IN-PLANE PERMEABILITY CHARACTERIZATION USING AN INVERSE METHOD BASED ON FLOW FRONT VISUALIZATION

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Abstract

In this study, we propose a method to reduce the total number of required one-dimensional resin flow experiments for in-plane permeability (K) characterization of isotropic fabrics by achieving either: (i) a characterization and further statistical analysis of spatially varying permeability in the presence of fabric irregularity and possible race-tracking along the fabric - mold wall interface, or (ii) permeability characterization at more than a single fiber volume fraction (v_f) in an experiment. The method is based on accurately detecting the flow front location in the flow propagation video frames and minimizing the deviation between experimental fill times and numerical fill times in Control Volume Finite Element based flow simulations through use of the Levenberg-Marquardt method.

The permeability of an isotropic random mat was characterized through reference experiments. K-v_f relationship was well represented by a power law. In cases with intentionally introduced race-tracking and with three sections of different v_f, permeability results were in agreement with the results of the reference experiments (a set of experiments in which fabric irregularity and race-tracking were eliminated as much as possible). The results indicate that the number of experiments, thus the material and time invested, can be significantly reduced using the proposed method with an additional benefit of obtaining valuable insights on the statistics of the spatial permeability distribution.

1. Introduction

One-dimensional resin flow experiments through a fabric are generally conducted to determine both its unsaturated (unsteady-state) and saturated (steady-state) permeabilities (K) at a pre-determined fiber volume fraction (v_f). Experiments at a fixed v_f must be repeated several times to gain insight on the statistical variation, and many experiment sets should be performed in a domain of v_f to build a K-v_f curve. In addition to these many required experiments, if undesired race-tracking occurs along the fabric - mold wall interface, it causes the flow to deviate from one-dimensional flow; these experiments with obvious race-tracking must then be discarded and repeated, thereby further increasing the total number of experiments.

In this study, we propose a method that is capable of mapping the spatially varying permeability which can occur either due to fabric irregularity and possible race-tracking along the fabric - mold wall interface or due to intentional variation of v_f within the mold (i.e., multiple sections with different v_f). Flow front propagation was recorded during the experiments and analyzed to obtain the instantaneous flow front location. A Control Volume Finite Element (CVFE) based simulation was implemented and simulations were performed with identical boundary conditions of the experiments. Deviation between numerical fill times and experimental fill times was minimized using the Levenberg-Marquardt method to obtain the permeability distribution.

2. Materials and Methods

One-dimensional resin flow permebility experiments were performed using a mold with a transparent upper half as detailed in our previous work [1,2]. A random glass mat (Suter Kunststoffe AG, superficial density, ρ_{sup}, 450 g/m^2) was cut to dimensions of 25 cm x 6 cm, layers were placed in the mold and infiltrated with an aqueous solution of polyethylene glycol containing a small amount of water based food dye, characterized in a previous study [2]. Fluid temperature and pressure were recorded at the mold inlet using a Keller S35X sensor. Flow propagation in each experiment was recorded by video through the transparent top, using a Canon EOS 650D camera; recorded videos were post-processed in Matlab to detect the flow front location with high accuracy in each frame of the experiment video using morphological operations after converting the video frames to binary images. The fabric surface in each image was subsequently discretized to square sections that coincide with the control volumes of the implemented CVFE solver.

A CVFE based solver was implemented to simulate the mold-filling. Pressure distribution within the filled part of the mold was obtained by coupling continuity equation

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

and Darcy's law

$$\vec{v} = -\frac{\boldsymbol{K}}{\mu} \nabla P \tag{2}$$

where $\vec{v}$ is the average fluid velocity, $\boldsymbol{K}$ is the permeability tensor of the porous fabric preform, μ is the fluid viscosity and ∇P is the pressure gradient. The resulting equation was converted to a set of algebraic equations by applying Galerkin formulation and solved for nodal pressure values. At each time step, the flow into the control volumes at the flow front from their filled neighbors was calculated using Eq. 2; time step was selected as the time required to fill the earliest filling control volume and boundary conditions were updated (i.e., the flow front position and outlet pressure at the that front). This procedure continued until the mold was completely filled.

Each experiment was simulated with the corresponding experimental parameters (i.e., pressure at the inlet and outlet, fluid viscosity, fiber volume fraction). Flow propagation in the CVFE simulation was iteratively converged to the experimental flow propagation, by updating the permeability matrix in the simulations at each iteration. To this end, deviation between numerical and experimental fill times was calculated at each iteration and the set of permeability values for the succeeding iteration was estimated using the Levenberg-Marquardt optimization method [3,4]. Permeability values were updated using the following relation

$$\{K\}^{i+1} = \{K\}^{i} + \{\delta K\}^{i} \tag{3}$$

where

$$\{\delta K\}^i = \left(\left([J]^i\right)^T\left([J]^i\right) + \lambda[I]\right)^{-1}\left([J]^i\right)^T\left(\{t_{exp}\} - \{t_{num}^i\}\right) \tag{4}$$

