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EXPERIMENTAL VALIDATION OF PRESSURE AND FILL-TIME FORMULATIONS FOR THE VACUUM INFUSION PROCESS

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SUMMARY: New experimental set-ups are presented for measuring the pressure profile and fill-times in the rectilinear and radial flow Vacuum Infusion (VI) processes. From these measurements, the validity of previously reported analytical formulations is investigated. The experimental results show a marked difference from analytical predictions at the start of injection. However, with flow progression, they change to match with analytical predictions. This observation is further supported by fill-times results. This phenomenon has not been observed previously and its analysis enhances the current understanding of the process physics, mainly the impact of compliance on the reinforcement thickness, fibre volume fraction and flow progression.

KEYWORDS: Polymer Composites, Vacuum Infusion, Liquid Composites Moulding

INTRODUCTION

Vacuum Infusion is a popular process for low volume production of large parts. The process uses a resin pressure gradient, created by evacuating the mould, to impregnate the porous preform. Due to the flexible mould top half, the fluid pressure balances off some of the compacting atmospheric pressure, leading to a dynamic mould cavity. The complexity of the process is increased as the preform flow properties such as the fibre volume fraction and permeability, which govern the pressure and velocity of the flowing resin, are thickness dependent. Hence, an improved understanding of the infusion stage, specifically the distribution of resin pressure and flow progression, is desirable to develop accurate mathematical and numerical models. Many authors [1-4] have reported analytical formulations, under limiting assumptions, for the rectilinear (or 1D) flow VI process. Modi [5] considered variation in flow-rate to derive a formulation (Eqn. (1)), without any limiting assumptions.

$$\frac{d^2P}{d\alpha^2} + \left[\frac{1}{K}\frac{dK}{dP} + \left(\frac{\phi+\alpha^2}{h\phi}\right)\frac{dh}{dP}\right]\left(\frac{dP}{d\alpha}\right)^2 = 0 \qquad (1)$$

Here, P is fluid pressure, K is reinforcement permeability, $\phi(=1-V_f)$ is reinforcement porosity, V_f is fibre volume fraction, $\alpha(=x/L)$ is non-dimensional distance, x is any position between injection gate and flow front, L is instantaneous flow front position and h is mould thickness. The author also developed a new analytical formulation for the radial flow VI process (Eqn. (2)).

$$\frac{d^2P}{d\alpha^2} + \left[\frac{1}{K}\frac{dK}{dP} + \left(\frac{\phi+\alpha^2}{h\phi}\right)\frac{dh}{dP}\right]\left(\frac{dP}{d\alpha}\right)^2 + \left[\frac{(R-r_{inj})}{r_{inj}+\alpha\,(R-r_{inj})}\right]\frac{dP}{d\alpha} = 0 \qquad (2)$$

Here, R is the instantaneous flow front position, r_{inj} is the injection gate radius, $\alpha=(r-r_{inj})/(R-r_{inj})$ is non-dimensional distance, and r is any position between injection gate and flow front. The relationships defining the dependence of permeability and thickness on fluid pressure were derived using the Kozeny-Carman equation and the empirical model suggested by

Robitaille and Gauvin [6]. For VI, Modi suggested that saturated expansion experiments should be used to estimate the values of compliance behaviour empirical constants. As the pressure formulations (Eqns. (1) and (2)) were coupled equations, their solutions were found using numerical methods. In addition, Modi [5] also showed that, for both 1D and 2D flow processes, the ratio of RTM and VI fill-times remains constant with flow progression.

Correia [4] measured pressure profiles and fill-times to validate his analytical formulation for a 1D flow VI process. The numerical results of the analytical formulation compared well with experimental results, and for the first time, demonstrated the pressure profile in a 1D flow VI process to be non-linear as suggested by various formulations. In his experiments, Correia [4] measured fluid pressure at four locations only, including at the injection gate and the vent, to generate the non-linear pressure profile. By using more pressure transducers, one can increase the accuracy and also, determine the evolution of the pressure profile with flow progression. This paper presents new experimental set-ups for continually measuring the pressure profile and fill-times in 1D and 2D, unsaturated flow VI processes. The validity of analytical formulations is also investigated through comparison with experimental results.

