DEVIATION FROM DARCY'S LAW DURING THE POST-FILLING STAGE OF RESIN INFUSION

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ABSTRACT: To allow for a better control of the quality of parts produced through the resin infusion process, it is necessary to understand the phenomenon happening during the post-filling stage of the process. This paper investigates the causes of the residual pressure gradient that can be observed at the end of the post-filling stage of the resin infusion and RTMLight processes. A modified formulation of Darcy's law is presented along with experimental evidence in an attempt to verify and quantify the existence of a threshold pressure gradient in the case of flow through porous media.

KEYWORDS: Darcy's Law, Threshold pressure gradient, Resin Infusion, RTMLight

INTRODUCTION

The resin infusion process is increasingly being used in the boat building and wind turbine industries to manufacture large components in one shot. Compared to traditional wet hand lay-up, this process provides potential for higher quality in the final product as well as increased repeatability, better control of the toxic volatile organic compounds, and also increased productivity. Using resin infusion it is possible to manufacture a complex shaped sandwich structure at once, and the absence of a rigid B side mould and lack of need for a large press or autoclave creates an economical solution. The process is ideal for manufacturing large pieces in relatively low quantities, as compared to other closed moulding processes such as pre-preg/autoclave or RTM and its variations.

Due to the potential cost savings, high tech industries such as aerospace are showing an increasing interest in resin infusion [1, 2]. However due to the flexible nature of the vacuum bag, preform thickness can change during the process as the compaction stress on the preform is a balance of the external atmospheric pressure and the local fluid pressure inside the laminate. The process can be divided into three stages, pre-filling, filling and post-filling as explained in [3, 4]. At the end of the filling stage, the fluid pressure ranges from atmospheric at the inlet to vacuum pressure at the vent, there is therefore a large variation of reinforcement compaction and thus of fibre volume fraction along the mould. Once the inlet is closed, during post-filling the fluid pressure inside the laminate decreases and tends to equilibrate. It is during this phase that the part reaches its final laminate quality. It is thus crucial to understand and model the post-filling to be able to provide accurate prediction and reach aerospace quality control. A comprehensive simulation model of the resin infusion must therefore be able to predict the fluid flow and reinforcement compaction throughout the filling and post-filling stages of the process, in order to be able to predict the final product quality.

The current analysis schemes adopted for LCM flow simulations assume resin flow through the preform is governed by Darcy's law:

$$q = -\frac{1}{\mu}\mathbf{K}\,\nabla P, \tag{1}$$

where q is the fluid averaged velocity vector, μ is the fluid viscosity, $\mathbf{K}$ the permeability tensor for the preform, and ∇P is the local pressure gradient in the resin.

Through monitoring of the resin infusion process, it was noted that, at the end of post-filling, while the local fluid pressures have stabilised and no apparent flow remains, a pressure gradient is still present in the laminate [3, 5]. This finding was also observed at the end of post-filling during RTMLight experiments [6]. The presence of a pressure gradient in the absence of any flow does contradict the commonly accepted definition of Darcy's law as presented in Eqn. (1). This paper will present a modified formulation of Darcy's law together with experiments aimed at validating this new formulation.

BODY OF THE PAPER

Theory

The modified Darcy's law presented here was developed from research in the Petroleum and geological field and presented by Prada and Civan in [7] where the authors introduced a threshold pressure gradient (∇P_{cr}) in Darcy's law. Eqn. 1 was modified as:

$$q = -\frac{1}{\mu}\mathbf{K}\,(\nabla P - \nabla P_{cr}) \text{ when } \nabla P > \nabla P_{cr}, \quad \text{and } q = 0 \text{ otherwise.} \tag{2}$$

The threshold pressure gradient was found to decrease with an increase of the fluid mobility ($\mathbf{K}/\mu$) and this relationship was defined as:

$$\nabla P_{cr} = \gamma \left(\frac{\mathbf{K}}{\mu}\right)^{-\lambda}, \tag{3}$$

where γ and λ are empirically defined coefficients.

