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Monitoring and Simulation of the Filling and Post-filling Stages of the Resin Infusion Process

by

Quentin Paul Nicéphore Marc Marie Govignon

The doctoral research presented in this thesis is focused on the resin infusion moulding process. The resin infusion process is part of the liquid composite moulding family where a dry reinforcement is impregnated with a liquid resin inside a closed mould to form a composite part. The specificity of resin infusion resides in the fact that only one side of the mould is rigid, the cavity being sealed by a vacuum bag. The preform compaction and fluid flow are driven by the pressure difference between the cavity and the ambient pressure. The reinforcement can therefore exhibit through thickness deformation as the resin penetrates the cavity. The aim of the research was to monitor and simulate the process. A number of previous studies have considered the impregnation process, but very little work had focused on the post-filling stage of the process, once the resin inlet is closed and the resin pressure field inside the mould is left to equilibrate.

In the first part of this study, the behaviour of two different fibrous reinforcements was experimentally characterised, and a new model was developed to replicate the compaction behaviour of the reinforcements. This model is based on elastic behaviour, but was able to account for the compaction history of the reinforcement.

A comprehensive monitoring system was designed and built to collect relevant experimental data to be compared with the simulation. This included
the development of a mould fitted with sensors, as well as a stereophotogrammetry system which provides full field monitoring of variations in reinforcement properties. This system measures local cavity thickness, allowing calculation of other parameters such as fibre volume fraction and permeability.

A 1D finite element simulation of the resin infusion process is subsequently presented. The simulation covers both the filling and post-filling stages of the process and uses a modified version of Darcy’s law to govern the flow of fluid through porous media.

Finally, an investigation of different factors affecting the post-filing is presented through both simulation and experimental evaluations.
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Chapter 1 INTRODUCTION

1.1 Composite Material

Composite Materials are by definition composed of at least two phases: the reinforcing phase (most often a fibrous reinforcement) and the binding phase, called matrix. These materials provide many advantages over the traditional materials such as metals, non reinforced plastics, ceramics or wood: they can be lighter, stronger, and have a better chemical resistance. They can have an improved fire resistance, a better thermal, electric or sound insulation. The manufacturing processes of composite materials enables the manufacture of complex functional shapes. The possibility of orienting the reinforcement also allows designing the material to directionally carry the loads in an application. Composite materials are used to improve performance or reduce weight compared to traditional materials; combining two or more materials together so that the resulting material has better properties than both its components.

CM can be divided by the type of matrix used; composites with a polymer, ceramic or metallic matrix. In this study we will only look at polymer matrix composites. These composites can again be divided between thermoplastic (TP) and thermoset (TS) matrices. TP matrices have a high viscosity and can be melted and reprocessed. TS matrices have a low viscosity but cannot be reprocessed once the thermoset cure reaction is complete.

For a given matrix and reinforcement, the quality of a composite can be described through the void content and fibre volume fraction ($V_f$). The void
content or porosity describes the amount of void and dry spots in the laminate. These are tiny defects, on the scale of a few microns to a couple of millimetres, which affect the mechanical properties of the composite by creating zones of local stress concentration. The $V_f$ represents the amount of fibre per unit of volume. In general a higher $V_f$ means higher mechanical properties, but in some cases, a lower $V_f$ can be desirable to increase the laminate thickness and achieve a stronger bending stiffness with the same amount of reinforcement. The $V_f$ and void content are influenced by the manufacturing process applied. Typically the operator has very little control over the void content, and the only aim is to minimise it. The $V_f$ on the other hand, depending on the chosen manufacturing process, can more or less be controlled to tailor the resulting composite material’s properties. A large part of this thesis is focused on predicting the $V_f$ evolution during the RI process.

Figure 1-1: A formula 1 car uses a significant amount of composite materials.

Typical areas of application of polymer composites are very wide and growing, from high-tech sports and leisure (Figure 1-1 and Figure 1-2) to art, from medical equipment to civil engineering, and from transportation to household equipment [1]. Polymer composite products range from mass produced short fibre reinforced thermoplastic components, to parts composed of high tech carbon or basalt fibre reinforced thermoset matrices.
Different applications make use of the various characteristics of composite materials. For medical equipment, the most sought after characteristics are resistance to corrosion as well as improved rigidity and weight savings. In the automotive industry the desired characteristics are the ability to manufacture complex shapes and integrate functions into the designed structure, as well as weight savings. In the construction and civil engineering industry, improved mechanical properties, thermal insulation, waterproofing ability and resistance to corrosion are crucial, and the ability to manufacture complex shapes allows for more creativity from architects. Composite materials are used in the electrical industry as they are lightweight, can provide electrical and thermal insulation, can have good fire retardancy properties and do not interfere with electro-magnetical fields. The use of composite materials is continuously increasing in the aeronautical industry in a drive to reduce weight and save on fuel for commercial aircraft such as the Airbus A350 on the left in Figure 1-3, or to increase performance of private planes such as the New Zealand made Furio on the right in Figure 1-3.
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Figure 1-3: The Airbus A350 (left) and the New Zealand made Furio (right) are examples of increased use of composites in the aeronautical industry.

1.2 Description of LCM Processes

The term Liquid Composite Moulding (LCM) describes a number of manufacturing processes where a dry fibrous preform is placed into a mould and then impregnated with a liquid polymeric resin. These processes provide good control over harmful volatile organic compounds generated by thermoset resins, making these processes compliant with the tougher new environmental standards put in place in many parts of the world. By placing the dry reinforcement in an open mould, the quantity and orientation of the fibres can be precisely controlled. By applying vacuum to the cavity, the porosity of the final part can be greatly reduced. The final $V_f$ achieved using LCM processes can be higher and more consistent than with more traditional open mould techniques.

There are four main LCM processes, all having some variations (RTM, I/CM, RTMLight and RI). The Resin Transfer Moulding (RTM) process, as schematically described in Figure 1-4, is the most simple to understand and model. The fibrous reinforcement or preform is enclosed in a rigid mould, and resin is injected through one or more injection ports. The moulds used for RTM are heavy and expensive, and the process often requires a press to close the mould. As the part grows larger, a bigger press is required and the cost
increases very quickly; the injection pressures may also dramatically increase with the dimension of the part to be manufactured. Due to the tooling cost, RTM is preferable for large manufacturing quantities of small to medium dimension parts. Having two or more rigid matched mould pieces enables production of parts with very tight geometrical tolerances, and good surface finish on all exterior surfaces.

![Figure 1-4: Steps in the RTM process](image1)

The RTMLight process is a variation of RTM where the B side mould is semi-rigid and can deform during the process. Steps in the RTM/Light process are described in Figure 1-5. The mould is usually closed using mechanical fasteners thus greatly reducing equipment costs. However as the part gets bigger, the stresses applied on the mould by the preform and the resin pressure gets larger, and deflection of the upper mould increases. The tooling cost for
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RTMLight is greatly reduced compared to RTM as the upper mould is much cheaper to manufacture. However due to the flexibility of the upper mould the geometrical tolerances of the part have to be increased. Also the upper mould is more subject to wear and is more suitable for medium quantity production runs.

![Diagram](image1)

Figure 1-5: Steps in the RTM/Light process

Injection/Compression Moulding, schematically described in Figure 1-6, is another variation of RTM, in which the rigid upper mould is partially closed maintaining a given cavity thickness greater than the final part thickness. The desired quantity of resin is then injected. Finally the mould is closed to its final position, compacting the preform to its final thickness, and establishing a compression driven flow pushing the resin into the un-impregnated portions of the preform. This process takes advantage of the higher permeability of the reinforcement when compacted at a lower $V_f$ in order to reduce the cycle time.
The I/CM process can allow for much faster cycle times than classical RTM with an increase in the forces applied to the mould, or on the other hand can reduce the forces needed while keeping the cycle time constant [2]. As for RTM the geometric tolerances achievable with this process can be very tight.

Figure 1-6: Steps in the I/CM process
1.3 Description of the Resin Infusion Process

Resin Infusion (RI) is also known as the Vacuum Assisted Resin Transfer Moulding (VARTM) process, Vacuum Assisted Resin Infusion (VARI), and Seeman’s Composite Resin Infusion Moulding Process (SCRIMP). In this process or “sub-family” of processes, there is only one rigid mould side. The B side is a flexible membrane sealed on the edges of the A side mould. In this process, the preform is compacted by evacuating the cavity and using the pressure differential with the ambient pressure. As the A side mould is subject to very little stress, the tooling costs are greatly reduced. As the vacuum bag employed during the process provides minimal rigidity, the preform thickness will vary in relation to the pressure inside the cavity, and so will the reinforcement permeability which is governed by the local reinforcement architecture. Figure 1-7 describes the components required for application of RI, and the different process stages. Initially, layers of fibrous reinforcement are laid on the mould to create the preform. A layer of peel-ply is generally laid over the preform, allowing for easy separation of the part from the consumables, and provision for a consistent part surface finish. Distribution media can be laid over the peel-ply to enhance resin flow if the reinforcement has low in-plane permeability.

Once the inlet(s) and vacuum port(s) are in place, the mould is closed using a vacuum bag sealed with sealant tape. With the cavity sealed, the inlet is clamped and vacuum is applied to the vents, this stage being referred to throughout this thesis as “pre-filling”. At the end of pre-filling, the inlet is opened and the resin penetrates the preform. During this “filling stage”, pressure inside the cavity varies in position and time. Once the resin front reaches the end of the preform, the inlet is usually clamped, stopping flow of resin into the cavity while the vents are maintained at a prescribed vacuum pressure. This “post-filling” stage involves removal of excess resin, and allows resin pressure and laminate thickness to equilibrate within the cavity. Once the resin is fully cured,
the vacuum is released and the part is lifted from the mould and separated from the consumables.

Figure 1-7: Steps in the RI process
During the full RI process the reinforcement comprising the preform is subjected to a complex deformation history that will be discussed in detail in Section 3.2.1.

