An Approach to Model Resin Flow through Swelling Porous Media made of Natural Fibers

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ABSTRACT: A theoretical model for the 1-D flow of a resin-like liquid in the natural-fiber fiber mats of resin transfer molding (RTM) mold is proposed. After assuming the porosity and the permeability to vary only a function of time, a theoretical formula for the front location is proposed after employing an altered form of continuity equation (which takes into account both the liquid absorption and the fiber swelling) and the Darcy's law for the single-phase flow. A comparison of the theoretical predictions with the experiments reveals that the variable permeability model offers a better match viv-a-vis the fixed permeability

Keywords: Resin transfer molding, RTM, liquid composite molding, LCM, natural fiber preform, swelling, permeability, porous media, Darcy's law

Introduction

Fiber-reinforced polymer composites have gained popularity through their advantages over the conventional materials including their low weight, high mechanical properties and low-temperature processing. Recently, some studied have used the natural fibers to reinforce the plastics rather than the conventional, inorganic fibers made from glass and carbon [1-3]. The main advantages of the natural-fibers composites over the synthetic-fiber composites are that the former are less expensive, have acceptable mechanical properties, are bio-based, are locally sourced (and thus have lower carbon footprint), and perhaps are going to be bio-degradable and recyclable in the near future [2]. One of the most common ways of making polymer composites is the liquid composite molding (LCM) processes which includes the resin transfer molding or RTM technique. The RTM is a technology for manufacturing the net-shaped composites parts that involves the injection of a liquid resin through a compressed fiber preform placed inside an RTM mold cavity. Rowell *et al.* [4] used jute to replace glass as the reinforcement in an RTM part. They compared the physical properties of both composites and concluded that the natural-fiber composites can be used as a replacement of the synthetic-fiber composites in a wide range of applications. O'Dell [5] used RTM for making specimens of the fiber-glass and natural-fiber composites, and exposed the samples in a weatherometer for 1200 hours to study the degradation of properties.

The science of modeling resin flow in an RTM mold to conduct a mold-filling simulation is quite mature [6-7]. The main concern of such modeling is the estimation of the permeability of porous medium formed from compressing fiber mats in an RTM mold. Rowell and Stout [8] observed that during the wetting of jute fibers, the fibers swell by 22% of their initial diameter, while assuming erroneously a constant permeability in a swelling medium with a decreasing porosity [9-12]. Masoodi *et al.* [13] used a simple linear model (in time) to model variations in permeability after the wetting of fibers in a jute fiber-mat. To the best of authors' knowledge as well as concluding from the above literature survey, there is no accurate model to predict permeability variations in a swelling porous medium made from natural fibers. In this paper, an experimental study on the swelling of wood fibers is conducted to model the permeability in such a swelling porous medium. Later, this model is employed to improve the accuracy of the liquid-front tracking RTM flow model based on the Darcy's law.

Theory

Most studies in the area of LCM flow modeling are confined to non-swelling porous media which assumes constant permeability over the time. In this paper, predictions on the flow-front progression by the theories of liquid flow in both rigid and swelling porous media are tested.

1. Flow in rigid porous media

One can model the single-phase flow behind a well-defined liquid front in an isotropic–rigid porous medium inside an RTM mold using the traditional continuity equation and the Darcy law as

$$\nabla \cdot \mathbf{V} = 0 \tag{1}$$

$$\mathbf{V} = -\frac{K}{\mu}\nabla P \tag{2}$$

where **V** and P are the volume-averaged liquid velocity and the pore-averaged liquid pressure, respectively [15]. Assuming one-dimensional fluid flow through a constant-permeability medium under constant flow-rate, one can use Darcy law, Eq. (2), and the continuity equation, Eq. (1), to derive a relation for the flow-front location as a function of time as

$$X_f = \sqrt{\frac{2K}{\varepsilon\ \mu}\int_0^t P_{in}(t')\,dt'} \tag{3}$$

where X_f is the liquid-front location along the injection direction, ε is the porosity, and $P_{in}(t)$ is the inlet pressure. One can use Eq. (3) to model changes in the flow-front location with time in rigid porous media.