Experimental Setup

To dissociate the residual pressure gradient from the flow/compaction coupling that occurs during the post-filling stages of resin infusion, rigid tooling in an RTM configuration were applied in experiment. To avoid problems caused by race-tracking along the edges of the preform, radial flow experiments were performed rather than linear experiments. The experiments consisted of fully saturated steady state flow [8, 9] with a range of injection pressure and target fibre volume fraction (V_f).

An aluminium bowl shaped mould, with an internal diameter of 300 mm and 100 mm high walls was used. A 280 mm aluminium disk with a thickness of 25 mm was used as top platen. To evacuate the excess fluid, an 8mm flexible hose was used as a siphon.

To be able to track and control the cavity thickness, the mould was placed in an Instron universal testing machine, the top platen being fitted with a spherical alignment unit to minimise the misalignment with the surface of the lower mould. To eliminate measurement errors due to the compliance of the alignment unit and load cell, the cavity thickness was measured using a laser gauge mounted on the top platen, measuring the distance to the bottom mould. The pressure at the inlet was measured using a pressure transducer with a range of -15 to 85 Psi (-1.03 to 5.86 bar), while the flow rate was monitored using a balance recording the mass of the fluid pot.

Sample Preparation

For a radial flow with a constant flow rate, using standard Darcy's law (Eqn. (1)), the fluid pressure inside the reinforcement can be calculated as [8]:

$$P(r) = \frac{\mu Q}{2\pi h K} ln\left(\frac{r_{out}}{r}\right), \tag{4}$$

where K is the isotropic permeability, h is the cavity thickness, r_{out} is the outer diameter of the preform, and r is the distance from the inlet at which the pressure is measured. The pressure gradient is therefore higher towards the centre of the mould, and the total flow can be significantly affected by small variations in local permeability toward the centre of the preform. To ensure all fluid velocity remain in-plane, a hole must be cut in the centre of the preform. A larger hole diminishes the influence of local variations in the reinforcement near the inlet and provides a more linear pressure field. However it will also decrease the remaining pressure at the inlet as the distance between inner and outer radii decreases. To balance these effects, the sample geometry was designed as a circular disk with an inner diameter of 50 mm and an outer diameter of 265 mm. Each sample consisted of 10 layers of a CSM reinforcement, having a nominal areal weight of 450 g/m^2. This material was characterised in [4, 10], and layers using concentric circular blades using a cutting press.

Procedure

After weighing the mass of fibre, the sample was placed into the bottom mould and centered on the inlet gate. The mould was then closed to a target V_f of 0.3. The preform was then saturated with fluid. At each target V_f, a series of steady-state flow rates were established with injection pressures of 2 bar, 1.5 bar, 1 bar and 0.5 bar, to measure the influence of the flow rate on the calculated permeability. The injection gate was then closed and the preform maintained at the target V_f for another 10 min to measure the residual pressure remaining at the inlet. Three samples were tested using a Mobil Vacuoline 537 mineral oil and two samples were tested using a Mobil DTE Heavy mineral oil (0.764 and 0.211 Pa.s at 25°C respectively) [10]. Table 1 presents the target volume fractions addressed along with the number of steps at which a series of steady state flow rates were established. During all experiments, the temperature was monitored to determine the fluid viscosity.

Table 1: Number of series of steady-state flow established for each target Vf and oil.

Target Vf	0.3	0.35	0.4	0.425	0.45	0.5	0.525	0.55	0.6
With Mobil DTE Vacuoline	4	2	4	2	4	5	2	4	5
With Mobil DTE Heavy	2	2	2	2	2	2	2	2	2

Results

Theoretically the threshold pressure gradient could be calculated though linear interpolation of a plot of the flow rate as a function of the pressure gradient applied. However, it was found that as the injection pressure changes, the fluid force on the mould was changing. This change was further enhanced by the viscoelastic relaxation of the reinforcement as the Instron endeavoured to maintain a constant cavity thickness; the decrease of total force on the mould led to a decrease in the compliance of the load cell, to cavity thickness changes, leading to modification of up to 0.01 in V_f (or 1.7% change). Static noise in pressure transducer readings, and the balance sensitivity also contribute to measurement accuracies at very low flow.