### 1.4 Industrial Application of the Resin Infusion Process

![Figure 1-8: Domain of application of the resin infusion process (source ASM [3]).](image)

As the compaction of the reinforcement is achieved using only vacuum, the moulds used for RI are subject to very little stress and can be manufactured much lighter and more easily out of polymer composite materials than for RTM or I/CM. Due to the relatively low initial cost of RI tooling, this process is particularly suitable for small to medium manufacturing runs as well as for medium to very large parts. The price of the consumables however increases the production prices for larger runs. RI technology is quite easily applicable as
an upgrade from wet hand lay-up, as hand lay-up moulds can be easily adapted. Figure 1-8 presents regions of application of different composite production techniques as a function of the achieved performance and production volumes. SMC stands for Sheet moulding compounds, GMT glass mat thermoplastics, SRIM is the structural reaction injection moulding process, and Low P/T stands for low pressure and temperature out of autoclave processing.

The boat building industry is particularly interested in RI as this process allows manufacturing a complete hull in one shot (as shown in Figure 1-9) with very little change to the mould used for wet hand lay-up or gun roving spraying, while also complying with the stricter new environmental rules concerning harmful VOC. This process may also increase the quality and repeatability of production.
a)

Figure 1-9: Infusion of the hull of a 68ft motor yacht.

The RI process is also widely used for manufacturing wind turbine blades (Figure 1-10), and in the building industry to realise large lightweight wall panels. In the automotive industry RI is often used to manufacture large body parts for trucks, trains and buses [1, 4].
In recent years with the development of knowledge and control over the process, the aerospace industry has been increasingly interested in out of autoclave techniques and particularly RI, for mould construction but also for manufacturing of parts, in a drive to reduce costs [5, 6].

1.5 Motivation for Numerical Simulation

During manufacture with an LCM process, the operator typically has little control over the advancement of the flow, and successful process development by trial and error requires experience and can be long and expensive. Reduction of development costs requires a good understanding of the process physics, and can benefit from development of an accurate simulation tool. Significant effort has been placed into establishment of RTM and I/CM simulations that accurately predict fill time, flow front advancement and dry spot formation [7-16]. These two processes, through the use of rigid mould tools, allow for accurate control of the laminate thickness and therefore the fibre volume fraction. Current rigid tool simulations can take into account localised phenomena [17-19], predict tooling forces [2, 15], and allow for automated process control via integrated sensing and simulation technology [20, 21]. The accuracy of these tools is dependant on the quality of provided permeability data, permeability quantifying the resistance to resin flow provided by the reinforcement materials comprising the preform. Research is ongoing into accurate measurement and prediction of reinforcement permeability [22-26].
As opposed to the RTM and I/CM processes, RI uses a single sided mould, the reinforcement being contained within a cavity formed and sealed by a vacuum bag. As the vacuum bag employed during the process provides minimal rigidity, the compaction of the fibrous reinforcement is governed by the pressure difference between the inside of the cavity and the external atmospheric pressure. The preform thickness will vary in relation to the resin pressure inside the cavity [27-31], and so will the reinforcement permeability which is governed by the local reinforcement architecture. The understanding and modelling of this coupling between preform compaction and resin flow is necessary to be able to accurately predict mould filling time and model the post-filling period in order to be able to control the final part quality after post-filling and cure of the resin.

1.6 Goals and Topics of Study

This thesis is focused on the RI process. The aim has been to both monitor and model the complete process, including the post-filling phase. The focus will be on the evolution of the laminate quality throughout the process. For this purpose a new reinforcement compaction model has been developed after experimentally studying two reinforcements often used with the RI process.

To monitor the evolution of laminate quality during the RI process, a new experimental monitoring setup has been developed including new moulds and a stereophotogrammetry system. Series of experiments are presented, addressing both the filling and post-filling stages of the RI process.

A one dimensional finite element simulation program has been developed to compare with the experiments. The differences between the experimental and predicted results call for some modifications of Darcy’s law, particularly for the post-filling stage. These modifications have been applied to the numerical model, resulting in increased accuracy of predictions.
1.7 Thesis Outline

An overview of the current state of the art in resin infusion monitoring and simulation is presented in Chapter 2; this chapter explains and analyses the efforts of research groups from all over the world to improve the knowledge of, and simulation tools for the resin infusion process.

Chapter 3 focuses on the characterisation of the materials used in this study. Of particular interest is the development of a new model for the compaction behaviour of the fibrous reinforcements during the resin infusion process.

Chapter 4 concentrates on resin infusion monitoring, with development of new mould and thickness monitoring capabilities. This chapter also provides data from a resin infusion test during both the filling and post-filling stages.

Chapter 5 deals with the development of a new one dimensional finite element simulation of the resin infusion process including coupling between flow and fibre compaction. The novel compaction model developed in Chapter 2 is implemented, this simulation providing prediction for both the filling and post-filling stages of the process.

Chapter 6 provides a case study where four different infusion scenarios are tested to investigate the influence of various factors on the post-filling. Both experimental and simulation results are compared side by side as a demonstration of the capabilities of the simulation.

Finally Chapter 7 summarises the thesis, draws conclusions and presents opportunities for further research work.
Chapter 2 Literature Review

There already exists a significant body of available literature regarding the LCM processes in general and the Resin Infusion process in particular. It is therefore advisable to undertake an initial review of the literature to gain an understanding of the theoretical knowledge as well as practical procedures and issues, before attempting to characterise and simulate the resin infusion process.

This chapter is divided into five main sections each addressing separate topics relevant to the study presented in this thesis. At first a general description of the resin infusion process will be considered along with different experimental monitoring techniques. In section 2.2, the mathematical theory of the RI process as used in this project will be presented. Section 2.3 will present various methods used to characterise fibrous reinforcement, both its compaction and permeability behaviour. Section 2.4 will look at previous attempts to simulate the RI process. Finally, in Section 2.5, some papers not related to the composite manufacturing processes, but relating to some modifications to Darcy’s law for fluids with a high viscosity, or in flow with a low pressure gradient will be presented.
2.1 Experimental Monitoring of the Resin Infusion Process

To first understand the different variations of the resin infusion process, it can be interesting to read the papers by Williams et al. [31] or Marsh [32] describing the different soft mould processes.

A number of experimental studies have been published, developing setups to monitor the RI process and changes in laminate properties during the process. This section will comment on a selection of these presented techniques. In [29], Hammami and Gebart analysed the RI process by only monitoring the flow front progression. However as the B side mould provides no rigidity (being a vacuum bag), the laminate compaction and properties can change as the pressure difference between the cavity and atmosphere is constantly changing. It is therefore valuable to monitor these changes by recording the fluid pressure within the laminate, and the laminate thickness.

In [33], Grimsley et al. used LVDT (Linear Variable Differential Transformers) sensors to measure the laminate thickness and pressure transducers to monitor the fluid pressure inside the laminate. In their infusion tests, the authors used a layer of flow enhancing media on top of the laminate. The resin front was therefore faster at the top of the laminate than at the bottom. To determine the position of the front on the mould surface, the authors used the pressure transducers, local pressure starting to increase once the flow front had passed the location of the transducer. However, this technique was limited by the number of pressure transducers used. Furthermore only the very top and bottom flow front could be monitored, with no indication of the shape of the front through the thickness.

In [34], Andersson et al. used some coloured marks to evaluate the progression of the flow through the thickness. This technique was based on the fact that the glass fabric becomes translucent once saturated with resin. As the through thickness flow goes from the top towards the bottom, by placing different coloured marker through the thickness of the laminate, each marker
would appear as all layers above became saturated and therefore translucent. Through this setup, the authors were able to gain a better understanding of the through thickness flow when using flow enhancing layers on top of the structural reinforcement.

Two methods of tracking the flow front were presented in [35]; Luthy and Ermanni used the linear direct current (LDC) sensing technique as well as ultrasound sensors to localize and track the flow front. These techniques showed promising results and are well adapted to the closed moulding processes when no optical tracking of the flow can be performed. One can also use the LDC technique to follow the curing of the resin. In resin infusion with the use of a transparent vacuum bag as the B side tool, optical tracking of the flow front might be considered an easier and cheaper solution.

In [36], Modi et al. used a webcam and image analysis processed with MATLAB to monitor the flow front in real-time, in order to implement an active control of the Infusion process. Using the webcam as a cheap image acquisition method, and making use of the built in image analysis toolbox of MATLAB, the images were easily filtered and binarized using the changing optical properties of the glass reinforcement to evaluate the shape of the flow front.

In [37], Tackitt and Walsh used an array of LVDTs to monitor the thickness variation during infusion and associated it with the SMARTweave sensor system to monitor the flow front position. The LVDTs are contact sensors and might therefore affect the measurement; furthermore a large number of sensors are required to allow measurement over an entire preform. To prevent the tip of the LVDT from indenting on the preform and therefore affecting the measurement, small lightweight square plates were placed under the tip of the LVDTs. The SMARTweave sensors need to be embedded in the laminate, and might therefore affect the fluid flow and preform compaction, and may also prove a costly consumable if used with resin.

In [38], Daval and Bickerton used laser gauges to measure the laminate thickness at three points along the laminate as well as three pressure transducers to record the fluid pressure at the same positions. The use of laser
gauges provided the advantage of being a non contact measurement, but these were still point measurements, limiting the amount of data available. Yenilmez et al. in [39] and Williams et al. in [40] used a similar kind of setup but replacing the laser gauges with LVDTs. By measuring the laminate thickness and fluid pressure at the same location, it is then possible to evaluate the compaction behaviour of the reinforcement during the infusion experiment and compare it to other reinforcement characterisation tests. But although the compaction behaviour was characterised in [39] using rigid tooling, they did not compare those results with results extracted from the RI experiments.

