A Reference Porous Medium made by Rapid Prototyping as a Calibration Tool for Permeability Measurement

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ABSTRACT: Permeability is a very important parameter for mold-filling simulation in liquid composite molding processes. The lack of a proper calibration tool for permeability measuring devices leads to great uncertainty about the accuracy of permeability measurements. In this paper, a reference porous medium made by rapid prototyping for use in the 1-D flow based permeability measurement setups is evaluated. A set of steady-state, as well as transient experiments were conducted to evaluate the performance of the reference medium, in which the principal permeabilities of the reference medium were measured. A good match of the measured and theoretical permeability values testified to the usefulness of the reference medium for calibration.

KEYWORDS: calibration, porous medium, permeability, mold-filling, LCM, RTM, VARTM, 1-D flow, Darcy's law.

INTRODUCTION

Fibers made of glass or carbon, are often used as reinforcements in composites. There are several ways to manufacture such composites—one such set of technologies is known as liquid composite molding (LCM) processes, such as resin transfer molding (RTM), vacuum-assisted resin transfer molding (VARTM), and Seeman composite resin infusion molding process (SCRIMP). Simulating the flow through the reinforcing fibers is used to determine the optimal locations of gates, inlets and outlets, as well as the injection resin temperature and pressure. Accurate mold-filling simulation highly depends on the accurate permeability estimation of the porous medium [1, 2]. The permeability values for reinforcement materials are often determined experimentally as it is difficult to estimate the permeability of such fibermats using the theoretical or CFD methods due to the shifting of fibers during the placement of fiber-mats in an LCM mold. Lack of proper calibration tools for permeability measuring devices leads to great uncertainty about the accuracy of reported permeability measurements. Often different permeability values for the same fiber mat are reported by different research groups as well as different devices. This problem can be mitigated to some extent if a reference medium, a porous material of known permeability, can be used in the permeability measuring setups for their calibration. In the recent years some researchers tried to design and evaluate reference materials for calibration measurement. Lundstrom et. al. [3] presented an experimental method to obtain the full in-plane permeability tensor of

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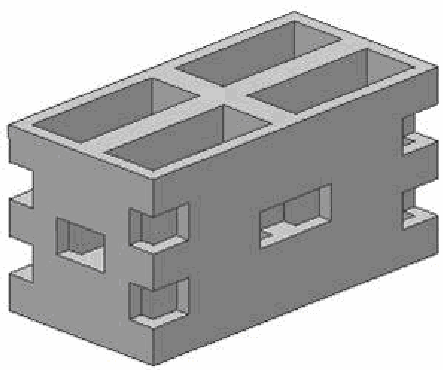
an anisotropic porous medium with constant-injection-pressure condition. Roy et al. [4] proposed a method to calibrate 1-D flow experimental set-ups using a reference medium made of aluminum with twenty five small, aligned holes of known dimensions. Tan et al. [5] suggested a method to estimate the accuracy of radial-flow based permeability measuring devices. Morren et al. [6] used an idealized reference material to test the radial flow experiments where this idealized porous medium is manufactured through stereolithography. The authors adopted the unit-cell designed by Morren et al. [6] to develop a modified reference porous-medium to calibrate both the 1-D and radial flow devices [7]. In this paper, we conducted further tests to demonstrate the usefulness of the reference medium for calibration purposes.

MODIFING A REFERENCE POROUS MEDIUM

An idealized porous medium was made using the unit-sell structure suggested by Morren et al. [6]. Repetition of this unit-cell along its principal directions allows one to create a homogeneous, anisotropic porous-medium of fixed permeability and of any size. Figure 1 shows a detailed view of the original unit-cell structure developed by Morren et al. [6]. In this design, all the corners are sharp and is not practical to create such completely sharp corners. We modified this design by changing the sharp corners to a round corner of diameter 0.127 mm, which is the diameter of the laser beam used in a commercial Viper Pro© stereolithography machine used to make our reference porous medium [7].



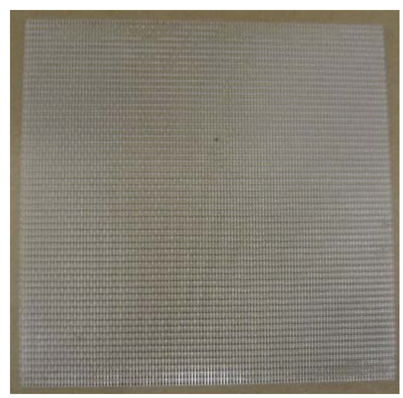


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Figure 1. Detailed view of a) unit-cell structure suggested by Morren et. al [6], b) reference porous-medium made by rapid prototyping.