EXPERIMENTAL SET-UP

Rectilinear (1D) Flow Set-up

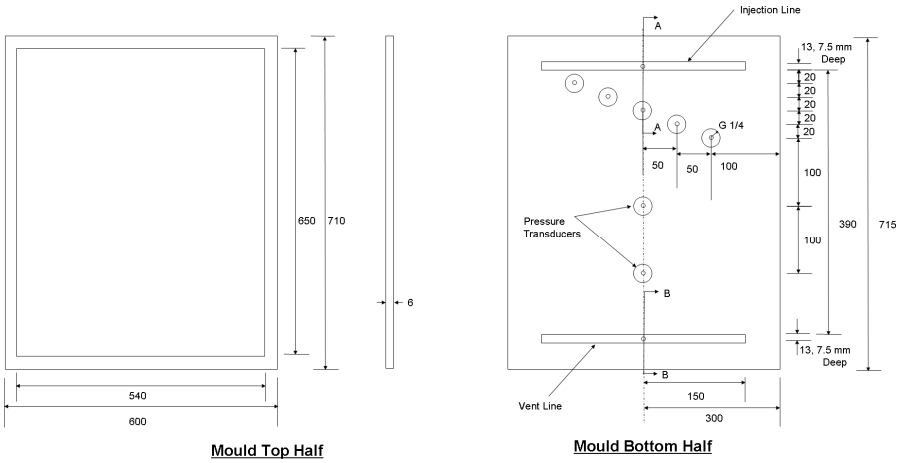


Figure 1 Experimental set-up for the rectilinear (1D) flow VI process.

In the new set-up, the top half was made from an aluminium frame (Figure 1) Using a sealant tape, a flexible polymeric bag was attached to the top side of this frame, while a `P' shaped draught excluder was attached its mould side. The use of a draught excluder allows a flexible mould sealing arrangement to be made for easy, fast and repeatable experiments. After placing the reinforcement on the mould bottom half, made from a 25 mm thick clear perspex sheet, it was covered with the mould top half. The transducers (RS Components Ltd, UK, Part No: 348-8093), with a housing diameter of 25 mm, need to be spaced apart by at least 50 mm to allow easy installation and removal. A total of eight transducers, including one at the injection and the vent lines, were used in the mould such that at least five of them were in the first 100 mm of the infused length. In addition, to ensure faster sensing of fluid arrival at any pressure transducer, a liner was placed inside each transducer pressure port. To create exact injection conditions, a groove was cut in the mould. A ‘C’ shaped channel, with a centre hole for fluid injection, was placed inside this groove and its height was set such that its open section remained in line with the reinforcement. Then, starting the vacuum pump evacuated the mould, driving infusing fluid through the injection line.

Radial (2D) Flow Set-up

In this case also, the design philosophy for experimental set-up was identical to 1-D flow case. To prevent the vacuum bag from blocking the injection gate by sagging into it, a small, rigid piece of plastic (2 mm thick) was placed between the reinforcement and the plastic bag, directly above the

injection gate. A centre hole, of 5 mm radius, was cut into the reinforcement to create uniform plug-flow injection conditions.

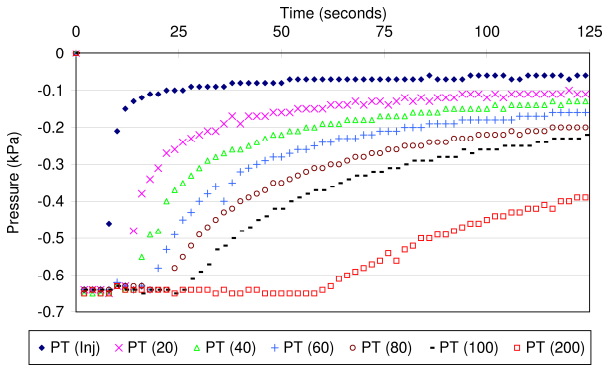
Before the start of experiments, all transducers were calibrated for the full pressure range. In all experiments, the injection and vent pressure was maintained at 95 kPa and 35 kPa- absolute, respectively, while the atmospheric pressure was assumed to be 100 kPa - absolute. Thus, the maximum driving pressure was 60 kPa, while the maximum and minimum compaction pressures were 65 kPa and 5 kPa, respectively. A computer connected through a data acquisition box logged the transducer readings at a sampling frequency of 10 Hz. All the experiments were recorded with a digital camera at a rate of 30 frames per second, with images analysed manually to calculate fill-times. In total, four experiments each, for both 1D and 2D flow cases were performed using a continuous filament random mat (Unifilo U750/375, 0.375 Kg m^{-2}, 4 layers). The infusing fluid (hydraulic oil, HDX 30, Trent Oil Ltd., UK) was drawn from a bucket, using a 0.5 metre long plastic injection pipe. All infusion experiments were performed in a climate controlled room with a set temperature of 18 ^{0}C. A Brookfield rheometer (model DV-II) was used to measure the viscosity at this temperature, providing a value of 0.3 Pa S, which was used for comparing the experimental and predicted fill-times results.