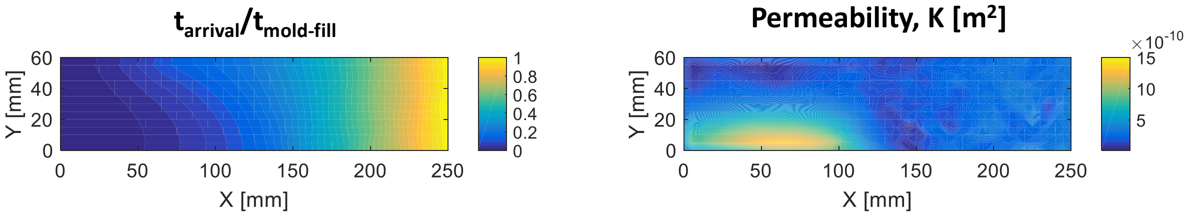
and $\{K\}$ is the vector of permeability values, superscript i is the iteration number, $[J]$ is the Jacobain matrix, $[I]$ is the identity matrix, and λ is the damping parameter.

Three different types of experiments were conducted: (i) reference experiments following the well-established guidelines for one-dimensional flow experiments [5–7], (ii) experiments with intentional race-tracking and (iii) experiments with multiple sections each with a different v_f. Multiple-section experiments were performed with either ascending or descending order of three different v_f along the flow direction.