MANUFACTURING THE MODIFIED POROUS MEDIUM

The modified reference medium was manufactured using the stereolithography based rapid prototyping technique. Using this technique, one can produce features that require high precision. In stereolithography, a UV laser passes a pack of photopolymer resin and solidifies it layer by layer to make the whole part. The additive nature of the stereolithography based rapid prototyping technique allows for making complex internal geometries that are impossible by the conventional material-removal processes such as machining. The reference medium used in our work is manufactured on a commercial Viper Pro© stereolithography machine which used a 1000 mW laser of beam diameter 0.127 mm on Accura 60 plastic [7].

THEORY

The Darcy's law is usually used to model the flow of a viscous liquid through porous medium:

$$q = -\frac{\mathbf{K}}{\mu}.\nabla p \tag{1}$$

Here K is the permeability tensor defined as

$$K = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix} \tag{2}$$

such that K_1 and K_2 are the principal permeabilities. The permeability along the flow direction under steady-state and transient flow conditions can be obtained using

$$\frac{Q}{A} = \frac{K_{ss}}{\mu}\frac{P_{inlet} - P_{outlet}}{L} \tag{3}$$

$$K_{tr} = \frac{v_{front}^2 . \mu.\varepsilon.t}{P_{inlet}(t)} \tag{4}$$

where K_{ss} and K_{tr} are the steady state and transient permeabilities respectively, ε is the porosity, μ is the viscosity, A is the mold cross-sectional area, and P is the pressure of the test liquid [7].

EXPERIMENTAL EVALUATION

The one-dimensional flow experiments were done using a test setup consisting of a rectangular aluminum mold machined out to accommodate rectangular test-preforms (see Figure 2). The reference medium was put in the mold and motor oil (test liquid) was injected into the set-up to measure the pressure drop along the medium. We used two approaches, the transient and steady-state flows to measure the principal permeabilities. Motor oil (SAE 10W-40) was injected into one side of the mold through a reinforced hydraulic hose, minimizing the pressure-relief effects due to hose expansion. Viscosity of the motor oil was measured using a Brookfield© Viscometer. There was a drain open to atmospheric pressure at the opposite end of the mold. Oil injection was achieved via a gear pump driven by a stepper motor in a closed-loop feedback control scheme with input from a flow meter. Pressure data from the experiment was collected via a transducer inserted on the inlet side of the preform (see Figure 1). The data for injection pressure and flow rate was gathered by a LabView© based data-acquisition system. A video camera also was used to record the flow-front progression for the transient flow analysis.

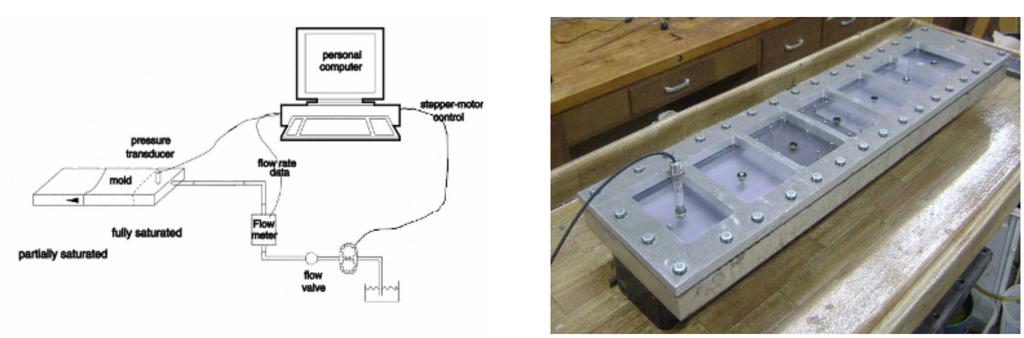

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Figure 2. Experimental setup: a) schematic view; b) 1-D flow experiment setup

We have used two approaches, the transient-flow analysis and the steady-state flow analysis, to estimate the permeabilities. (Details of our approaches are described in Ref [7].) The 1-D flow tests for permeability evaluation were performed on both the principal directions of the test material. Figure 3 shows the two principal permeability values, K_1 and K_2, for four different flow-rates obtained using the steady-state flow configeration. The results are compared with the numerical results obtained in [7] and show average errors of 3% and 14% for K_1 and K_2 respectively.

