A TOOL FOR MINIMIZATION OF RACE-TRACKING EFFECTS IN PERMEABILITY MEASUREMENTS

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Introduction

In Liquid Composite Molding (LCM) processes, mold-filling simulations are used for predicting the flow patterns and estimating the mold-filling times, thus ensuring high-quality end products. In-plane permeability of the reinforcement is a key parameter in determining the accuracy of the mold-filling simulations and it is characterized either by one-dimensional rectilinear flow experiments along the two principal directions of the permeability or a radial flow experiment [1]. Though radial flow experiments provide the two principal permeability values simultaneously, one-dimensional rectilinear flow experiments are usually preferred since the experiments are easier to set-up, saturated and unsaturated permeability for a pre-determined volume fraction can be obtained from a single experiment, and reproducibility of the results is high [2].

In one-dimensional flow experiments, race-tracking channels might form along the fiber preform-mold wall interface due to inconsistent labor and/or irregularity of material. Common practice is to discard the result of the experiments if the flow front is significantly altered by the race-tracking channels, and to repeat the experiments. The present study proposes a methodology to correctly estimate the permeability in the presence of race-tracking channels by combining image processing techniques and finite element analysis.

Materials and Methodology

The reinforcement is an isotropic random glass mat (Suter Kunststoffe AG) with a superficial density (ρ_{sup}) of 450 g/m^2 and a bulk fiber density (ρ_{bulk}) of 2.60 g/cm^3. Test fluid is selected as polyethylene glycol (PEG, Sigma Aldrich, 35000 molar mass) diluted in a mixture of water based food dye and distilled water to reach a viscosity of 0.1 Pa.s, measured in a concentric cylinders rheometer. Experiments with constant pressure injection boundary condition are conducted using a mold with a transparent upper plate. Propagation of flow front is recorded by a video camera (Canon Eos 650D, 1920×1080 pixels resolution, recorded at 30 frames per second) and injection pressure is recorded by a pressure transducer (Keller S35X, 0 – 10 bar operation range, 0.02 bar accuracy).

In the post-processing stage, flow front location is detected for each frame of the recorded video using image processing techniques based on morphological operations and boundary detection (see Figure 1b). For each frame, the surface area of the reinforcement is discretized into a 2D grid of square elements and saturation of each element is recorded.

A solver is implemented by coupling the solution of pressure distribution using Finite Element Analysis and flow propagation using Element Control Volume Method. The solver has a capability of taking into account of spatially varying permeability, and saturated incompressible flow in a rigid porous medium is assumed. Starting from a uniform permeability distribution, permeabilities of partially saturated elements (elements at the flow front) are calculated and updated to minimize the deviation between experimental and numerical flow front propagation.

Results

Several permeability experiments are conducted where fiber volume fraction (V_f) ranged between 0.36 and 0.50 by changing number of layers in a fixed thickness of 3 mm. In these experiments, permeability is calculated following the squared flow front (SFF) approach as detailed in the permeability benchmark exercise [2] and the results are presented in Figure 1. In one set of experiments, fabric stacks are cut and placed carefully to prevent any race-tracking as shown in Figure 1. Kozeny-Carman equation is fitted to the results of these experiments and the corresponding curve and the equation are given in Figure 1.

Another set of experiments is conducted where race-tracking is introduced intentionally by cutting the fabric stacks narrower in pre-determined regions. For brevity, one of these experiments is presented here. In this experiment, $V_f = 0.422$ and permeability is calculated following the SFF approach and found to be 1.94×10^{-10} m^2 as depicted in Figure 1. Theoretical permeability value for $V_f = 0.422$ is calculated using the Kozeny-Carman equation fitted from results of careful experiments in Figure 1 and it is found to be 1.52×10^{-10} m^2, yielding a deviation of 27.6% between theoretical and experimental permeability values.