3. Results

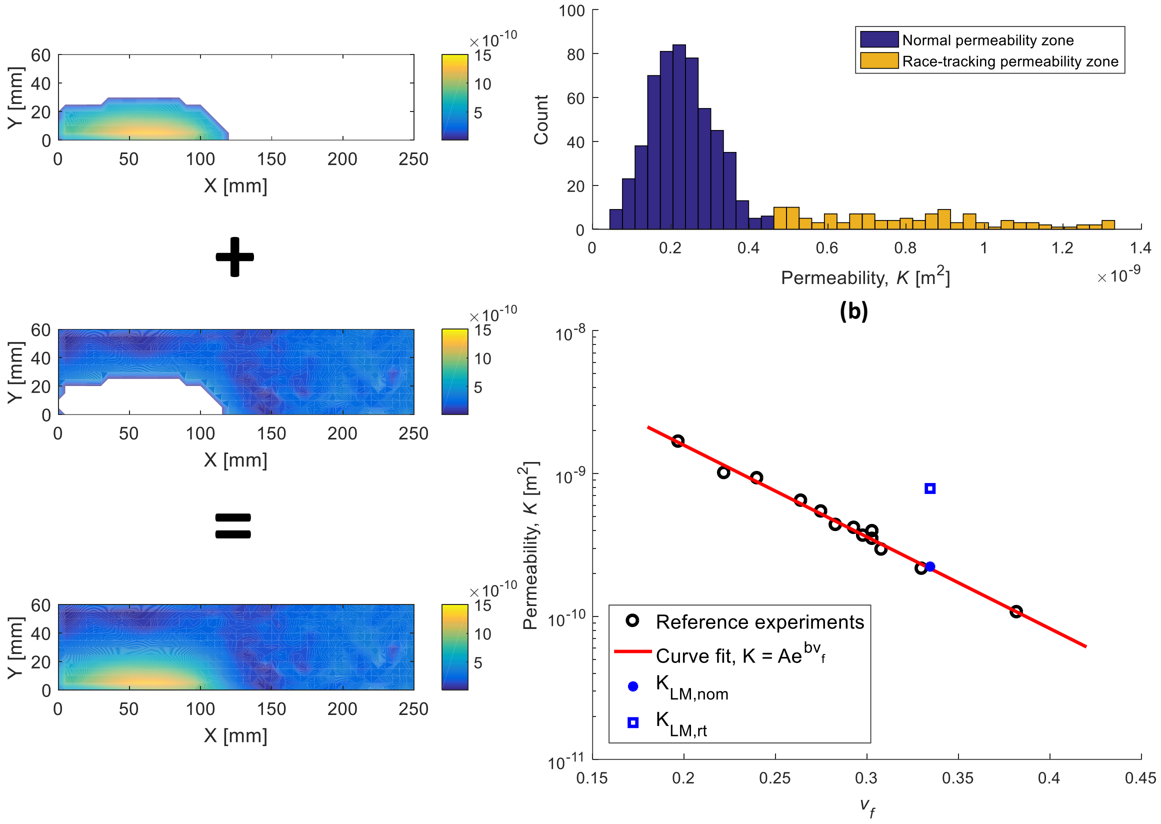
3.1. Race-tracking experiments

Figure 1a shows the flow propagation in an experiment with intentional race-tracking along the bottom fabric - mold wall where flow is strongly diverted from one-dimensional flow. Estimated permeability distribution for this flow propagation is shown in Figure 1b; rapidly-filled regions have higher permeability values. The resulting permeability map was divided into two classes using Otsu's method [8], one class corresponding to race-tracking zones and the other corresponding to the normal flow zones as seen in Figure 2a. A histogram of the permeability map is presented in Figure 2b, showing the two classes with distinct characteristics. Median values of both zones, $K_{LM,nom}$ and $K_{LM,rt}$, were calculated and median permeability of normal flow zone, $K_{LM,nom}$ was correlated to the nominal permeability. $K_{LM,nom}$ and $K_{LM,rt}$ are plotted along the results of reference experiments in Figure 2c, and the good agreement between $K_{LM,nom}$ and reference experiments validates that $K_{LM,nom}$ can be used to estimate the nominal permeability in the presence of race-tracking.



(a) (b)

Figure 1. (a) Flow front reach time normalized by complete mold-filling time in an experiment with intentional race-tracking, (b) corresponding permeability distribution. Resin enters the mold cavity from the left edge, and the vent is located along the right edge.



(b)

(a)

(c)

Figure 2. Permeability results of an experiment with intentional race-tracking along the bottom edge. (a) Output of Otsu's method, (b) histogram of permeability map and (c) median values of normal flow zone $(\boldsymbol{K_{LM,nom}})$ and race-tracking zone $(\boldsymbol{K_{LM,rt}})$ along with the results of reference experiments and best-fitting curve.

3.2. Multiple-section experiments

We performed multiple section experiments with two different configurations, either ascending or descending order number of layers (thus of v_f). In ascending order experiments, 4-, 5-, and 6-layer sections had lengths of 9 cm, 8 cm and 8 cm, respectively and the number of layers increased along the flow direction. In descending order experiments, the lengths of sections were the same but the number of layers decreased along the flow direction. In the optimization procedure, a separate permeability value was assigned to each section and the optimal set of permeability values were estimated iteratively.

Estimated permeability values of two experiments are plotted (one for each configuration) in Figure 3 along with the results of reference experiments. Permeability values align better with the reference results in the ascending order configuration (denoted as K_{LM} (4-5-6) in the figure) than the values of descending order configuration (K_{LM} (6-5-4)). It is suspected that the lower accuracy in the descending order experiments is due to the lower permeability of filled section which slows down the flow propagation in the succeeding sections (with higher permeability) and results in underestimation of permeability.

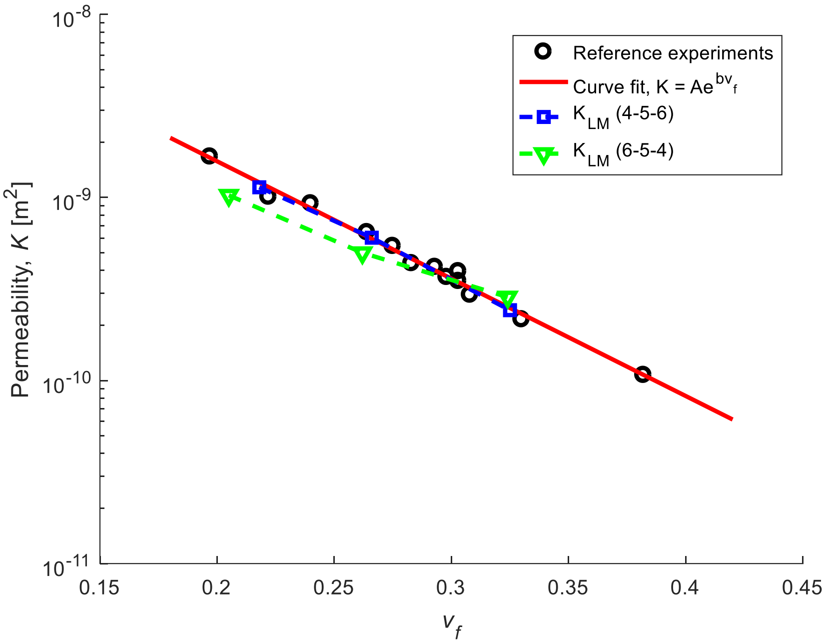


Figure 3. Results of two multiple-section experiments along with the results of reference experiments.

4. Conclusions

This study introduced a new method that combines experimental and numerical techniques to interpret the flow propagation of one-dimensional resin flow experiments in the presence of spatial variability, either due to race-tracking or due to several sections with different v_f, and to obtain the spatial permeability distribution. Mold-filling was simulated using a CVFE based simulation tool and the flow propagation was converged to the experimental flow propagation iteratively using the Levenberg-Marquardt method.

Results showed that the proposed method is capable of estimating the nominal permeability, as well as the spatial distribution of permeability, in the experiments with race-tracking and in the experiments with multiple sections. The talk will focus on the details of experimental and numerical techniques, and will elaborate on the analysis of results as well as on the comparison with results found in the literature.

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