RESULTS AND DISCUSSION

Pressure Profile Results

Figure 2 shows typical results of pressure measurements in 1D and 2D flow VI processes. It is clear that in the 1D flow process, realisation of the full injection pressure is not immediate at the start of injection but needs some time. Correia [4] reported similar results and showed that the rise in the injection pressure depends on the reinforcement permeability and the flow resistance in the injection pipe. The immediate rise in injection pressure in 2D flow experiments shows that type of flow is also important.

a) Rectilinear Flow



b) Radial Flow

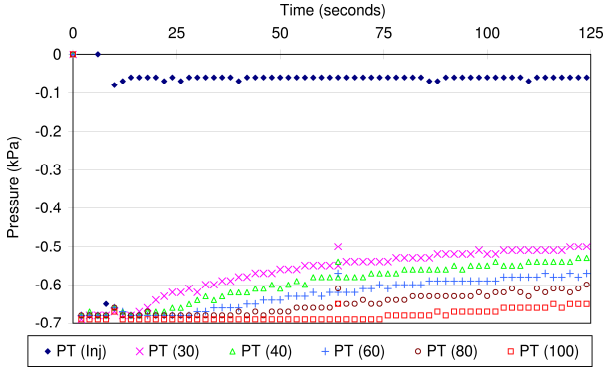


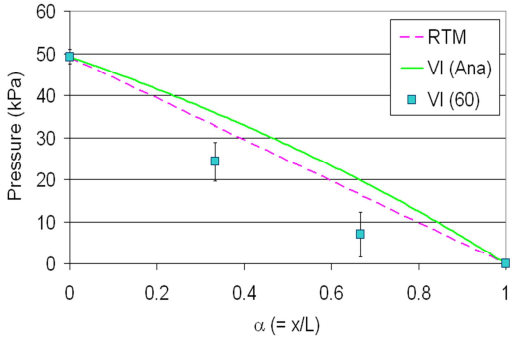
Figure 2 Pressure Measurements in 1D and 2D flow VI processes. The location of any pressure transducer (PT) from the injection gate is signified by the number in brackets (mm).

Figures 3 and 4 show an average pressure profile and its evolution with flow progression in 1D and 2D flow VI processes, along with the scatter in results from four identical experiments. The RTM and VI pressure profiles were calculated using Eqns. (3)-(4) and Eqns. (1)-(2), respectively. The injection pressure was assumed to be equal to the instantaneous experimental injection pressure, while the compaction pressure was taken as the difference between the fluid pressure and the atmospheric pressure. In addition, the values of compliance behaviour constants in the empirical model suggested by Robitaille and Gauvin [6] were taken from saturated expansion experiments [4].

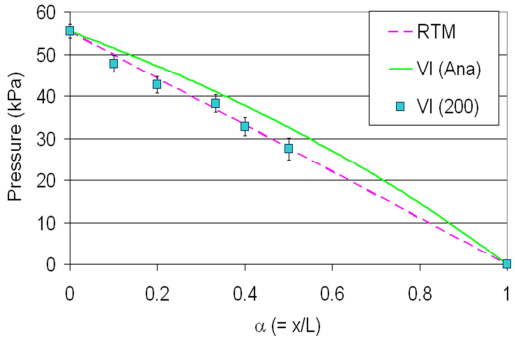
$$\text{1D Flow}: \quad P = P_{inj}\left(1 - \frac{x}{L}\right) \quad \text{and} \quad t_{RTM} = \frac{\mu\phi L^2}{2K\Delta P} \tag{3}$$

$$\text{2D Flow}: \quad P = P_{inj}\left(\frac{ln\left(\frac{r}{R}\right)}{ln\left(\frac{r_{inj}}{R}\right)}\right) \quad \text{and} \quad t_{RTM} = \frac{\mu\phi}{2K\Delta P}\left[R^2 \ln\left(\frac{R}{r_{inj}}\right) - \frac{1}{2}\left(R^2 - r_{inj}^2\right)\right] \tag{4}$$