In [41], Anderson et al. utilised a speckle photography technique to measure the thickness variation. This technique offers the double advantage of being a non contact measurement method as well as providing measurement over a whole surface instead of a limited number of points. The accuracy reached by this system was claimed to be less than 10 microns of out of plane displacement, when measuring over a square area of 250 mm side length.

In [42], Li et al. utilized a 3D laser digitizer to monitor the dynamic thickness changes. In their experiments they focused solely on the laminate thickness and the thickness gradient between the inlet and vent, and are one of the rare published studies addressing the post-filling stage of the RI process. Kessels in [43] used a laser gauge mounted on a sliding rail for a similar purpose.

From the literature, it can be established that the fluid pressure and laminate thickness are key parameters to be measured in addition to monitoring the flow front position. It is desirable to measure the thickness through non contact method, and measuring the thickness over the entire laminate will provide much more information than at single points. No system was found to provide measurement of the fluid pressure over the entire mould surface, and care must be taken not to disturb too much the flow when using pressure transducers. Few publications presented studies on post-filling, it is a part of the process still not well understood and that requires more investigation.
2.2 Theory of the Resin Infusion Process

2.2.1 Continuity Equations

2.2.1.a Conservation of Solid Mass

The porosity ($\phi$) is the measure of the volume of interstitial space in a unit volume of a porous medium. Porosity is defined as:

$$\phi = \frac{V_{\text{voids}}}{V_{\text{voids}} + V_{\text{solid}}} = \frac{V_{\text{voids}}}{V_{\text{total}}}, \quad 0 \leq \phi \leq 1. \quad (2-1)$$

The fibre volume fraction ($V_f$) of a preform represents the fraction of solid per unit volume. It is defined in a similar way to porosity:

$$V_f = \frac{V_{\text{solids}}}{V_{\text{voids}} + V_{\text{solid}}} = \frac{V_{\text{solids}}}{V_{\text{total}}}, \quad 0 \leq V_f \leq 1. \quad (2-2)$$

Therefore:

$$V_f + \phi = 1 \quad \text{or} \quad V_f = 1 - \phi. \quad (2-3)$$

Defining $h_0$ and $V_{f0}$ as respectively the thickness and volume fraction of a preform submitted to zero compaction stress; the assumption that the fibres in the preform are incompressible and that the compaction does not cause strain in directions perpendicular to the loading axis, leads to:

$$\rho_f \cdot h_0 \cdot V_{f0} = \rho_f \cdot h \cdot V_f, \quad (2-4)$$

with $\rho_f$ the density of the fibre, and $h$ and $V_f$ the thickness and volume fraction of the preform under any given compaction stress. The Equation of conservation of solid mass (2-4) can then be reformulated as:

$$\frac{V_{f0}}{V_f} = \frac{h}{h_0}. \quad (2-5)$$


2.2.1.\textit{b} Conservation of Fluid Mass

Consider a one-dimensional flow of fluid through a porous medium as illustrated in Figure 2-1. The fluid is assumed incompressible, and therefore its density remains constant.

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{fig2-1.png}
\caption{Diagram of one-dimensional flow through porous media.}
\end{figure}

\(Q_x\) is the volume flow rate of the fluid. \(q_x\) is the volume-averaged velocity of the fluid, also called the Darcy velocity or superficial velocity, which takes into account the porosity of the porous medium. The Darcy velocity is equivalent to the flow rate divided by the cross section area of the porous media. If the flow rate is considered constant during a time \(\Delta t\), the volume of fluid flowing in and out of an elemental volume can be expressed respectively by:

\begin{align}
Q_x(x,t) \cdot \Delta t &= q_x(x,t) \cdot h(x,t) \cdot \Delta t, \quad (2-6) \\
Q_x(x + \Delta x,t) \cdot \Delta t &= q_x(x + \Delta x,t) \cdot h(x + \Delta x,t) \cdot \Delta t. \quad (2-7)
\end{align}

The change of porous volume \((\Delta V_{\text{pores}})\) inside the elemental volume of porous media during the time \(\Delta t\) can be expressed as:

\begin{align}
\Delta V_{\text{pores}}(\Delta t) &= \frac{\Delta x}{2} \left( \frac{\phi(x,t + \Delta t) \cdot h(x,t + \Delta t) + \phi(x + \Delta x, t + \Delta t \cdot h(x + \Delta x, t + \Delta t)}{2} - \frac{\phi(x,t) \cdot h(x,t) + \phi(x + \Delta x, t) \cdot h(x + \Delta x, t)}{2} \right), \quad (2-8) \\
\Delta V_{\text{pores}}(\Delta t) &= \frac{\Delta x}{2} \left( \frac{\phi(x,t + \Delta t) \cdot h(x,t + \Delta t) + \phi(x + \Delta x, t + \Delta t) \cdot h(x + \Delta x, t + \Delta t)}{2} - \phi(x,t) \cdot h(x,t) - \phi(x + \Delta x, t) \cdot h(x + \Delta x, t) \right).
\end{align}

Due to the incompressibility of the fluid, the conservation of fluid mass implies:
\[ Q(x,t) \cdot \Delta t - Q(x + \Delta x,t) \cdot \Delta t = \Delta V_{\text{pores}}(\Delta t), \]
\[
\begin{align*}
\left( q_s(x,t) \cdot h(x,t) \cdot \Delta t - q_s(x + \Delta x,t) \cdot h(x + \Delta x,t) \cdot \Delta t \right) & = \frac{\Delta x}{2} \left( \phi(x,t + \Delta t) \cdot h(x,t + \Delta t) - \phi(x,t) \cdot h(x,t) \right) \\
& + \left( \phi(x + \Delta x,t + \Delta t) \cdot h(x + \Delta x,t + \Delta t) \right) \\
& - \phi(x + \Delta x,t) \cdot h(x + \Delta x,t) \\
\frac{1}{\Delta x} \left( q_s(x,t) \cdot h(x,t) - q_s(x + \Delta x,t) \cdot h(x + \Delta x,t) \right) & = \frac{1}{2 \cdot \Delta t} \left( \phi(x,t + \Delta t) \cdot h(x,t + \Delta t) \right) \\
& - \phi(x,t) \cdot h(x,t) \\
& + \left( \phi(x + \Delta x,t + \Delta t) \cdot h(x + \Delta x,t + \Delta t) \right) \\
& - \phi(x + \Delta x,t) \cdot h(x + \Delta x,t) \\
\end{align*}
\] (2-9)

Taking the limits as \( \lim_{\Delta x \to 0} \) and \( \lim_{\Delta t \to 0} \) results in:

\[ - \frac{\partial (q_s \cdot h)}{\partial x} = \frac{\partial (\phi \cdot h)}{\partial t}, \] (2-10)

Using Equations (2-3) and (2-5), the right hand side of Equation (2-10) can be rewritten as follows:

\[ \frac{\partial (\phi \cdot h)}{\partial t} = \left( 1 - \frac{h_0 \cdot (1 - \phi_0)}{h} \right) \frac{\partial h}{\partial t} = \frac{\partial (h - h_0 \cdot (1 - \phi_0))}{\partial t} = \frac{\partial h}{\partial t}, \] (2-11)

The continuity Equation for the resin infusion process is therefore expressed as:

\[ - \frac{\partial (q_s \cdot h)}{\partial x} = \frac{\partial h}{\partial t}. \] (2-12)

It should be noted that apart from a few recent publications [27, 43-45], most previously available literature did not account for the preform compaction flux term \( \frac{\partial h}{\partial t} \). This term has been typically set to 0 [46], and the continuity equation is often also simplified by the removal of the \( h \) term from the left-hand side of Equation (2-12). Other publications [27, 47] write the continuity Equation in a slightly different manner, extracting the \( h \) term from the left hand side and placing it in the right hand side:

\[ - \frac{\partial q_s}{\partial x} = \frac{1}{h} \frac{\partial h}{\partial t}. \] (2-13)
2.2.2 Flow Equations

Resin flow through a fibrous reinforcement is usually described using Darcy’s law, provided here for 1D flow in the $x$ direction:

$$q_x = -rac{K_{xx}}{\mu} \frac{dP}{dx},$$

(2-14)

where $K$ is the permeability of the preform, $\mu$ is the fluid viscosity and $P$ is the local fluid pressure. Darcy’s law is an empirical relationship first expressed by Henry Darcy in his 1856 book ‘Les Fontaines Publiques de la Ville de Dijon’. It has been since then theoretically derived from the Stokes Equations by Whitaker [48]. Darcy’s law intrinsically requires that the resin is a Newtonian fluid, and that the flow is laminar, i.e. with a low Reynolds number ($<1$).