It was therefore decided to measure threshold pressure gradient as the residual pressure measured at the inlet once the fluid pressure in the laminate has settled after closing the gate. Figure 1 presents the measured residual inlet pressure as a function of V_f. It can clearly be observed that as the V_f increases, the residual fluid pressure at the inlet increases. Figure 2 presents a plot of the threshold pressure gradient as a function of the fluid mobility, while Table 2 provides the coefficients γ and λ calculated from the experiments, along with the coefficient of determination (R^2).

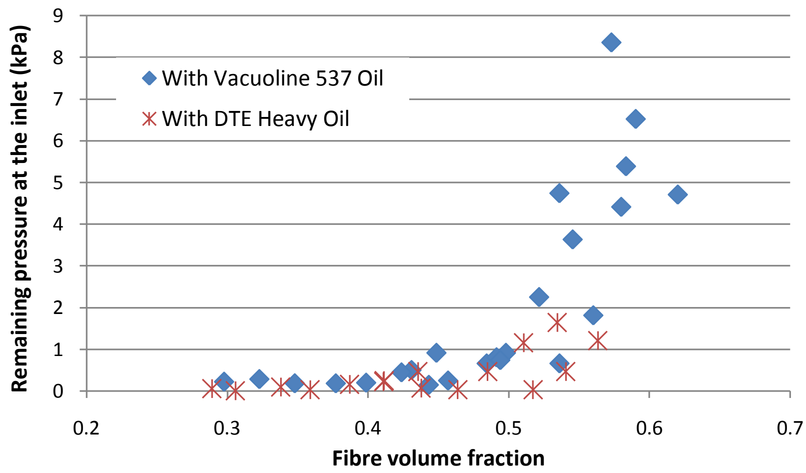

Figure 1: Residual pressure at the inlet as a function of V_f

Table 2: Coefficients of the threshold pressure gradient calculations.

test	All	All Vacuoline	All Heavy	CSM Vacuoline 1	CSM Vacuoline 2	CSM Vacuoline 3	CSM Heavy 1	CSM Heavy 2
γ	1.58E-04	8.76E-09	4.02E-03	2.24E-05	1.59E-06	4.18E-11	1.26E-03	8.78E-03
λ	0.473	0.884	0.332	0.549	0.677	1.103	0.393	0.288
R^2	0.622	0.82	0.576	0.674	0.856	0.951	0.762	0.562

Discussion

It can be observed that fitting all the tests at once results in a relatively low coefficient of determination. The experiments using the less viscous Mobil DTE Heavy resulted in higher variability, which may be due to limitations of the experimental setup, notably static noise from the pressure transducer making measurements harder at low pressures. It is also noted that the power law regressions show a significant difference between the two different oils used in this experiment. The relationship between threshold pressure gradient and fluid mobility might therefore need to be redefined.

To put the results in perspective, in a resin infusion application resulting in a V_f of 0.5, using a fluid viscosity of 0.7 Pa.s, the resulting residual pressure gradient would be about 10 kPa/m. Therefore in a 1m long preform, at the end of post-filling, the compaction stress on the preform at the inlet would be 10% less than at the vent this would result in a 1% increase in thickness at the inlet considering the compaction behaviour of the CSM reinforcement. The presence of a residual pressure gradient will also influence evolution of pressure and laminate thickness, and should be considered in efforts to simulate laminate properties through the post-filling phase.