a) Infused Length = 60 mm



b) Infused Length = 200 mm



c) Infused Length = 300 mm

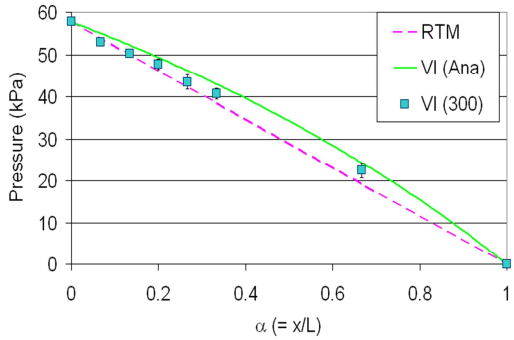
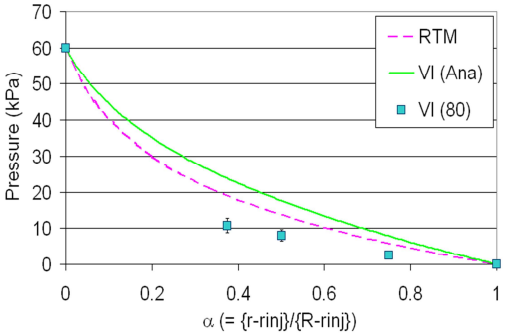
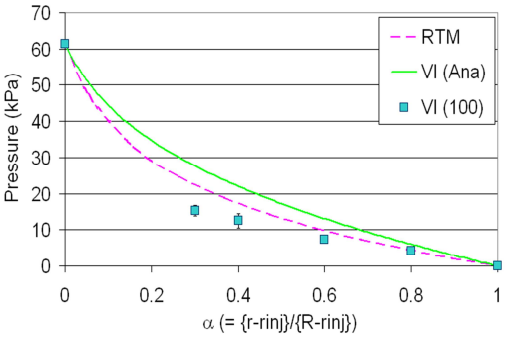


Figure 3 Pressure profile evolution with flow progression in the rectilinear flow VI experiments.

a) Infused Length = 80 mm



b) Infused Length = 100 mm



c) Infused Length = 160 mm

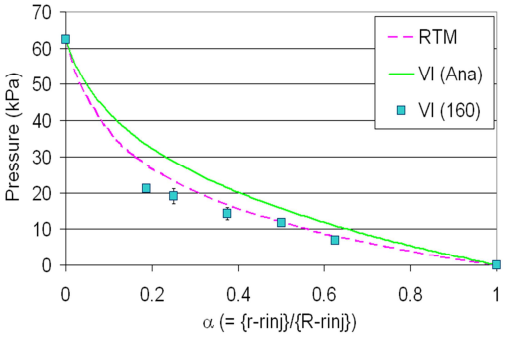


Figure 4 Pressure profile evolution with flow progression in the radial flow VI experiments.

In both flow processes, the initial pressure profile in the filled region is below the RTM analytical pressure profile (Figure 3-a, Figure 4-a). Furthermore, with flow progression, the pressure profile in the 1D flow process levels with the RTM pressure profile (Figure 3-b) before rising above it to give a non-linear pressure profile (Figure 3-c). In radial flow, although the pressure profile has not risen to match with analytical predictions, a trend similar to 1D flow experiments is observed (Figures 4-b, c). This dynamic behaviour in pressure profiles is contrary to one's expectation.

Fill-times Results

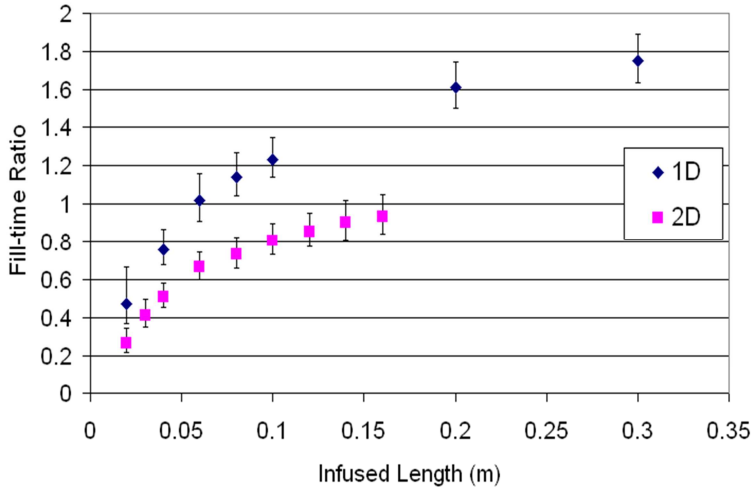


Figure 5 RTM vs. VI fill-times ratios with flow progression in 1D and 2D flow processes.

