DUAL FLOW FRONT MEASUREMENTS FOR IMPROVED PERMEABILITY CHARACTERISATION

Mikhail Y. Matveev, I. Arthur Jones, Andrew C. Long and Andreas Endruweit

Composite Group, Faculty of Engineering, The University of Nottingham,
Nottingham, NG7 2RD, United Kingdom
Email: Mikhail.Matveev@nottingham.ac.uk,
Email: Arthur.Jones@nottingham.ac.uk,
Email: Andrew.Long@nottingham.ac.uk
Email: Andreas.Endruweit@nottingham.ac.uk

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Abstract
The paper presents comparison of two experimental techniques for flow front tracking for measuring the unsaturated permeability of fibre reinforcements: one based on pressure transducers and the other using video recording of the evolving flow front. These two techniques were compared for several types of single- and dual-scale reinforcements. A correction of the systematic uncertainty in the pressure recordings is presented. The paper presents a discussion on other uncertainties in permeability measurements.

1. Introduction

Composite manufacturing using Liquid Composite Moulding (LCM) processes is often supported with numerical simulations to guarantee complete impregnation and targeted filling time [1]. One of the key parameters for these simulations is permeability of the reinforcement, which can be obtained from experiments for the required material configurations. However, despite the efforts to standardise the measurement procedure and develop the best experimental practice in the framework of the International Permeability Benchmark study [2] there are still some uncertainties on the experimental procedure, specifically on flow front detection in unsaturated flow experiments and its accuracy. Most participants in the International Permeability Benchmark study used visual methods to detect flow propagation and derive permeability values. However, the use of sensors, e.g. pressure transducers, makes it possible to fully automate the measurements and enriches the experiment with extra data in cases where the flow front propagation is more complex than linear.

This work attempts to investigate possible discrepancies arising from flow front detection by two techniques: one using pressure transducers and the other using a video recording of the evolving flow front. Both methods were employed simultaneously during the experiments, tracking the same flow front propagation. Several types of single- or dual-scale reinforcements including those exhibiting isotropic (random glass fibre mat), strong anisotropic (unidirectional stitched tows) and orthotropic (cross-ply preform) properties were used for experiments. A correction of the systematic uncertainty in recorded pressure data for improvement of permeability measurements is presented.

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2. Experimental setup

The experimental setup comprised a rig which simulated 1D linear flow in a closed RTM (resin transfer moulding) mould with two rigid plates as shown in Figure 1. The bottom mould was a steel plate, and the top mould was made from a transparent acrylic plate with a thickness of 25.4 mm. A picture frame for adjustment of the cavity height was inserted between the two mould halves and sealed with a rubber O-ring and silicone grease to avoid any possible leakages. The fibre reinforcements were injected with synthetic oil with well-defined viscosity properties through a linear injection gate at a constant pressure of 1-2 bar depending on the reinforcement.

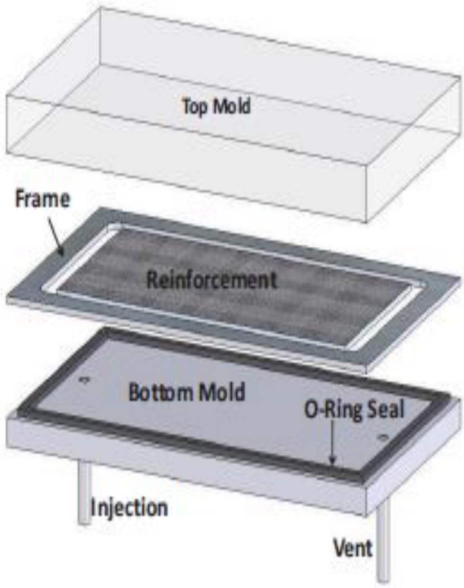

Figure 1. Principal scheme of the permeability rig [3]

The permeability rig was fitted with eight pressure transducers which were connected to a PC with LabView™ software enabling automatic processing of the data. Two of the transducers were located at the injection gate and near the vent, and the other six transducers were placed in pairs with a symmetric pattern as shown in Figure 2.