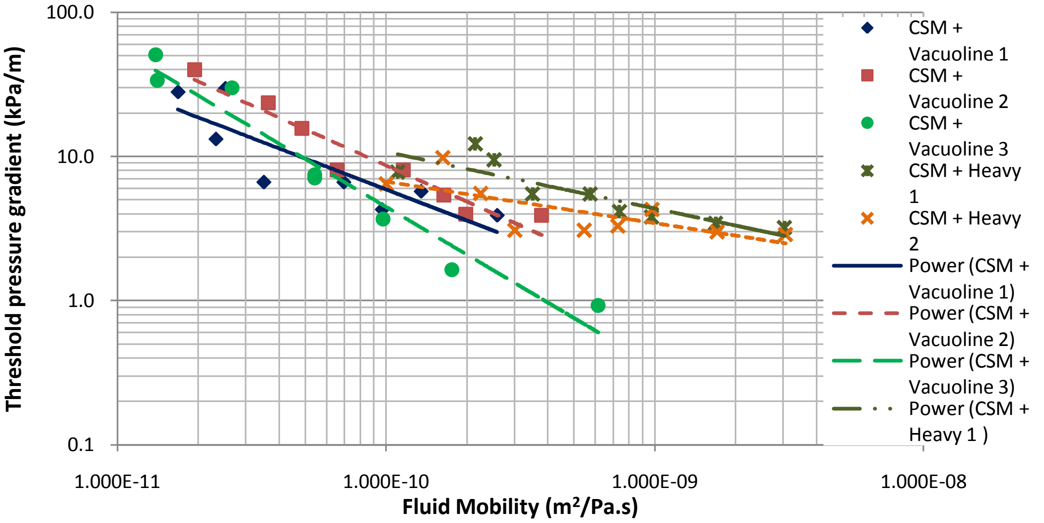

Figure 2: Plot of the threshold pressure gradient as a function of the fluid mobility.

CONCLUSIONS

A modified formulation of Darcy's law was presented including a threshold pressure gradient. An experimental program demonstrated existence of this threshold pressure gradient, the experiments show an existing residual pressure gradient that can be of significant magnitude. This confirms previous observations made in resin infusion and RTMLight experiments, an effect that should be considered in simulation of resin pressure and laminate thickness variation during post-filling.. The characterisation of the coefficients to determine the threshold pressure gradient proved difficult with the equipment available but further development of the setup can improve accuracy.

REFERENCES

1. P. Lunn. "Tooling materials ideal for resin infusion", *Reinforced Plastics*; 48(8). 28-30. (2004)
2. A. C. Loos, B. W. Grimsley, R. J. Cano, and P. Hubert. "VARTM processing of tailored composite structures for aerospace applications". In: *Proceedings of SAMPE Conference*. Long Beach, CA, United States, 2409-2423
3. Q. Govignon, S. Bickerton, J. Morris, and P. A. Kelly. "Full field monitoring of the resin flow and laminate properties during the resin infusion process", *Composites Part A: Applied Science and Manufacturing*; 39(9). 1412-1426. (2008)
4. Q. Govignon, S. Bickerton, and P. A. Kelly. "Simulation of the reinforcement compaction and resin flow during the complete resin infusion process", *Composites Part A: Applied Science and Manufacturing*; 41(1). 13. (2010)
5. B. Daval and S. Bickerton. "Exploring the potential for laminate quality control using VARTM". In: *Proceedings of 36th Int. SAMPE Technical Conference*. San Diego, CA, 15 - 18 November 2004.
6. J. Timms, Q. Govignon, S. Bickerton, and P. A. Kelly. "Observation from the Filling and Post-filling Stages of Axisymmetric Liquid Composite Moulding with Flexible Tooling". In: *Proceedings of 10th International Conference on Flow Processes in Composite Materials (FPCM10) Conference*. Monte Verita, Ascona, Switzerland,
7. A. Prada and F. Civan. "Modification of Darcy's law for the threshold pressure gradient", *Journal of Petroleum Science and Engineering*; 22(4). 237-240. (1999)
8. M. J. Buntain and S. Bickerton. "Compression flow permeability measurement: a continuous technique", *Composites Part A: Applied Science and Manufacturing*; 34(5). 445-457. (2003)
9. R. Umer, S. Bickerton, and A. Fernyhough. "Characterising wood fibre mats as reinforcements for liquid composite moulding processes", *Composites Part A: Applied Science and Manufacturing*; 38(2). 434-448. (2007)
10. Q. Govignon. "Monitoring and Simulation of the Filling and Post-filling Stages of the Resin Infusion Moulding". Department of Mechanical Engineering, The University of Auckland. *PhD Thesis* (2010)