiles: benchmark II, Composites Part A: Applied Science and Manufacturing (61), 172–184, 2014.

[2] Masoodi, R., Pillai, K. M.: A general formula for capillary suction-pressure in porous media, Journal of Porous Media, 15 (8): 775–783, 2012.

[3] Masoodi, R., Pillai, K. M.: Wicking in Porous Materials, CRC Press 2012

[4] Masoodi, R., Tan, H. and Pillai, K. M.: Darcy's Law–Based Numerical Simulation for Modeling 3D Liquid Absorption into Porous wicks, J. AIChE, Vol. 57, no. 5, pp. 1132–1143, 2011.

[5] Masoodi, R., Pillai, K. M., and Varanasi, P. P.: Darcy's law based models for liquid absorption in polymer wicks, J. AIChE, Vol. 53, no. 11, pp. 2769–2782, 2007.