Dependence of the 1-D permeability of fibrous media on the fibre volume content: comparison between measurement and simulation
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Abstract
Since the beginning of this decade a growing interest of the industry in the Liquid Composite Moulding (LCM) processes could be observed. These manufacturing methods meet the requirements of today’s series productions of advanced continuous fibre reinforced composite. There are several examples of successful series productions in RTM (Resin Transfer Moulding) and VARI (Vacuum Assisted Resin Infusion), but currently the use of the full potential of these processes is restricted by the limited knowledge of the resin flow behaviour in fibrous media. To improve this situation, several sophisticated flow simulation software packages have been developed during the last 5 years to help the process engineer to optimise mould design and process parameters. This study deals with LCMFLOT which is a very promising software developed by the Centre de Recherche Appliquée sur les Polymères (CRASP) in Montréal.

A basic condition to obtain a useful flow simulation is accurate permeability (k) measurement of the fibrous medium. The permeability depends on fibre volume content (V_f). In many applications the permeability varies along the flow path in the part according to draping. Therefore it is very important to characterise the dependence of the permeability on a wide range of V_f.

An experimental study was performed in a 1-D flow channel to quantify the dependence of the permeability from V_f. The material using is an isotropic (k_x=k_y=k) non-crimped fabric fibre (biaxial glass fibre, +/- 45°). A model fluid
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(Silicon oil) performs the fibre impregnation. Our study has shown that 3 or 4 permeability measurements with different $V_f$ are sufficient to create a fitting curve providing a good agreement between simulation and experiment.

1 Introduction

Mould filling through porous media or two phases medium (fibre/void) is the governing phenomena in a number of composites manufacturing process such as resin transfer moulding (RTM). The main focus of this work is the investigation of the influence of the fibre volume content $V_f$ on the flow behaviour.

Flow in anisotropic media requires a characterisation of both the media and the flow. Porous media represent an extremely complicated network of channels and obstructions. There are usually described with a full media by a statistically volume average (e.g. Advani [1], Greenkorn[2]).

The reason of the permeability measurements versus the fibre volume content is that after draping a complex form with a given material the fibre volume is not spatially constant. In order to start a filling simulation, the software programme requires accurate permeability value for a given porosity.

This paper recovers an experimental part which will show the 1-D permeability dependence on the fibre volume content for a given non-crimped fabric fibre and a second part will compare the fluid flow through a 2-D form (glasstool) surface containing obstacles with a simulation (LCMFLOT).

2 Permeability Measurement

Accordance between simulation and experiment depends on the measurements of the physical parameters as viscosity, pressure or the permeability. Before processing, accurate permeability measurements are required to get good simulation parameters.

2.1 Darcy’s Law

The model used in the simulation software is the Darcy’s law. In the tridimensional case, Darcy’s law can be expressed as:
Darcy’s law (1856) is an empirical law which states that the flow rate in a porous media is proportional to the pressure gradient in the medium. The constant of proportionality is called the permeability and the magnitude is a function of the pore structure, which contains the porosity or fibre volume content. The Darcy’s law is valid as long as the velocity is not too large in order to neglect the inertia effects. The Reynolds number, given by:

\[ R = \frac{l \cdot Q \cdot \rho}{\eta \cdot \phi} \]  

where \( l \) is a characteristic dimension of the porous medium, \( Q \) is the flow rate, \( \rho \) is the density, \( \eta \) is the viscosity of the fluid and \( \phi \) the porosity of the media. We can mention that the ratio \( Q/\phi \) represents the mean velocity of the fluid. As mentioned in some paper, the Darcy’s law is still valid for maximum Reynolds number varies from 0.1 to 75 (e.g. Dullien [3]).

### 2.2 Experimental Set Up

Our laboratory is equipped with two main experimental set-ups for the permeability measurements. Measurements in a 2-D flow glass tool with a central injection is necessary to determine the main axis of the material which define the direction of the 1-D measurement in the flow channel. The one (1-D) dimensional flow channel is suitable to the determination of accurate and reproducible permeability values. All 1-D permeability measurements are accomplished in the flow channel. The experimental part compared with the simulation is accomplished in the glass tool containing three obstacles.
2.2.1 2-D Experimental Set-Up : Glasstool

The glasstool is 108 cm long, 58 cm wide and 0.2 cm thick. There are different injection possibilities: line or several inlet holes. The determination of the main axis of the permeability used the central injection inlet. The entire mould is heatable until 80 °C. It is equipped with 5 pressure and 4 temperature sensors to follow the evolution during the experiment. A SCXI-card performs (D/A) acquisition and transfers of the data to a computer which can display the different sensor signals at a frequency of 1 Hz. The upper glass of the tool allows the visual observation and the record of all the experiment on a video band for further digital image processing.

2.2.2 1-D Experimental Set Up : Flow Channel

The channel is 100 cm long, 13 cm wide and 0.2 cm thick. The thickness can be changed in order to vary the porosity. The length of the textile material is usually 55 cm. A metal frame holds both glass plates together. The upper glass plate contains the inlet and outlet hole (figure 1). Two pressure sensors are on a glass plate in order to control the gradient pressure during the experiment. Visual observation and video record are allowed through the upper glass plate. Data transfer and processing are achieved on a computer.