Intentional race-tracking channel, captured flow front propagation and estimated permeability map of this experiment are presented in Figure 2a, 2b, and 2c, respectively. Histogram of the permeability map (with a median of 1.58×10^{-10} m^2) and corresponding probability density function (with a peak at 1.50×10^{-10} m^2) are depicted in Figure 2d and 2e. Deviation of the median and peak values from theoretical value are 3.95% and 1.32%, both of which are significantly smaller than the deviation obtained following the traditional approach.

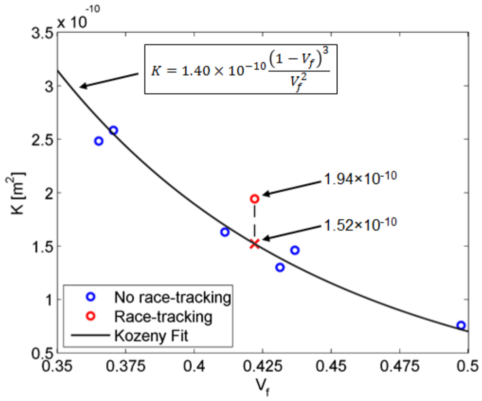

Figure 1: *Results of one-dimensional rectilinear permeability experiments.*

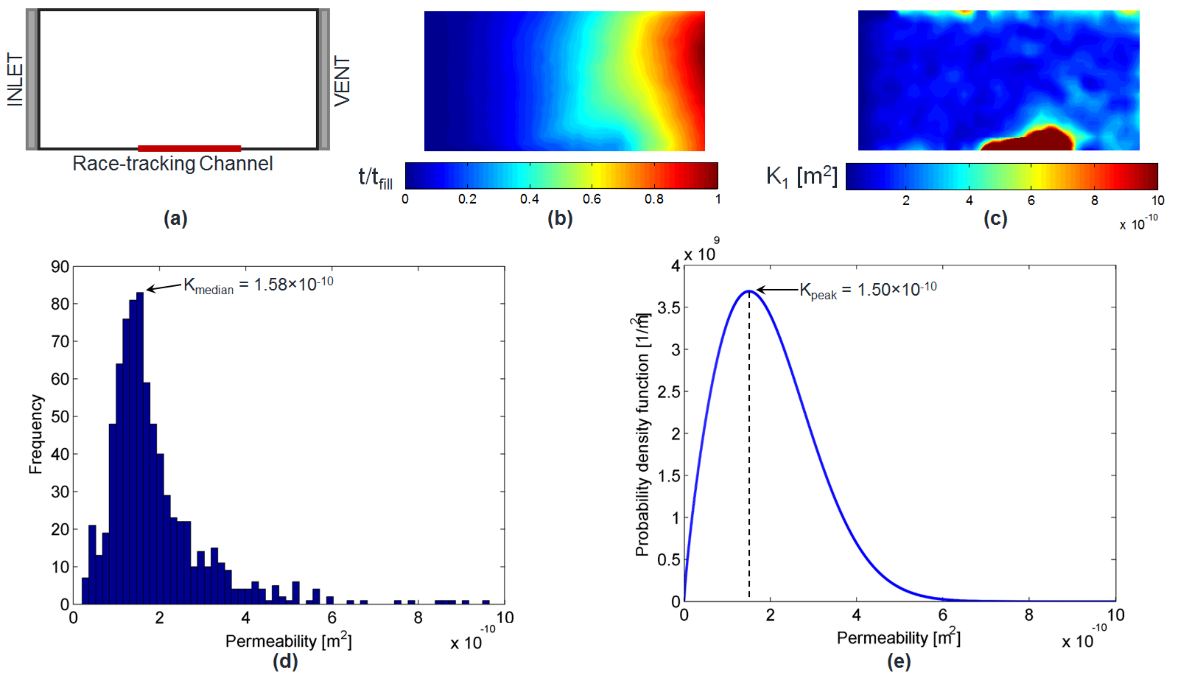

Figure 2: *Results of an experiment with a race-tracking channel introduced intentionally. (a) Mold details, (b) flow front propagation in the experiment, (c) estimated permeability map, (d) histogram of the estimated permeability values, (e) probability density function corresponding to the histogram.*

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