2. Flow in non-rigid, swelling porous media

Continuity equation, Eq. (1), can be modified to include the effects of swelling in the porous-medium matrix as well as the 'sink' effect due to liquid absorption [14] as

$$\nabla \cdot V = -S - \frac{\partial \boldsymbol{\varepsilon}}{\partial t} \tag{4}$$

Following Masoodi and Pillai [14], the sink term in the Eq. (4) is assumed to be

$$S = b\frac{dv_f}{dt} \tag{5}$$

where the absorption coefficient, *b*, lies in the range of $0 \le b \le 1$. Further assumptions: 1) the effect of gravity on the flow is neglected; 2) the porosity and permeability values are considered to be functions of time only, i.e., $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}(t)$, *K=K(t)*; 3) these values are constant throughout the *wet* porous medium. By substituting the sink term, Eq. (5), in the modified continuity equation, Eq. (4), and using the Darcy law, Eq. (2), the analytical solution for the liquid flow-front position is obtained as

$$X_f = \sqrt{\frac{2}{\varepsilon_0 \mu} e^{(b-1)\frac{\varepsilon}{\varepsilon_0}} \int_0^t e^{(1-b)\frac{\varepsilon}{\varepsilon_0}} P_{in}(t') K(t') dt'} \tag{6}$$

When the swelling rate of fibers matches the volumetric (liquid) absorption-rate into the fibers {case: $b = 1$ in Eq. (5) [14]}, Eq. (6) is simplifies to

$$X_f = \sqrt{\frac{2}{\varepsilon_0 \mu} \int_0^t P_{in}(t') K(t') dt'} \tag{7}$$

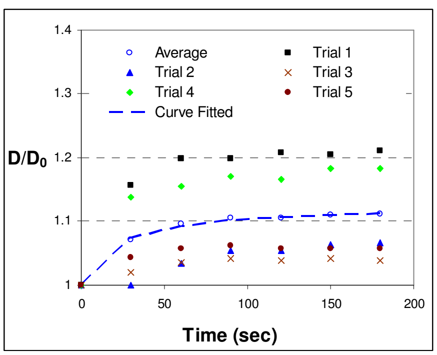
The above equation is used to predict the flow-front location in our theoretical model. It should be noted that for the constant K case, Eq. (7) reduces to Eq. (3).

Experimental & Theoretical Results

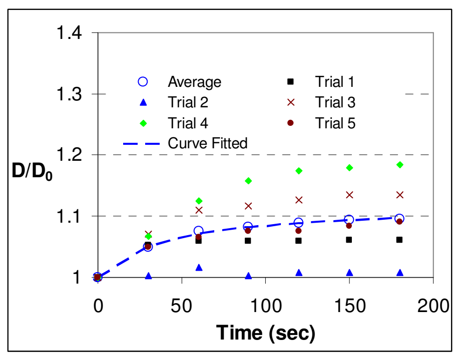
The 1-D injection experiment with a constant flow-rate is used to study the flow in the swelling and non-swelling porous media. The natural fiber mat of %100 Kenaf is used along with two different liquids, motor oil 10W-40 and the diluted corn syrup with %40 water. The motor oil (a non-polar liquid) does not cause swelling in the natural fibers while the water-diluted corn syrup (a polar liquid) causes swelling in this medium.

Change in Fiber Diameter due to Liquid Absorption & Swelling

To experimentally study the diameter change in the wetted natural fibers due to swelling, five random fibers (either broken or unbroken) were picked from a Kenaf wood fiber-mat.



a



b

Figure 2. Swelling diameter as function of time for a) broken wood fibers and b) unbroken wood fibers. (The fibers are wetted by the water-diluted corn syrup.)