Combining Equation (2-14) with the continuity Equation (2-12) gives:

$$\frac{\partial}{\partial x} \left( \frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} \right) = \frac{\partial h}{\partial t}.$$  

(2-15)

Using a non-mixed finite element method with conservative elements [49], $q_x$ at the flow front can be approximated as follows. Using linear finite elements, the first derivative of the pressure is constant over an element. Using a Taylor series about the centre of the element one finds that:

$$q_x = -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} + (x - x_c) \frac{\partial q_x}{\partial x}.$$  

(2-16)

Where $x_c$ represents the $x$ position of the centre of the element. As thickness and hence permeability varies spatially along the length, the velocity gradient can be expressed as:

$$\frac{\partial q_x}{\partial x} = \frac{\partial}{\partial x} \left( -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} \right) = -\frac{1}{\mu} \left( \frac{\partial K_{xx}}{\partial x} \frac{\partial P}{\partial x} + K_{xx} \frac{\partial^2 P}{\partial x^2} \right).$$  

(2-17)
and Eqn. (2-15) can then be expanded to:

\[
\frac{1}{\mu} \left( \frac{\partial K_{xx}}{\partial x} \cdot h \cdot \frac{\partial P}{\partial x} + K_{xx} \cdot \frac{\partial h}{\partial x} \cdot \frac{\partial P}{\partial x} + K_{xx} \cdot h \cdot \frac{\partial^2 P}{\partial x^2} \right) = \frac{\partial h}{\partial t} .
\]  

(2-18)

Combining Eqns. (2-17) and (2-18) leads to:

\[
\frac{\partial q_x}{\partial x} = \frac{1}{h} \left( \frac{K_{xx}}{\mu} \frac{\partial h}{\partial x} \frac{\partial P}{\partial x} - \frac{\partial h}{\partial t} \right).
\]  

(2-19)

The governing Equation for the volume-averaged velocity is therefore:

\[
q_x = -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} + \left( \frac{x - x_0}{h} \right) \left( \frac{K_{xx}}{\mu} \frac{\partial h}{\partial x} \frac{\partial P}{\partial x} - \frac{\partial h}{\partial t} \right).
\]  

(2-20)

It should be noted that the volume-averaged velocity is different to the velocity of the flow front \(v\) for the resin infusion process. The flow front velocity can be related to the Darcy velocity through:

\[
v = \frac{q_x}{\phi}.
\]  

(2-21)

2.3 Reinforcement Characterisation

In order to produce an accurate simulation, it is important to correctly characterise the porous preform through which the resin is flowing. The preform permeability plays a major role in the flow equations presented in the previous section. Another important material parameter that was defined in the previous section is the laminate thickness and rate of thickness change. The laminate thickness is governed by the number of reinforcement layers and its compaction state. It should also be noted that the laminate permeability is dependant on the local reinforcement structure or deformation state, which depends on the applied compaction stress.
2.3.1 Reinforcement Compaction Behaviour

A large number of studies have been published evaluating the compaction behaviour of fibrous reinforcements for composites manufacturing. Although the vast majority of the research was aimed at measuring and providing a better understanding of the physics of the compaction and relaxation phenomenon during rigid tool processes such as RTM and I/CM [50-61], these studies still have some relevance to the compaction occurring during the RI process. A few publications present studies specifically on the compaction occurring during the RI process [33, 39, 42, 62-67]. In this section, different experimental methodologies to determine the compaction behaviour will be presented.

In [56] Saunders et al. performed compaction tests on dry and saturated reinforcements using an Instron testing machine. The samples tested were plain woven glass reinforcements. The samples were tested by compacting at a constant crosshead speed up to a target load. The authors tested the influence of the crosshead speed at 0.05, 0.1 and 0.5 mm/min, and found no influence of the compaction speed; they therefore assumed the reinforcement had an elastic behaviour. They also found very little influence of the number of layers. When testing reinforcements in the wet state, it appears that the authors did not account for the fluid pressure in the compacting preform. They therefore found that the saturated preforms reached a lower $V_f$ than the dry ones, but by decreasing the compaction speed the trace of the saturated preform tended towards that of the dry preform.
Figure 2-2: Schematics of the compaction apparatus used by Robitaille [54].

Robitaille and Gauvin in [54] devised an experimental setup to measure the compaction and relaxation of dry and saturated reinforcements. The schematics of the setup are presented in Figure 2-2, the reinforcement being placed on the surface C and compacted with the surface A. Pressure transducers (denoted by B) recorded the fluid pressure to subtract from the total compaction pressure. The reinforcements were compacted at a constant compaction rate up to a chosen pressure. The cavity thickness was then maintained constant for a chosen period to measure stress relaxation, and then increased at a rate equal to the previous closing rate.
Umer et al. in [61], following from Bickerton et al. [68], performed compaction and permeability characterisation using the setup presented in Figure 2-3. The compaction response was evaluated during both dynamic compaction tests as well as static compaction tests. In the dynamic compaction test, the preform was compacted at a constant closing speed up to a target volume fraction. Once the target $V_f$ was reached, the samples were held at constant thickness for ten minutes to allow for most of the stress relaxation to occur. For the wet compaction tests, the fluid pressure near the injection gate was recorded to extrapolate the fluid pressure inside the preform, in order to extract the compaction stress applied to the preform out of the total force measured by the load cell. For the static compaction tests, the samples were compacted at a constant speed to a number of progressively increasing target $V_f$. At each $V_f$, the samples were then maintained at constant thickness for 10 minutes to allow stress relaxation to occur, as presented in Figure 2-4. In Figure 2-4b, the compaction load can be seen rising sharply as the compaction is applied, once the desired thickness is reached and held, the load decreases.
first quickly and then slowly, to tend towards a static compaction load. The stress at the end of each relaxation period was then recorded and used to trace the static stress versus $V_f$ relationship. The authors demonstrated that the compaction response of fibrous reinforcements was dependant on the strain rate, and was displaying stress relaxation when maintained at constant thickness.

Figure 2-4: Example of reinforcement relaxation from [68].

In [58, 59], Somashekar et al. performed compression tests to determine the non elastic behaviour of dry glass fibre reinforcement. The main objective was to measure the relaxation and permanent deformation occurring after compaction. The tests were performed by compacting the preform to a target $V_f$, and then opening the cavity and measuring the amount of instantaneous and time dependant spring back, and evaluating the permanent deformation. The authors performed either single compaction or multiple compactions to evaluate the effect of cycling on the maximum loads and amount of spring back. Figure 2-5 presents the effect of a repeated cyclic compaction up to a constant $V_f$, on a fibrous reinforcement. From this figure it can be observed that the peak compaction stress decreases and tends toward a steady value with the increasing number of cycles. It can also be observed that the reinforcement displays a different behaviour in compaction and unloading.
Hammami, in [62], performed compaction experiments aimed at the RI process. The preform samples were placed between two flat plates in an Instron testing machine and compacted at a constant closing speed up to a load equivalent to 100000 Pa of compaction pressure. Once this pressure was reached, the sample was maintained at constant thickness. The author tested various preform materials in both dry and saturated states. While this was a good step towards monitoring the compaction happening during the RI process, it can be argued that at the end of compaction the load should have been kept constant rather than the thickness, to allow for creeping of the preform instead of stress relaxation. It is also of interest to note that no unloading experiments were tested; the preforms were only tested during compaction.

In [33], Grimsley et al. used their RI monitoring setup to characterise the compaction behaviour of the reinforcement by correlating the measurement from the pressure transducer and the LVDTs. They performed dry compaction experiments by slowly evacuating the bag pressure to full vacuum. Once the displacement was stabilised, the preform was slowly vented back to atmospheric pressure. For the wet preform test, the preform was first impregnated with resin by applying a small pressure gradient. Once the preform was fully impregnated, full vacuum was applied until a steady state compaction
was reached. The bag was then slowly vented by opening the inlet and allowing resin to flow back in. This setup provided relatively good results when comparing the results from compaction tests and RI infiltration monitoring.

![Figure 2-6: Compaction test setup as used by Yuexin et al. [66].](image)

In [66], Yuexin et al. presented a very simple setup to evaluate the compression response of the preform. The setup is depicted in Figure 2-6; a 100 mm x 100 mm preform was placed on a glass plate and covered by a vacuum bag. The laminate thickness is measured using a dial gauge. For dry preforms, the compaction pressure was evaluated by measuring the vacuum pressure delivered by the pump and subtracting that pressure from atmospheric pressure. The thickness of the dry preform was measured at 20000, 40000, 60000, 80000 and 100000 Pa of compaction pressure, while cycling the vacuum pressure up to three times. The authors found that the trace of the first compaction cycle was quite different from the following cycles, revealing the existence of significant permanent deformation. Much less difference was observed between the second and third vacuum cycle. The authors also found that the thickness traces were different, depending on whether the vacuum pressure was increasing or decreasing. After completing the dry compaction, the resin inlet valve was opened to infuse the preform with salad oil under a compaction pressure of 60000 Pa. The laminate thickness was then measured under compaction pressures of 60000, 80000 and 100000 Pa with the resin inlet valve closed. It is not clear if the fluid pressure was recorded or was assumed to be equal to the vacuum pressure delivered by the pump. Further compaction was observed in the wet preform when compared to its dry state. However, too few measurement points prevented conclusion on the shape of
the wet compaction traces. The study went on evaluating the influence of the stacking of the reinforcement, with different fibre orientation and different fabrics. Joubaud et al. also used a relatively similar set-up in [69].

In [39], Yenilmez et al. performed compaction experiments using the cup and compaction cylinder set up depicted in Figure 2-7. To minimise the tilting between the compaction surfaces, the cylinder and base cup were smooth fitted. Four vertical resin removal channels were also slotted in the compaction cylinder to allow for removal of any excess resin in the chamber. A load was applied on the compaction cylinder and the laminate thickness was measured using four dial gauges attached to the top of the cylinder. The authors performed compaction and unloading measurement for both wet and dry preforms, and measured the creep happening at the end of the compaction (fibre settling) and after unloading (fibre relaxation) for thirty minutes each time (as presented in Figure 2-8). They found different compaction behaviour between compaction and unloading for both wet and dry preforms. The setup described appeared relatively cheap and simple to implement. However, there is no mention of monitoring the fluid pressure to evaluate and account for the pressure build up that may occur during compaction of a saturated reinforcement. Also, with the diameter of the reinforcement being bigger than the diameter of the contact surface of the compression cylinder, there might be some significant edge effects given the dimension of the samples. The setup was further refined and explained in [67], but the authors did not characterise

---

Figure 2-7: Schematics of the compaction setup by Yenilmez [39].
the wet compaction that occurs during post-filling. Also the loading and unloading rates appear to be rather fast, and there was no mention of studying the effect of loading rate.

From the review of the presented studies, it is clear that the fibrous reinforcements display a different behaviour whether compacting or unloading. The behaviour of the reinforcement is also different for a saturated preform than for a dry preform. The reinforcement behaviour was also shown to be time and rate dependant and displayed relaxation and creep when held at constant thickness or constant compaction stress respectively. It is therefore very important to properly design the plan of experiments to characterise the reinforcement in conditions matching those of the desired LCM process.

