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TITLE: A novel concept for characterisation of the micro-permeability of fibre bundles based on macro-scale flow experiments

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ABSTRACT:

In Liquid Composite Moulding processes, the permeability of the fibrous reinforcements is a parameter required in the analytical description or numerical simulation of the resin injection process. It is essential for prediction of the process cycle time and the product quality in terms of the level of reinforcement impregnation, i.e. it plays an important role in the optimisation of industrial manufacturing processes. Aiming to enable the reliable and consistent determination of reinforcement permeability values, considerable efforts have been made by the worldwide composites community to standardise experimental methods for permeability characterisation. However, the test standard developed so far [1] provides guidelines for the characterisation of the macro-scale permeability of fabrics, i.e. it applies to thin flat specimens with in-plane dimensions in the order of 0.5 m and thickness of several millimetres. It assumes that the properties of the reinforcement, which is typically made from fibre bundles in a defined architecture, can be homogenised over the specimen dimensions.

If resin flow is to be analysed or simulated at a smaller scale, the permeability of fibre bundles is also an important parameter. The bundles consist of several thousand individual filaments at fibre volume fractions between approximately 45 % and 70 %, depending on the level of compaction. The bundle width is in the order of millimetres, and the thickness in the order of 0.1 mm. Because of the alignment of filaments within fibre bundles, the axial and transverse bundle permeabilities typically differ by two orders of magnitude. The small size and high level of anisotropy cause challenges in the experimental permeability characterisation.

In many cases, uni-directional flow experiments are run, and the permeability is derived based on measurement of flow rate and applied pressure gradient (saturated flow) or of the propagation of the flow front with time at an applied pressure gradient (unsaturated flow). The formation of gaps between the fibre bundles and any tooling used in the experiments is hard to avoid. Hence, injection experiments based on individual fibre bundles placed in a small-scale injection tool will typically be affected by racetracking, which makes any results unreliable as the permeabilities will be overestimated [2]. To suppress racetracking and leaking along the edges, fibre bundles are sometimes embedded in sealant, plasticine or polymer [3, 4]. Use of a vacuum bag has also been reported, which conforms to the bundle shape and allows leaking to be suppressed [5]. In an alternative test set-up, a fibre bundle is wound into a circular disk. Then, the through-thickness permeability of the bundle can be measured in unsaturated radial flow experiments on the disk [6], while conducting saturated unidirectional flow experiments normal to the disk allows to obtain the transverse bundle permeability [7].

Here, it is proposed to conduct experiments in a transparent rigid tool and track the flow front propagation visually for characterisation of the axial and transverse bundle permeability. The novel aspect of the proposed method is that racetracking is an essential part of the solution. Instead of trying to minimise racetracking, which may result in unpredictable flow patterns if it cannot be controlled accurately, reproduceable racetracking is induced in the experiments. The rectangular geometry of the experiment (Fig. 1) contains racetracking channels and the fibre bundle, which is aligned with the long edges of the tool. When the tool is closed, the fibre bundle is held in position through the applied compaction force and effects of friction on the tool surfaces. The fibre volume fraction in the bundle can be calculated from the cavity height and is assumed to be uniform along the specimen length.

When a test fluid is injected through the central inlet at a given pressure, flow will propagate in the fibre bundle first. Once the flow front reaches the edges of the bundle, racetracking will develop in the gap between the bundle and the cavity wall. At long experiment times, flow will be dominated by racetracking

(Fig. 2). Because of the interaction between impregnating flow and racetracking, data reduction schemes for permeability calculation typically used in linear or radial injection experiments will not be applicable, as they only consider idealised (straight or elliptical) flow front patterns in the respective configurations. Hence, a previously developed inversion algorithm [8] is applied to the observed flow patterns and fluid pressure values. As long as two-directional flow develops in the fibre bundle, through appropriate definition of boundary conditions for the injection, this allows three unknowns to be determined, namely the equivalent permeability of the channel and the axial and transverse bundle permeabilities.

Application of the inversion algorithm to the recovery of the fibre bundle permeability will be demonstrated, and results will be discussed quantitatively.

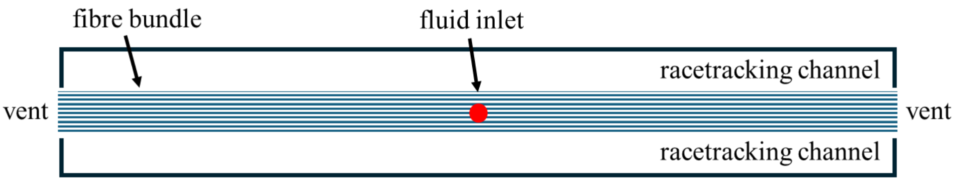

Figure 1. Schematic of experimental set-up (not to scale).

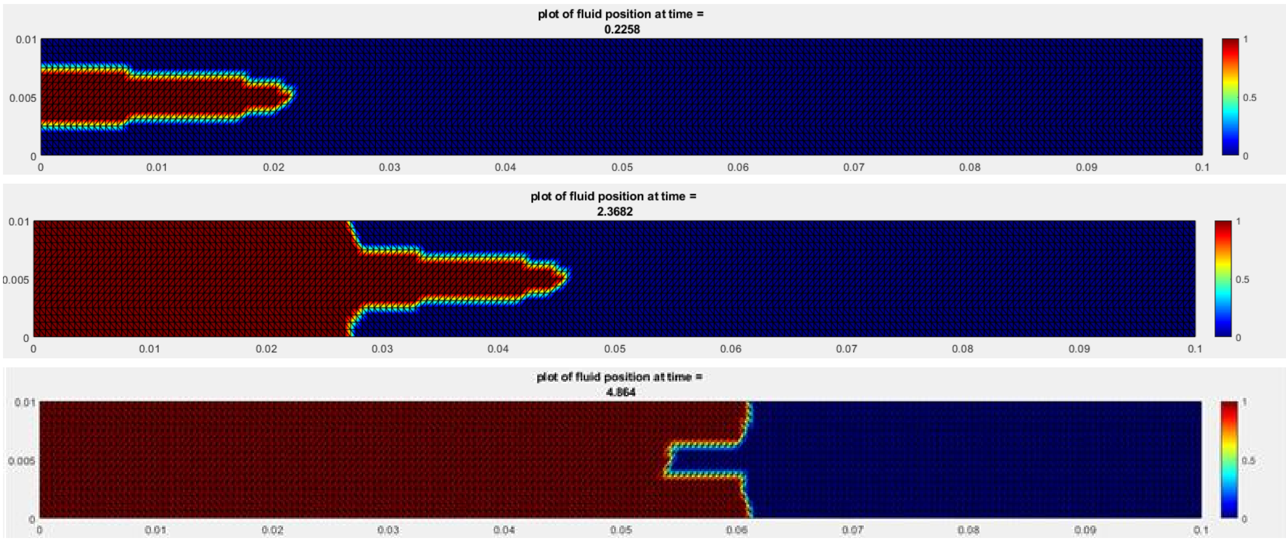

Figure 2. Flow front shapes at different experiment times (for half of the symmetrical geometry). Top: Flow in fibre bundle only. Middle: Flow in bundle and racetracking. Bottom: Flow dominated by racetracking. Example data obtained using a Matlab implementation of the Finite Element/Control Volume method [9].

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