Then a cover slip was placed on top of the wood fibers placed in a liquid pool in a petri dish. A microscope was used at 10x magnification to capture the growth of fiber diameter every thirty seconds for the total duration of three minutes. Figure 2 shows the experimental data on fiber diameters as they were swelling with time.

Table 1- Swelling fiber diameter as function of time. The parameters correspond to a curve fit of $D_f(t) = a.\exp(\frac{b}{c+t})$ to our experimental data.

	Broken Wood fiber	Unbroken Wood fiber	Average Values
a	1.126	1.117	1.1215
b	-2.313	-3.935	-3.124
c	19.516	35.432	27.474
RRS	3.261×10^{-5}	3.261×10^{-5}	

Table 1 describes the details on the fitted curves used in Figure 2.

Porosity measurement

Porosity is defined as the ratio of the void volume to the total volume in any porous medium. Initial porosity, ε_0, is obtained to be 0.85 (details in [17]).. The porosity of the swelling porous medium is a function of time. One is able to obtain such a relation for porosity by using the time-dependent fiber-diameter [14]:

$$\varepsilon(t) = 1-(1-\varepsilon_0)(\frac{D_f(t)}{D_{f0}})^2 \quad (8)$$

Permeability Measurement

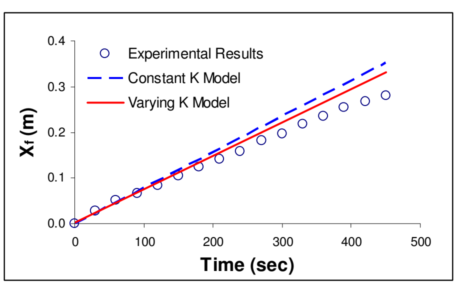
Since the porosity ε is not constant in a swelling porous medium, we need to use a variable permeability, i.e., $K=K(\varepsilon)$, for solving the Darcy law. Substituting $\varepsilon(t)$ from Eq. (8) and the fiber diameter $D_f(t)$ from Table (1) in the Kozeny-Carman permeability model [18], the permeability as function of time [14] is obtained as

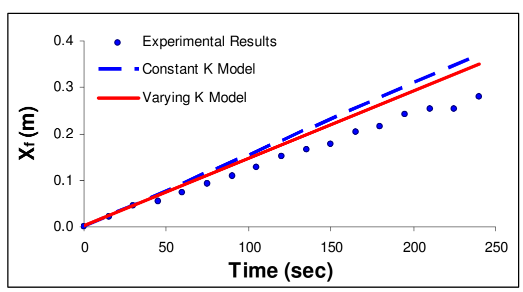
$$K = D_f(t)^2 K_0 (\frac{\varepsilon_f}{\varepsilon_{f_0}})^3 \frac{1-\varepsilon_{f_0}}{1-\varepsilon_f} \quad (9)$$

The steady-state 1-D flow experiment with the motor oil were used to determine K_0, the initial permeability.

Flow-Front Position: Measurement and Estimation

The flow-front positions were tracked by reviewing the mold-filling video along with a stop watch. Figure 3 shows the comparison of flow-front locations at different time obtained from our theoretical modeling and the texperimental results. This shows that the varying permeability model, Eq. (7), predicts the flow-front more accurately than the constant K model, Eq. (3).





a b

Figure 3. Flow-front position versus time plot for the flow rates of a) Q = 1 mL/s and b) Q = 2 mL/s

Summary & Conclusions

The flow of resin through swelling porous media made from natural fibers is modeled using a modified form of continuity equation and the Darcy's law. The 1-D flow experiments in RTM molds at constant injection-rates are used to validate the proposed theory. A new permeability model as a function of time is estimated by studying the time-dependent swelling of the kenaf wood fibers. The flow-front prediction with the varying permeability model compares better with experiments than the constant permeability model.

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