2.3.2 Reinforcement Permeability

The determination of reinforcement permeability has always been a major requirement for any LCM simulation. Fibrous reinforcements typically have

Figure 2-8: Example of the creep effect when maintaining constant compaction stress. From [39].
different permeability in different directions, due to the orientation of the fibres. For most fibrous reinforcement, three principal permeability coefficients are defined $K_{xx}$, $K_{yy}$ and $K_{zz}$ for the three principal directions. However for random mats, the in plane permeability coefficients $K_{xx}$ and $K_{yy}$ are considered equal as the fibres orientations are randomly distributed in the plane. Two types of permeability can be determined for the reinforcement. The unsaturated permeability is measured as the preform is progressively filled with a viscous fluid. When measuring the unsaturated permeability, two types of flow are taken into account: the macro-flow (or inter-tow flow), and the micro-flow (or intra-tow flow). In the latter fluid capillary forces can play a major role. The saturated permeability is measured once the porous medium is saturated with the fluid, and a steady flow is created due to an applied pressure gradient. Breard et al. analysed the difference between those two types of flow in [70]. When dealing with reinforcement composed of relatively large tows, the preform presents two levels of permeability at the macro and micro levels. The intra-tow permeability for the resin to impregnate the tow is some order of magnitude lower than the inter-tow permeability. For an unsaturated flow, the saturation of the fibre tows appears as a sink from the flow around the tows. The unsaturated permeability is therefore lower than the saturated permeability, and an intermediate saturation zone, where the fluid is present but the reinforcement is not yet saturated, appears at the flow front.

Many different research groups have tried to develop permeability measurement setups allowing fast and accurate permeability measurement and prediction [22-26, 60, 71-81]. In this section, a few significant methods of measuring reinforcement permeability will be reviewed.

Trevino et al. proposed two different apparatus [60], depicted in Figure 2-9, one for measuring the in-plane permeability and one for measuring the through thickness permeability. In both cases, the fluid is pushed through the reinforcement at a constant flow rate and the pressure is measured at the inlet. The permeability measurement was started once a steady state flow was established. The permeability is then calculated using Darcy’s law:
where $Q$ is the volumetric flow rate and $A$ is the cross sectional area of the medium. In both cases, the sample thickness is fixed by the use of a spacer; the number of layers can be varied to measure the permeability at various $V_f$.

Figure 2-9: Apparatus for measuring a) the in-plane permeability, b) the through thickness permeability. From Trevino et al. [60].

In [22], Ferland et al. used a system very similar to that used by Trevino for the in-plane permeability, but they added some pressure transducers along the length of the preform. The authors measured the unsaturated permeability, the measurements performed as the preform was filled and included the flow front advancement. The fluid injection was performed at constant flow rate and at constant injection pressure. From the data collected, the permeability was calculated with three different methods: “elementary method”, “interpolation method” and “single point method”. They concluded that to be accurate, the preform had to be longer than a minimum acceptable length, and the injection
pressure had to be below a maximum pressure. The maximum injection pressure and minimum length were found to be functions of the reinforcement permeability, the fluid viscosity and of the preform length or injection pressure.

Hammami tried to evaluate the permeability of a fibrous reinforcement during the RI process, by recording the progression of the flow front [74]. However the author found that this technique did not provide satisfactory results with all reinforcement materials.

Hoes et al. in [75] devised a set-up capable of simultaneously measuring the permeability in the $x$ and $y$ directions using a mould with embedded sensors. The flow sensing platen is depicted in Figure 2-10. The permeability calculation for a radial flow are based on the calculations presented by Adams et al. in [82]. The electric sensors shown on Figure 2-10 detect the arrival of the flow as the fluid creates a conductive bridge between the plate and the sensors. A pressure transducer is located at the injection gate to measure the inlet pressure. The top half of the mould consist of a flat steel plate and the cavity thickness is controlled using a set of spacers allowing for cavities of 2, 2.5 and 3 mm thickness. This system showed good accuracy and repeatability for the measurement of unsaturated permeability. A very similar setup was developed by Liu in [26].

![Figure 2-10: Sensor plate of the set-up by Hoes et al. [75].](image-url)
Nedanov and Advani presented in [76], a permeability measurement system also based on the shape of the flow front, but able to measure the unsaturated permeability in the three principal directions in one experiment. A schematic of the setup is presented in Figure 2-11. A thick stack of reinforcement was placed on an acrylic plate and was sealed by a vacuum bag. The bag was evacuated using a vacuum pump. The fluid was injected from a single point from the top at the centre of the preform. An electronic mass balance was used to record the mass of the resin in the pot, and a video camera recorded the shape and size of the flow in the top plane of the preform. As the mould was transparent, the exact instant at which the flow reached the bottom of the preform could be determined with the camera. This system allows for an easy measurement of the permeability in the three principal directions. However, it is difficult to adjust the laminate thickness to determine variation of the permeability components with $V_f$.

![Figure 2-11: Schematics of the permeability measurement setup developed by Nedanov [76].](image)
Buntain et al. in [24] presented a technique to measure the permeability of a reinforcement over a range of $V_f$ in one test. The set-up used in that study is presented in Figure 2-12. A circular preform was placed in the mould and saturated with fluid. The mould was then closed at a constant speed while recording the fluid pressure at the centre of the preform. The permeability was then calculated using the following Equation:

$$K = -\frac{\mu \dot{h}}{4P_0 h} r_0^2. \quad (2-23)$$

with $P_0$ the pressure at the centre of the preform and $r_0$ the diameter of the preform. In this method the reinforcement is assumed to have isotropic in-plane permeability, this method is therefore not suitable for all types of reinforcement, but is very useful for random mats. The method was then compared with a more classical steady state pressure driven method.

![Schematic diagram of the setup used by Buntain in [24].](image)

Scholz et al. in [80], developed a setup to measure the transverse permeability using gaseous and liquid flow. A big advantage of using gaseous flow over liquid is that there is no need for cleaning the fluids between each test.
The schematic of the setup is presented in Figure 2-13. By mounting the rig in a hydraulic press, the cavity thickness can be adjusted to allow for measurement of the permeability as a function of the $V_f$.

![Figure 2-13: Schematics of the set-up by Scholz [80].](image)

Bickerton et al. in [83], showed that the permeability of a preform can be affected by the deformation induced by mould curvature when laying up the preform. Heardman et al. in [73], looked at the effect of shear on the in-plane permeability of fibrous reinforcements. Some efforts have also been placed into predicting the permeability based on physical factors instead of empirical equations [81].

### 2.4 Numerical Simulation

#### 2.4.1 Compaction Behaviour

From the large number of models used for characterizing reinforcement compaction behaviour, this section will present a few significant models used in the literature. The compaction behaviour of fibrous reinforcement can be studied at different levels. At the micro level, the interaction between the fibres are evaluated, the fibres sometimes modelled as bending beams with contact points between each other. A significant amount of research has been
published on that matter [84-91]. Studying compaction on a micro-scale enables a better understanding of the physics behind compaction behaviour. However a micro-scale model would be too computationally expensive to implement directly within an LCM process simulation.

Compaction response can also be evaluated on a slightly larger scale, considering the fibre bundles constituting stitched or woven Performs. This is designated as the meso scale. Studies at the meso scale typically consider the reinforcements as a repetition of unit cells. The meso scale is often used to predict nesting of layers on top of each other [92-94].

For the simulation of LCM processes, the most computationally efficient models are usually macro-scale empirical models derived from curve fitting of experimental testing [51, 52, 54, 55, 95].

Robitaille and Gauvin in [53], presented a thorough review of the state of the art for the modelling of reinforcement compaction behaviour. One of the earliest and most cited works on reinforcement compaction in the RI literature is the paper by Gutowski et al. [89], in which the authors consider the preform to behave as bundles of aligned wavy beams meeting at multiple contact points. The proposed \( \sigma_f(V_f) \) relationship was described by:

\[
\sigma_f = A_s \left( \frac{V_f - 1}{V_{f_0} - 1} \right)^4
\]

(2-24)

where \( \sigma_f \) is the compressive stress applied to the reinforcement, \( V_{f_0} \) is the original fibre volume fraction (i.e. when no compressive stress is applied), \( V_a \) is the theoretical maximum available fibre volume fraction (i.e. when an infinite stress is applied), and \( A_s \) is a “spring constant”. This model was developed for the compaction of pre-preg material systems, and considers a lubricated unidirectional fibre bundle. Subsequent studies have shown this model to adequately capture the elastic compaction behaviour of more complex reinforcements.
Andersson et al. [96] linked $V_f$ to the compaction stress as follows:

$$\sigma_f = kE(V_f^m - (V_{f0} + \kappa)^m),$$  \hspace{1cm} (2-25)

where $E$ is the stiffness of the fibres, $k$ and $m$ are constants derived from compaction measurements. $\kappa$ accounts for the softening of reinforcement due to the presence of a fluid (zero for a dry fabric and greater than zero for a wetted fabric). By using two non-linear elastic behaviour models, the authors were able to simulate the reinforcement lubrication effect occurring at the flow front. However the use of a model based on wet compaction for the filling stage of Resin Infusion is not rigorously correct, as during filling the compaction stress on the preform decreases with time.

Hue and Newton in [97], while working on cotton fabric proposed an exponential function to relate the compaction pressure and laminate thickness:

$$\sigma_f = e^{\alpha h - \beta} - 1,$$  \hspace{1cm} (2-26)

where $\alpha$ and $\beta$ are parameters extracted from experiments. This method provided reasonable results for high compaction level but resulted in significant error at low compaction levels.