Figure 5 shows fill-times ratio with flow progression for 1D and 2D flow processes along with scatter from four experiments. RTM fill-times were calculated using Eqns. (3) and (4). For this, the values of compliance behaviour empirical constants were taken from dry compaction experiments [4], while the compaction pressure and the reinforcement permeability were taken to be 65 kPa and $10^{-9}\ m^2$, respectively [7].

It is clear that contrary to analytical predictions of constant fill-times ratio, it changes in both processes. Correia [4] reported similar results for 1D flow and attributed it to the variation in injection pressure. However, 2D flow experiments, where full injection pressure is realised at the start of injection, also exhibit a similar variation. Hence, it can be concluded that variation in the pressure profile rather than variation in the injection pressure is responsible for this behaviour. As a result, the VI fill-times for 1D flow will not vary with square of the infused length, while for 2D flow, the fill-times will not vary in a similar fashion with flow progression as in RTM. In addition, as the pressure profile in 1D flow VI converges towards the analytical prediction, the fill-times ratio also converges to a single value. For 2D flow VI, although the pressure profile in VI is below RTM, it is reasonable to expect that once it converges to analytical prediction, it will lead to a convergence in the fill-times ratio. Furthermore, it is clear that the experimental fill-times ratio depends on the assumed value of reinforcement permeability for RTM fill-times calculations in Eqns.(3) -(4). This is the reason behind the difference in absolute values of analytical [5] and experimental fill-times ratios (Figure 5).

Discussion

As experimental results show a rising behaviour that leads to converging pressure profiles towards analytical solutions, derived using conservation of mass law and Darcy's law without any limiting assumptions [5], the validity of analytical solutions can be assumed. Then, it can be concluded that the observed pressure profile variation is a consequence of the process physics. As the analytical pressure formulations did not show any transient terms, the variation in the pressure profile can only be explained through the reinforcement compliance behaviour. In the compliance characterisation experiments [4], first a pre-wetted reinforcement was compacted to the required degree between two solid tool surfaces. During this phase, extra fluid in the intra-tow and inter-tow spaces was forced out.

Then, during the expansion phase, the tools were moved apart mechanically to remove the compaction pressure. However, no fluid was available at this stage to fill the empty spaces created due to the reinforcement expansion. Hence, it can be concluded that during the expansion phase, a significant proportion of the load was supported by the reinforcement.

In the actual VI process, the flexible bag is supported at the fibre/tow contact points, while it sags (i.e. is pulled or deformed) into in the inter-tow spaces. The reinforcement compaction is also due to this sagging and the related tension in the plastic bag. After fibre wetting and compaction due to the arrival of fluid, the rising fluid pressure acts against the atmospheric compaction pressure. In addition, it also reduces the bag sagging, leading to a further reduction in reinforcement compaction. It is clear that at least some, if not all, of the compaction pressure is supported by the infiltrating fluid. In addition, the stresses in the plastic bag may be important. This difference in events may lead to a different compliance behaviour, possibly resulting in a different empirical model that will enable one to explain the rising pressure profile in both the flow cases. However, it is clear that to verify this hypothesis, one will need to conduct a new set of compliance characterisation experiments.

CONCLUSIONS

Using new experimental set-ups, pressure profiles, their evolution and fill-times were measured in 1D and 2D unsaturated flow VI processes. These new set-ups employed eight pressure transducers. The results showed that, in 1D flow VI process, the full injection pressure is not realised immediately. Also, the pressure profile is initially lower than the RTM pressure profile. With flow progression, it rises to level with and ultimately exceed the RTM pressure profile. A similar trend is also observed in 2D flow VI process, even though full injection pressure is realised at the start of the injection. This is in contrast to analytical formulations, which suggest that the fluid pressure profile should remain constant or move in a similar direction as the corresponding RTM profile. It is concluded that this variation in the pressure profile is an integral part of the process physics. It was hypothesised that the time-dependent pressure profile evolution is due to the difference in events in the reinforcement compliance characterisation and actual VI experiments. In direct relation to the pressure profile evolution, fill-times results also showed variable RTM vs. VI fill-times ratio for both 1D and 2D flow VI processes.

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