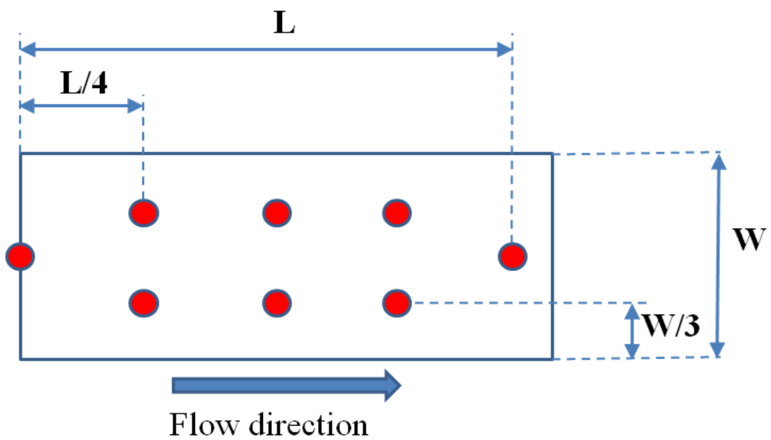

Figure 2. Location of the pressure transducers (in red) in the permeability rig, dimensions are L = 250 mm, W = 114 mm

In addition to the pressure transducers, the experimental setup was fitted with a video-camera which allowed the flow of the test fluid through the reinforcement to be recorded. Videos from the camera had to be processed after the experiment using MatLab™ software.

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3. Processing of the data

Data from the pressure transducers used in the permeability rig were processed automatically within LabView™ software which measured the flow front arrival time at each transducer. The algorithm was based on a simple thresholding of the recorded pressure-time readings with a value, P_{th}, (to suppress noise on the signal) and assuming the first pressure increase above this value to correspond to the flow arrival time. Arrival time at the paired transducers was averaged due to the assumption of 1D flow.

Image thresholding and edge detection were applied to extract flow front position from the video files at any given time step. Maps of arrival time were produced as a result of such processing as shown in Figure 3. One of the problems with the visual flow front tracking was setting up a light source to achieve uniform brightness across the tool surface while simultaneously avoiding reflections from the transparent upper mould. Furthermore, the flow front was not clearly visible for some of the reinforcements.

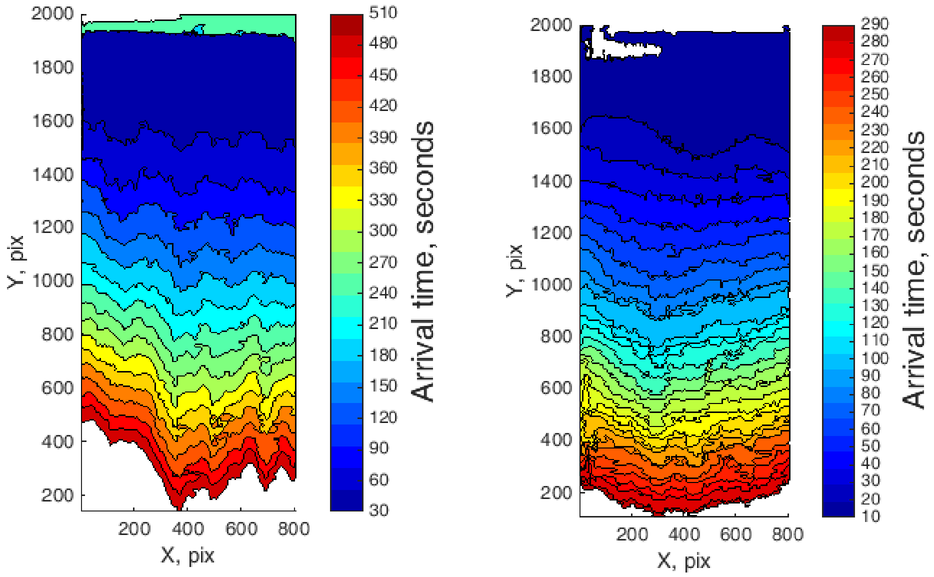

Figure 3. Map of flow front arrival times in unidirectional (0_9) and ($0_4/90_5$) reinforcements, porosity 0.42

Usage of two techniques applied simultaneously makes it possible to compare the results from both. However, it is important to note that the time obtained from the transducers through thresholding is not the actual time of the flow front arrival. Indeed, the pressure distribution in the impregnated part of the preform is linear as shown in Figure 4, and the flow front position corresponds to zero gauge pressure. This makes the time obtained from the transducer greater than the time of actual arrival of the front at this position. The difference between both times increases with increasing length of the impregnated part of the preform and with decreasing injection pressure (i.e. with decreasing pressure gradient). This inconsistency can be easily corrected by replacing the position, x_s, with the corrected flow front position, x_{ff}.

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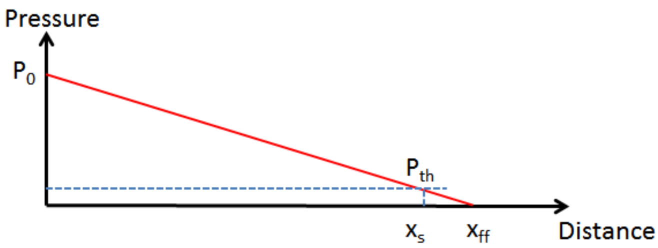

Figure 4. Pressure distribution in 1D flow

It is straightforward to derive the actual position of the flow front at time t_s from Figure 4:

$$x_{ff} = \frac{x_s}{(1 - P_{th}/P_0)} \tag{1}$$

where P_0 is the injection pressure and P_{th} is the thresholding value for the transducers.