Joubaud et al. [69] used in their RI simulation a compaction model similar to that used by Robitaille et al. [53]:

$$V_f = a \sigma_f^b,$$  \hspace{1cm} (2-27)

where $a$ and $b$ are experimental parameters dependant on the reinforcement used. While it is not clearly stated in the paper, it appears that the authors have used a single compaction model based on wet compaction experiments. By using a single compaction model based on the wet reinforcement, the thickness (and permeability at the flow front) of the dry reinforcement was misrepresented, which may lead to an error in the progression of the flow front. It should also be noted that further error can be attributed to the use of a compaction model whereas, as mentioned above, the reinforcement is actually subject to unloading during the filling stage of the process.
Yenilmez et al. [39] used tabulated values of a dry compaction/dry unloading and dry compaction/wet unloading series of experiments in a presented simulation. After showing that there is a significant difference between the compaction and unloading traces, the authors then used the dry compaction data to determine the compaction of the reinforcement before the arrival of the fluid, and used the unloading data to simulate the thickness changes in the saturated part during the filling stage of the RI. Simulation results were compared to filling experiments, demonstrating that significantly improved results were obtained using the dry compaction and wet unloading model.

It appears that the use of empirical models using simple equations fitted to characterisation experiments is the most effective choice for the simulation of LCM. These models are simple, but to be accurate, they require the characterisation experiments to be performed in conditions very similar to that observed during the actual LCM process. There is therefore a balance to find between the simplicity and the versatility of the model.

### 2.4.2 Flow Front Tracking

The accuracy of a mould filling simulation depends largely on the ability to correctly estimate the position of the flow front. To reduce error, it is possible to simply reduce the element size of the FEM mesh, but a global mesh refinement can be computationally very expensive for a limited gain. In this section a few mesh refinement techniques used in LCM simulation will be presented.

Chang et al. in [98], proposed an adaptive re-meshing method for the simulation of the RTM process. The method works in four steps. First the finite element approximation error was calculated; if that error was greater that a defined threshold, the domain would be divided into sub-domains according to the approximation error. The sub-domains were then re-meshed as required. The nodal information were then transferred from the old mesh to the newly generated mesh. This technique allowed mesh refinement only when and where needed but can be costly if many re-meshing steps are required.
In [99], Bechet et al. proposed an adaptive mesh generation used for solving RTM mould filling. In that paper the authors proposed a mesh refinement based on the part geometry and material properties of the reinforcement, to create a fixed mesh that is optimised for the intended simulation. The mesh refinement was performed before the start of the process simulation. This technique requires a relatively small and refined mesh, but can be faster than the re-meshing method in complex non-isothermal cases where the method of Chang et al. would have required a large number of re-meshing iterations.

In [100], Kang and Lee proposed a method of mesh refinement for tracking the flow front using floating imaginary nodes and elements (FINE) to track the flow front. The method proposed to divide a flow front element into four sub-elements. Using triangular elements, two new “imaginary” nodes are added at the intersection of the flow front and the boundary of the element, and a third node is added in the middle of the third side of the original element as depicted in Figure 2-14. By using temporary nodes and elements, the tracking of the flow front can be refined with minimal computational cost. This method was designed for an RTM simulation, but was then used for RI simulation [30].

![Figure 2-14: Schematics of the FINE mesh refinement process.](image)
2.4.3 Resin Infusion Simulation

Attempts presented in the literature to simulate the resin infusion process are rather recent. Earlier on, RI was considered as a variant of RTM, and RTM simulations were used to predict the flow path for RI. A number of presented simulations did not account for laminate properties changing with time, only considering the flow through the distribution media and into the preform [101-103].

In [104], Dong used a 2D RTM simulation to evaluate flow front shape and position, and then applied dimensionless VARTM parameters to estimate the time at each time step. Song et al. used a quasi-static model to simulate the infusion, ignoring the temporal height derivative [46]. They also demonstrated the need for a correct boundary condition at the inlet by evaluating the influence of modelling different type of junction between the inlet and preform. In [63], Grimsley et al., included preform deformation in their simulation to estimate the quantity of fluid to penetrate the preform. However, it appears that they used a classic RTM equation, not taking into account the change of thickness for the flow calculation.

Kang et al in [30] introduced preform compaction into the flow equations but used a simplified governing Equation (2-13), instead of the full transient Equation (2-12). Kessels et al. presented a 2 1/2 D simulation using Control Volume FEM (CV/FEM) taking into account the transient thickness change and preform compaction flux as well as dry and wet compaction [43]. However they used wet compaction rather than wet unloading during the filling stage. In [96, 105], Anderson et al. implemented the equations of the RI process taking into account the compaction flux using a commercially available CFD code. Yenilmez et al. in [39], uses the formulation proposed by Correia in [27], but it should be noted that in this formulation the method of transition from a partial differential equation to an ordinary differential equation is not clearly explained.

Acheson et al. [44], Kang et al [47], Joubaud et al [69], and Parnas et al. [106] demonstrated the need for coupling the flow equation with the compaction of the reinforcement, and also with saturation the fibre tows. Bayldon and Daniel
proposed a model based on CV/FEM, including the compaction flux and tow saturation flux [107]. While previous models used only dry and fully saturated compaction behaviour, the compaction model used in their simulation was a function of the pressure as well as tow saturation to better simulate the saturation zone at the flow front.

While the search for a better understanding of the physics of the flow processes in RI is ongoing, other research has focused on adding specificity to the simulations. For example in [108], Simacek and Advani presented the influence of gravity in an RI simulation. In [109], Hsiao et al. looked at the optimisation of the flow distribution network for complex parts, to reduce the part defects and resin wastage. Lawrence et al. in [110], evaluated the influence of embedded impermeable inserts on the resin flow during the RI process. However most simulation only concentrates on the filling stage of the RI, when the resin saturates the preform, but very little work has been published on simulating the complete process including the post-filling and curing of the resin.

2.4.4 Post Filling

Most published research, whether numerical or experimental, only deals with the filling stage of the RI process. However it is during the post-filling stage that the manufactured part reaches its final quality. At the end of filling there is a large gradient of fluid pressure and laminate thickness along the part. During post-filling, as the resin starts to cure, the excess resin is drawn out or redistributed inside the part and the laminate thickness tends to equilibrate. A good control of the phenomenon taking place during post-filling can ensure a superior quality of the manufactured composite parts. This section will present the published research available regarding the post-filling stage of the RI process.

Li et al in [42] looked at post-filling experimentally as well as in a numerical model. However, they studied a different scenario to those considered in this thesis by clamping both inlet and vent at the end of filling. There was therefore no flow in or out of the preform during post-filling, just the pressure equilibrating. The experiments provided proved a relatively good match with the simulation.
In [111], Simacek et al. evaluated the flow induced by possible distribution media collapse, during post-filling in the RI process. As the fluid pressure decreases, the volume of fluid contained in the distribution media is pushed into the preform to help saturate the fibre tows. No experiments were provided to validate the simulation.

Robinson in [112], also proposed a resin bleeding simulation for the RI process. As the authors used a fixed mesh to represent the preform, they introduced an equivalent volume fraction calculation to account for the change of thickness and the flow created by that change of thickness. The proposed experiment consisted of a preform with a distribution layer on top. The use of the equivalent volume fraction made a great improvement on the post-filling prediction, however the predicted pressure decay during the post-filling was still slightly faster compared to the experiment. Due to the use of a distribution media, the flow consisted of through thickness flow in the preform and in-plane flow in the distribution media.

Simacek et al. presented a theoretical analysis of post-filling in [113]. In the cases evaluated they did not account for any flow out of the preform, considering cases in which a semi-permeable membrane was used to let gas flow, while blocking resin flow. No experiments were provided to compare with the simulation.

The monitoring and modelling of the post-filling stage of the RI remains very seldom approached in the literature. It is during that final stage that the part reaches its final state and quality. A good understanding of the physics governing the post-filling is therefore very important to have a good control over the quality of the parts manufactured by resin infusion.

### 2.5 Modified Darcy’s Law

Flow through porous media is important in fields other than composite materials. Darcy’s law was formulated based on flow of water through beds of sand. And flow through porous media is used in ground water flow, fluid
dynamics, geology, petroleum industry and many more applications. Some deviations from Darcy’s law have been characterised for turbulent flow, or flow with a compressible or non Newtonian fluid. And the limits of Darcy’s law are well defined for the fast flow with high pressure gradient, high permeability or low viscosity [114]. However the lower limits of application of Darcy’s law are not well defined and understood. A majority of studies assumes that Darcy’s law applies all the way, for slow flow with low permeability and high fluid viscosity. However, a small number of researchers in the fields of petroleum and ground water flow [115-118] have demonstrated the existence of a pressure gradient threshold under which there is no flow. This is because the pressure gradient is not sufficient to overcome the frictional effect. In [118], Prada et al. proposed a modification of Darcy’s law:

\[
q_x = \begin{cases} 
- \frac{K_{xx}}{\mu} \left[ \frac{dP}{dx} - \left( \frac{dP}{dx} \right)_{CR} \right] & \frac{dP}{dx} > \left( \frac{dP}{dx} \right)_{CR} \\
0 & \frac{dP}{dx} \leq \left( \frac{dP}{dx} \right)_{CR}
\end{cases}
\]  \tag{2-28}

where \((dP/dx)_{CR}\) represents the threshold pressure gradient. The authors then looked at the influence of the fluid mobility \((K_{xx}/\mu)\) on the threshold pressure gradient by studying the flow of saturated brine through one sample of Shaly sandstone, four samples of Brown sandstone, and three samples of sandpacks. They established the following relationship:

\[
\left( \frac{dP}{dx} \right)_{CR} = 16 \left( \frac{K_{xx}}{\mu} \right)^{-0.8}.
\]  \tag{2-29}

It was noted that by isolating the four samples of Brown sandstone or the three samples of sandpack, the relation between fluid mobility and threshold pressure gradient appears to be dependent on the type of porous medium as well. This issue requires further research.
By generalising Equation (2-29) to:

\[
\left( \frac{dP}{dx} \right)_{cr} = \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda},
\]

(2-30)

with \(\gamma\) and \(\lambda\) parameters determined from experiments; the corrected Darcy's law (2-28) was then rewritten as:

\[
q_x = \begin{cases} 
-K_{xx} \frac{dP}{dx} - \gamma \left( \frac{K_{xx}}{\mu} \right)^{1-\lambda} & \frac{dP}{dx} > \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \\
0 & \frac{dP}{dx} \leq \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} 
\end{cases}
\]

(2-31)

It was noted during the experimental investigations, that the pressure decay in the preform was slower than expected and that some pressure gradient remained in the mould even after a very long post-filling time. This remaining pressure gradient did not accord to the formulation of Darcy’s law and was the reason to search into the literature of different fields of research confronting the same conditions of high viscosity fluid flowing through low permeability media with a low pressure gradient.