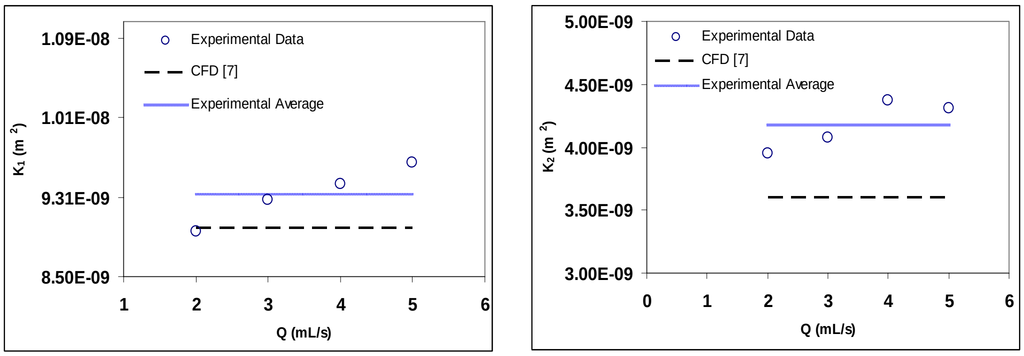

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Figure 3. Comparison of the experimental results obtained using the 1-D steady-state experiments with the CFD simulation results obtained from [7] for the principal permeabilities K_1 and K_2.

Figure 4 shows the permeabilities along the principal directions for four different flow rates using the transient, 1-D flow experiment. Results are compared with the CFD results obtained from [7] and show 19% and 49% errors for K_1 and K_2 , respectively.

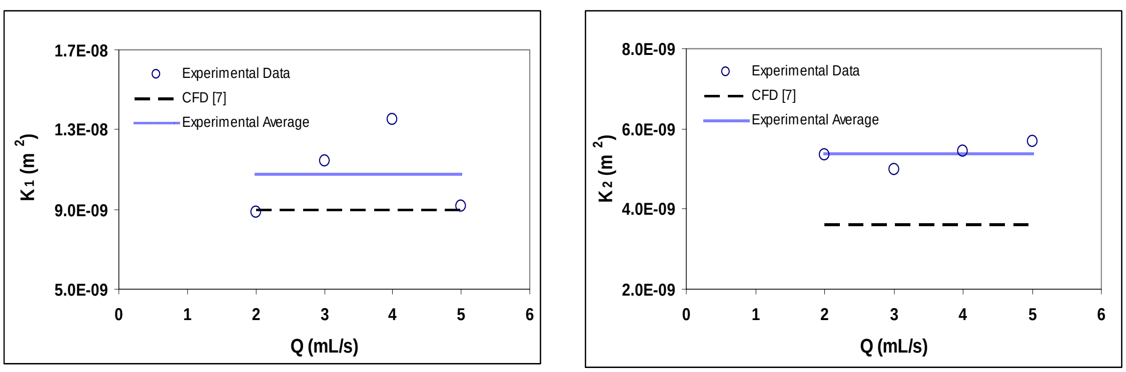

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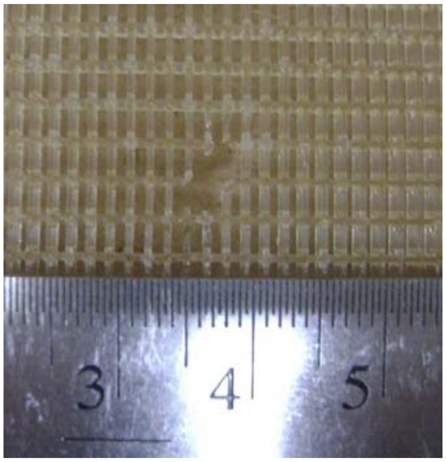
Figure 4. Comparison of the experimental results obtained using the 1-D transient-filling experiments with the CFD simulation results obtained from [7] for the principal permeabilities K_1 and K_2.

CORRECT PROCEDURE

It is important to handle the reference medium carefully and perform the experiments accurately, especially when the reported parameters are very crucial for flow modeling. In Figure 5, it is depicted that any extra pressure or carelessness can cause damage and deformation to the reference porous medium. Figure 5a shows the damage which happened due to extra pressure from the sealing gasket on top and bottom that caused elongation in one direction of the media, and the hole created as a result of the mishandling. For reporting accurate permeability values in this paper, a new reference media was created.



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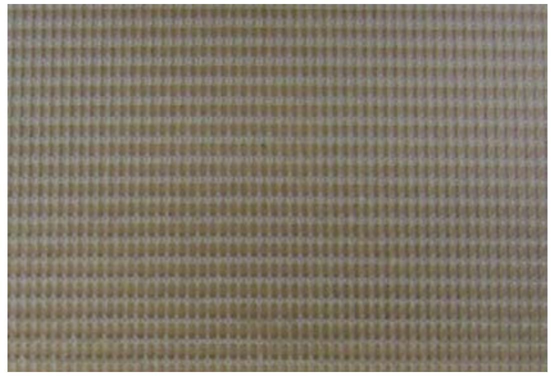

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Figure 5. Reference media: a) a damaged and deformed reference medium, b) a reference medium in sound condition

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