Arrival times obtained for each of the transducers and detected by visual measurements were used to predict the permeability, *K*, according to the equation derived from Darcy's law:

$$K = \frac{\mu \varphi x^2}{2 P_{in} t} \tag{2}$$

where μ is viscosity of the test fluid, φ is the porosity of the reinforcement, P_{in} is the injection pressure, *x* is the distance of the transducers from the injection gate and *t* is the flow arrival time at the transducers.

4. Comparison of the two techniques

Permeability experiments were carried out on several reinforcements which had significant difference in their structure. Choice of the structures aimed to highlight possible discrepancies between the two measurement techniques. It is worth mentioning that two techniques measure the flow front at different surfaces of the preforms (visual: top surface of tool; transducers: bottom surface) and hence may be incomparable if there is a through-thickness gradient in material properties in the preforms.

The first reinforcement, glass fibre random mat, was chosen for its quasi-isotropic permeability and because it is a single-scale porous medium. It was expected that for this simplest case both of the measurement techniques would produce identical results because effects of partial saturation cannot occur for this material. Other reinforcements were various modifications of unidirectional (UD) and cross-ply layups as listed in Table 1, i.e. dual-scale media. The pure UD lay-up was expected to produce the same results for both material surfaces due to uniformity of the permeability in the through-thickness direction. Other lay-ups were designed to have drastically different permeability at the top and bottom surface.

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Table 1. Parameters of the reinforcements used in experiment and their permeability

	Reinforcement	Layup	Porosity	Permeability, 10^{-10} m^2	
				Transducers	Video
1	Glass fibre random mat (Unifilo)	-	0.72	58.1	69.9
2		0_9		3.29	3.75
3	UD (glass fibre)	$90_5/0_4$	0.42	3.42	3.95
4		$0_4/90_5$		3.67	3.81
5	Dry carbon fibre tape	$(0/90)_8$	0.45	1.46	1.7
		$(90/0)_8$		1.44	2.0

Permeability calculated for random fibre mat using the corrected flow front arrival time and visual measurement produced comparable results within 15%. The UD reinforcement with blocked 0º plies on the top ($90_5/0_4$) produced the results which were expected – slower flow in the bottom layers (low permeability) and faster flow in the top layers. However, the reversed layup (0º plies on the bottom) was not consistent with the previous results. It was found that according to the visual measurements the flow in the 90º plies is faster than in 0º plies. Similar results were produced for the dry carbon fibre tape lay-up when 0º and 90º plies were either at the top or at the bottom of the mould.

5. Discussion & conclusions

The work aimed to compare two permeability measurement techniques and establish the correspondence between them if possible. A simple technique has been presented for correcting the time measurement in order to enable direct comparison between the techniques. Introducing this correction factor made it possible to relate the measurements by both techniques for the cases of the isotropic reinforcement and the reinforcement with uniform through-thickness permeability. However, slight inconsistency was observed for highly anisotropic reinforcements where the flow at the top and bottom of the mould was expected to be different. It was found that the visual measurements consistently provide the permeability which is higher than that measured by the transducers.

It can be argued that even if the measurement techniques are applied simultaneously during the experiment for isotropic reinforcement they are not necessarily measuring the same quantities. One of the possible differences is what type of flow is picked up by the techniques – capillary flow, partial saturation or saturated flow. For the random mat, effects of capillary flow and partial saturation are not expected to occur since there is only one scale of porosity in the material. Using the visual measurement technique, it is sometimes possible to see the saturation process or thin film of fluid propagating above the reinforcement but it is harder to quantify it. If capillary effects are present, it is possible to identify impregnated yarns through colour contrast, while inter-yarn gaps are still not filled with fluid. If pressure transducers are used, the flow front is detected when “free” fluid is in contact with the sensing area, and the local pressure increases. An increased pressure reading will not be triggered by flow in the yarns driven by capillary pressure. The pressure reading does not indicate what effects of dual-scale flow (micro-scale flow within fibre bundles or meso-scale flow between the bundles) are predominant, i.e. if free fluid is detected while the bundles are still dry, or if the bundles are already impregnated while propagation of free fluid through gaps between the bundles lags behind.

In general, both techniques produce similar results if care is taken during the data processing. The simultaneous employment of both methods results in richer data and makes it possible to perform more detailed analysis of the flow within the reinforcement.

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