2.6 Conclusion

In this chapter, previous work relevant to the objectives of this thesis were presented and analysed.

From the review of the experimental monitoring of the RI process, it was established that on top of monitoring the flow front progression, it is desirable to also be able to monitor the fluid pressure inside the mould and local laminate properties during the process. The method for acquiring fluid pressure previously in use at The University of Auckland was deemed satisfactory. However the method previously available to monitor the changes in laminate
properties did not provide satisfaction. It was estimated that the development of a full field laminate thickness measurement system would be beneficial.

The review of the characterisation of the reinforcement compaction showed that fibrous reinforcements display highly non-linear behaviour. The reinforcement behaviour being very different whether dry or saturated and whether in compaction or unloading. Some rate dependency was revealed as well as creep and relaxation. It was also demonstrated that the compaction behaviour was dependant on the previous compaction history. The reinforcement characterisation setup available at the University of Auckland was proven to be highly competitive for reinforcement compaction measurement, but some work was required to improve platen misalignment. To provide accurate input for a simplified model, a properly designed plan of experiments had to be designed to replicate the compaction experienced in actual RI conditions.

Due to the selection of materials studied in this thesis it was decided that the simple steady state flow permeability measurement system available at the University of Auckland was sufficient for characterising the desired permeability data.

From the review of previous simulation work on resin infusion, it was demonstrated that an accurate simulation needs to account for the coupling between the fluid flow and reinforcement compaction. It was also shown that empirical models for the reinforcement behaviour provided very good results as long as the characterisation was done in conditions similar to that experienced during the process. It was therefore decided to develop an empirical model that would cover the pre-filling, filling and post-filling stages of the RI process using a mixed elastic approach.

Very little work was found on the post-filling stage, it was therefore decided to put a strong focus on the monitoring and simulation of that particular stage of the process. As was explained in Chapter 1, it is during post-filling that the laminate reaches its final quality. Understanding and controlling that part of the process is therefore the key to a better control of the final product quality.
Chapter 3 MATERIAL CHARACTERISATION

Any numerical process model requires that the user provides relevant material data. It is important to understand what are the key material characteristics that will affect the accuracy of the simulation results. Depending on the type of simulation and desired results, the important characteristics might not be the same. Once those significant characteristics have been isolated, the operator needs to determine whether these characteristics are constant or a function of another variable. The range of values that these parameters will experience also needs to be evaluated in order to devise the best test procedures to characterise these parameters. Regarding the RI process, if no distribution media is used and the vacuum bag is considered to have a negligible rigidity, there are only two materials to characterise: the fibrous reinforcement and the resin.

Considering the fibrous reinforcement, two main parameters influence the flow of resin: the porosity which is the measure of void or free space in the material, and the permeability which is the measure of the ability of the material to transmit fluid. For a given reinforcement, the permeability will vary as a function of the porosity. The porosity and its opposite, the fibre volume fraction are dependant on the compaction stress and deformations applied to the reinforcement.
The influential parameter for the resin is viscosity. Depending on the resin type, the viscosity will vary with the temperature, shear rate, and degree of cure.

3.1 Materials

Two different fibrous reinforcements were used in this study. A Chopped Strand Mat (CSM) M705 and a Continuous Filament Mat (CFM) M8635 both reinforcements were manufactured by Owen Corning and supplied by Aurora Glass, the two reinforcements are shown in Figure 3-1. Both reinforcements have an average surface weight of 450g/m². The CSM is characterised by short randomly oriented bundles of fibre and a medium to high fibre volume fraction. The CFM consists of continuous randomly oriented fibre bundles and has a high resistance to compaction. These two reinforcements were chosen as due to their highly random nature, they provide a better repeatability than more structured fabrics. A woven or stitched fabric, will display significant variation depending on the nesting of the tows between consecutive layers [59, 119], the variation of tow size and distance between the tows also affect the reproducibility of those fabrics [120]. These effects are negligible in the CSM and CFM due to the high statistical randomness of these reinforcements. The difference of nesting and tow size appear on a micro scale, resulting in much more homogeneous properties on the macro scale used in this study. The CFM and CSM reinforcements also have very different characteristics and behaviour, providing a selection of challenging scenarios for the development of the simulation presented in subsequent chapters.
During cure, a chemical process leading to solidification, thermoset resins have a complex behaviour as different components are reacting with each other, making its characteristics time dependent. The viscosity of the resin will vary as a function of the temperature and the degree of cure. The degree of cure itself is a function of the temperature, percentage of catalyst or hardener and time. In a typical RI process, the resin system will be chosen so that very little cure occurs during the filling stage. It was therefore decided that to reduce the variability and complication due to the curing of resin, mineral oils would be used as a test fluid in this study. The choice of mineral oil over other test fluids such as corn syrup was motivated by the fact that these oils have a viscosity that stays constant in time, and mixing or diluting were not required. Corn syrup used in early trials also demonstrated changes of viscosity after degassing and over time as the water content tended to decrease. To study the effect of fluid viscosity, a range of oil has been used, supplied by Kauriland Petroleum: Mobil DTE Light, Mobil DTE Medium, Mobil DTE Heavy, and Mobil DTE Vacuoline 537. The behaviour of an infusion grade epoxy resin Nuplex R300 without
3.2 Reinforcement Compaction

3.2.1 Introduction

The principles and different stages of the RI process were explained in Section 1.3; during the whole process the reinforcement comprising the preform is subjected to a complex deformation history. During pre-filling vacuum is applied, and as the pressure differential between the cavity and the atmospheric pressure increases, the reinforcement is subjected to a ‘dry compaction’ (the dry preform is compacted to a volume fraction higher than the volume fraction at zero compressive stress). The rate of the dry compaction depends on how quickly the pressure differential is allowed to increase. Next comes the filling stage. Note that, before the fluid is injected, the preform will creep, that is, the volume fraction increases under the constant pressure differential. During filling, within the saturated region, the total compaction pressure applied to the cavity is partly carried by the fluid and partly by the preform. This balance of atmospheric pressure by the fluid pressure and preform compaction stress was expressed by Terzaghi [121]. The saturated part of the reinforcement is thus subjected to a ‘wet unloading’, that is, as the local fluid pressure increases, the compaction stress on the reinforcement decreases, and the local fibre volume fraction decreases.

During post-filling, the fluid pressure decreases as the excess resin is drawn out of the cavity. Therefore the preform compaction stress increases and the reinforcement is subjected to a ‘wet compaction’. Note that during the three phases, dry compaction, wet unloading and wet compaction, the preform responds not just elastically, but viscoelastically. In other words, the volume fraction will depend not only on the compaction stress, but also on the rate at which the compaction stress is changing, and these rate effects may be significant. As the permeability is governed by the local reinforcement hardener was also studied to provide some comparison with the oils used as test fluid.
architecture, accurate simulation of resin infusion requires a realistic model of the reinforcement compaction behaviour.

To understand and quantify the compaction behaviour of the fibrous reinforcement during the RI process a series of compaction tests have been performed using an Instron 1186 universal testing machine with a 200kN load cell (model 2518-111, with an auto-ranging resolution of 0.0001 kN up to 1 kN and 0.001 kN up to 10 kN as certified by the Australasian Calibrating Services Limited). These tests were performed in load control mode, where the controlling factor is the applied load. For RTM research the controlling factor in compaction tests has always been the $V_f$ or the thickness as the preform compaction is governed by the displacement of the mould. However in the RI process, the compaction is governed by the pressure difference between the inside and outside of the cavity, it was therefore preferable to perform the characterisation by controlling the load and measuring the resulting $V_f$ rather than the inverse.

3.2.2 Experimental Setup

The setup used for the characterisation of the reinforcement compaction behaviour is depicted in Figure 3-2 and described in this section.
3.2.2.a Platens

To perform compaction characterisation tests, the samples were placed between two flat platens. The lower platen is a 350x350 mm square plate of steel, 25 mm thick, with the surfaces ground flat. A 15 mm diameter channel has been machined on the perimeter of the platen to collect any overflowing fluid during wet characterisation tests. In the centre of the platen, a 10 mm diameter hole was drilled through as an injection gate. The injection gate is connected to a pressure transducer and a shut-off valve. The valve is then connected to a pressure vessel containing mineral oil and pressurised at two bar. The top platen consists of a 300 mm diameter aluminium disc, having a thickness of 40 mm.
3.2.2.b Spherical Alignment System

Figure 3-3: 3D CAD model of the spherical alignment unit, assembled view on the left and cross section of the exploded view on the right.

To minimise the misalignment of the two platens, a spherical alignment unit was employed. The system works like a modified universal joint, consisting of two seated concentric sphere parts maintained together by bolts. The top spherical seat (in blue on Figure 3-3) is bolted to the load cell, and the bottom part (in red on Figure 3-3) is connected to the top platen through a clevis system. The top and bottom components are held together with six bolts (in green on Figure 3-3). To ensure good contact with the bottom part of the unit despite the axis misalignment each bolt is mounted with a set of hollow (in yellow on Figure 3-3) and concave (in orange on Figure 3-3) spherical washers, forming a universal joint.