Figure 1: Flow channel: 1-D measurement tool
2.3 Materials

The experiments have been carried out with silicon oil. Advantages of this model fluid is the small temperature dependence of the viscosity. Measurements have shown that the standard deviation from the mean value of the viscosity (0.115 Pa·s) is 5 % around the room temperature (18.5-24.5°C).

An isotropic (kₓ=kᵧ=k) non-crimped fabric is used in this initial study. As the thickness of the cavity is constant, the fibre volume content depends on the amount of the layers, inserted in the mould.

2.4 Procedure

Prefabricated layers of the fabric with known dimensions (12.5 x 55 cm) are laid down in the flow channel at a distance of 10 to 15 cm from the inlet hole of the upper glass plate in order to achieve a flow front as straight as possible when reaching the fabric. The metallic frame of the flow channel embraces the glass plates. After connecting the inlet pipe to the flow channel and closing the outlet hole, compressed air is introduced in the channel to check for leaks and to calibrate the pressure sensors. Silicon oil is injected using a pressure pad. A PID system allows to maintain the pressure constant during all experiment. The working pressure area is between 1 to 2 bar. The experiment starts as soon as the setting pressure is introduced in the software which manages the data acquisition and controls the valve. The video record of the experiment allows an analyse of the flow front evolution in order to calculate the permeability and to accomplish further image processing.

2.5 Data Analysis

The 1-D Darcy’s law (1) can be formulated as follows:

\[ v_f = \frac{K_x \cdot \Delta p}{\eta \cdot x_f} \]  

\[ v_f : \text{flow front velocity} \]
\[ K_x : \text{x-direction permeability} \]
\[ \eta : \text{viscosity} \]
\[ \Delta p : \text{pressure difference} \]
\[ x_f : \text{flow front position} \]
Four mathematical methods can be considered to analyse the experimental data:

- elementary method
- interpolation method
- single point method
- slope method

The interpolation and slope method take in account all the experimental data of the experiment and calculate a mean or fitting value of the permeability. The elementary permeability derives directly from the raw data. The single point method evaluates the deviation between the theory (Darcy) and the raw data.

2.6 Results and Discussions

Each (1-D or 2-D) measurement is performed with a constant injection pressure and with a model fluid (silicon oil).

2.6.1 1-D Permeability Measurements

Permeability measurements have been performed with a fibre volume content between 27 to 53 %.

![Graph](image-url)

Figure 2: 1-D Permeability as a function of the fibre volume content. CRASP and ETH measurements.
We must keep in mind that the permeability is an intrinsic constant (for a given porosity) of the fibre medium which is inverse proportional to the resistance to the flow through the material. Figure 2 shows that when the fibre volume decreases the magnitude of the permeability value is larger. Theoretical and empirical laws, as exponential or potential (3) regression, are proposed in order to get a relation between the permeability and the fibre volume content. (e.g. Gebart[4], Gauvin[5], Binetruy[6]). The figure 2 shows that the relation is not linear. Some papers (e.g. Goulley [7]) propose a potential relation (4):

\[ K = A \cdot \phi^B \]  

Or:

- \( K \): permeability
- \( A, B \): constant
- \( \phi \): porosity

With :

- \( V_f = 1 - \phi \)
- \( V_f \): fibre volume content

From the potential regression, we can calculate the value of A and B. Our measurements give an order of magnitude which is comparable with the results of other studies on different fibre materials (Breard[8]).

### 2.6.2 Flow in a 2-D Form (glasstool) containing Obstacles: Experiment compared with Simulation

To compare results from the simulation and experiment, we have made a measurement in the glasstool (58 x 108 cm^2) with fibre material containing obstacles (ellipse, open square and triangle, figure 4). 0.2 cm thick glasstool is filled with 6 layers of the pre-cut biaxial non-crimped fabric. The calculated fibre volume content is 53 %. Before closing the mould, a plastic material fills the different hole spaces. Compression of the plastic material due to the glass allows to get no leak into the obstacles. The measured permeability value used in the simulation software is determined in the glasstool to avoid errors on the calculation of the permeability due to eventually deformations of the form. Figure 3 shows the experimental and simulated flow front position.
Figure 3: Flowfront position in the glassstool without obstacles. Comparison between experiment and simulation for the biaxial material. Fibre volume content: 53%, silicon oil at room temperature.

Figure 4 shows a good agreement between the measurement and the simulation for the experiment in the glassstool.
3 Conclusions

Flow simulation is an useful tools for the optimisation of a liquid composite moulded part. One of the model used for the simulation of liquid flow through porous medium is the Darcy's law. The accuracy of the simulation depends on the flow regime and also physical parameters included in this law. Permeability is the one of these parameters which represents the largest measurement difficulties.

In our laboratory, measurements are reproducible from one set-up to the other. Further experiments will allow to compare our results with another research group as CRASP and to obtain consistent results.
References