To adjust the system, the bolts are first loosened; the top platen can then be oriented to be fully in planar contact with the bottom platen by raising the crosshead to have both platens just touching. All the bolts are then progressively tightened one by one to lock the spherical unit in place. Care
should be taken to slowly increase the torque on the bolts one after the other diametrically opposed, as failure to do so will result in misalignment of the platens. The crosshead is then lowered and raised again to verify the accuracy of alignment. The misalignment is evaluated using a feeler gauge when the two platens are just touching with a reading of the load cell of around 10 N. Correct setting of the alignment unit will result in an alignment accuracy of less than 0.01°.

To eliminate the error of measurement due to the compression of the spherical alignment unit or the compliance under load of the Instron machine, a Banner LG10A65PU laser gauge with a resolution of 10 μm and a range of 75 to 125 mm, was fixed to the top platen and pointed to the lower platen. This was calibrated to measure the distance between the two platens.

3.2.2.c Sample Preparation

![Figure 3-4: Cutting press with the cutting blade and a sample of CFM.](image)

The samples were prepared by stacking the desired number of layers of the reinforcement and cutting 200 mm diameter discs using a pre-shaped blade and a cutting press (Figure 3-4). A 15 mm diameter hole was punched from the centre of the sample to ensure that there was no through the thickness flow
during the fluid injection and compaction phases of the tests. This central hole also enables easy positioning of the sample on the lower platen by aligning it with the injection gate.

### 3.2.2.d Procedure

As discussed in Section 2.3.1, the reinforcement compaction behaviour is highly non-linear, exhibiting some visco-elastic behaviour and permanent deformation. However in this study the goal was to try to use only elastic models. As the compaction behaviour depends on the speed of compaction, to use an elastic model requires characterising the reinforcements at compaction speeds similar to that experienced during the RI process. Some preliminary RI experiments were thus necessary to evaluate the rates of change of the compaction stress during the process. In Section 3.2.1 three distinct phases of compaction were described. The compaction tests therefore need to provide data relating to these three phases.

Each specimen was weighed before testing so that the fibre volume fraction can be evaluated using Equation (3-1):

\[
V_f = \frac{m}{\rho_f \cdot A \cdot h},
\]

where \( m \) is the sample mass, \( \rho_f \) is the density of the fibre material, \( A \) is the area of the sample, and \( h \) is the sample thickness. The laminate thickness has been evaluated as the distance between the top and bottom platens measured using the laser gauge.
Figure 3-5 schematically presents the loading sequences applied to the samples during the compaction tests. To simulate the dry compaction occurring during pre-filling, the sample was compacted to an equivalent pressure of 1.0 bar (3.124 kN applied to a sample 0.031 m$^2$) at a rate of 0.3 kN.min$^{-1}$ (corresponding to 160 Pa.s$^{-1}$, or the full vacuum being pulled at a constant rate over 30 min). The load was then maintained for five minutes to allow for any significant creep to occur. The sample was then unloaded to an equivalent pressure of 0.01 bar (0.031 kN), again held for 5 minutes to allow for creep, and then reloaded to 1.0 bar at the same rate of 0.3 kN.min$^{-1}$. It is this second, reloading, compaction curve which is used for the dry compaction curve for simulation. This was done in order to replicate the compaction history during pre-filling, for which vacuum is first applied and then slowly released while looking for leaks in the bag. This procedure is commonly applied in industry before final application of vacuum prior to the filling stage, and was also employed during the RI experiments for this study.

The sample was then wetted while compacted by injecting a low viscosity mineral oil (Mobil DTE light, viscosity data provided in Section 3.4.2) through
the centre of the lower platen, mimicking the wetting process at the flow front. The fluid was injected at a pressure of 2.0 bar until the sample was completely saturated; the injection time was typically around one to two minutes. The choice of mineral oil was made after preliminary tests to ensure that the type of fluid did not influence the compaction behaviour. The lower viscosity of the Mobil DTE Light ensured a fast distribution of the oil and decreased the pressure build up during compaction to the point of being negligible.

After waiting for eight minutes to allow for creep to occur, the saturated sample was then unloaded to an equivalent pressure of 0.01 bar at a rate of 0.05 kN.min\(^{-1}\) (which is equivalent to 26.7 Pa.s\(^{-1}\)). This replicates the reduction of compaction stress applied to the preform during the filling stage when the local resin pressure inside the cavity increases. To replicate the post-filling stage, the saturated sample was then re-compacted to an equivalent pressure of 1.0 bar at a rate of 0.05 kN.min\(^{-1}\). From this point on, the wet unloading to 0.01 bar, will be referred to as the “main wet unloading” and the wet compaction from 0.01 bar will be referred as the “main wet compaction”.

During an actual resin infusion process, at the completion of filling, there exists a gradient of fluid pressure ranging from approximately atmospheric pressure at the inlet, to the applied vacuum pressure at the vent. Therefore, the compaction state of the preform at the completion of filling varies along the length of the part from stress-free at the inlet to 1.0 bar of compaction stress at the vent. The inlet is typically closed at the onset of post-filling, while the excess fluid is being drawn through the vent from this point in time. As a result, the fluid pressure inside the laminate decreases, thus increasing the compaction stress on the fibres.
As described in Section 2.3.1 and in [53-55, 59], reinforcement compaction behaviour is dependant on the compaction history. The reinforcement at the inlet, being fully unloaded at the completion of filling, will behave differently to that closer to the vent, which is still partially compacted. Figure 3-6 schematically depicts the reinforcement compaction state along the length of the preform at the completion of the filling stage and presents experimental traces of the main wet unloading and main wet compaction behaviour of the CSM reinforcement. At the onset of post-filling, the material has undergone a wet unloading. However, due to the resin pressure profile along the preform, this unloading results in a fibre volume fraction distribution along the length of the preform. This is indicated by the black lines linking different points within the preform to the main wet unloading trace in Figure 3-6. As post-filling proceeds, the material is next wet compacted. However, one cannot use the main wet compaction data directly (indicated by the red line in Figure 3-6). This is because the main wet compaction data was obtained after a complete unloading (zero stress), whereas during post-filling the material is actually re-compacted from non-zero stress-states (as indicated by the red arrows in Figure 3-6), the material state moving towards the main wet
compaction as post-filling progresses. To evaluate the compaction response during this period, another series of tests were conducted in which the samples were first compacted twice and wetted under the same conditions as described above. Unlike the previous tests, the samples were then unloaded to various compaction levels and subsequently re-compacted to an equivalent pressure of 1 bar at a rate of 0.05 kN.min$^{-1}$. The blue lines in Figure 3-5 schematically describe the series of re-compaction tests performed to evaluate the influence of the compaction history.

Table 3-1 presents the plan of experiments for the compaction tests. Preliminary tests showed good repeatability with less than 5% deviation between each test. As these tests were fairly long due to the slow compaction speed of the wet reinforcement, it was decided not to repeat each individual test. Instead, the dry cycle and wet unloading were used as an indicator of the validity of the specimen. If the compaction trace of the specimen was deviating from the normal behaviour, the results would then be discarded and another specimen tested. However this never happened, the only discarded samples were due to testing error such as late wetting or empty oil container.

Table 3-1: Plan of experiments for the compaction tests.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Unloading Level (in mbar)</th>
<th>Number of Repeats</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>11</strong></td>
</tr>
</tbody>
</table>
3.2.3 Results

3.2.3.a Chopped Strand Mat

Figure 3-7 presents the traces of all eleven compaction tests for the CSM during the dry cycles and wet unloading. From Figure 3-7a, some disparity in the compaction traces can be seen more clearly at the low compaction stress, but tends to decrease with the rising compaction stress. Figure 3-7b Figure 3-7c show very good repeatability. The initial disparity visible in Figure 3-7a can therefore be explained by some differences in the compaction history during cutting and handling of the specimens. As expected, all the partial wet unloading traces follow the main wet unloading trace (Figure 3-7d). The samples have had the same loading history and at the beginning of the unloading are all under the same condition (lubricated and submitted to 1 bar compaction), they were then unloaded at the same rate but stopping at different compaction level (as schematically presented in Figure 3-5), therefore all the traces should overlap.
Figure 3-7: Comparison of the compaction traces of the different CSM specimens; a) during the first dry compaction; b) during the dry unloading; c) during the second dry compaction; d) during the wet unloading.

Figure 3-8 presents the wet re-compaction traces for the CSM compaction test series. Each wet re-compaction curve appears to stem from the main wet unloading trace (the dashed red line). All of the traces appear to converge in a point around 70000 Pa and 47% volume fraction. Beyond this convergence point, for higher compaction stress, the trend is not quite as clear.
3.2.3.b Continuous Filament Mat

Figure 3-9 presents the traces of all eleven compaction tests for the CFM during the dry cycles and the wet unloading. From Figure 3-9a to Figure 3-9c some disparity in the compaction traces can be observed, these differences are higher than for the CSM reinforcement but still below 5% variation from one another. Figure 3-9d shows much greater repeatability of the tests once the samples have been subjected to a full loading cycle and have been wetted. The dry cycling and wetting of the samples provide a more prominent loading history than the storing, cutting, and handling of the reinforcement. This tends to minimise the effect of the different pre-history of each individual specimen.
In Figure 3-9a and c, a small jump can be seen on the dry compaction curves of the CFM at around 10000 Pa of compaction stress. This is only an artefact due to the compaction speed and the gain of the Instron machine. The Instron machine used in the study uses a screw to move the crosshead, so intrinsically it is in displacement control; the force control mode uses the force measured by the load cell to update the displacement of the crosshead. At the lower compaction stresses, the $V_f$ changes very quickly with the compaction stress and the Instron machine does not instantly pick up the change in rigidity, therefore the load peaks up slightly before being corrected.
Figure 3-9: Comparison of the compaction traces of the different CFM specimens; a) during the first dry compaction; b) during the dry unloading; c) during the second dry compaction; d) during the wet unloading.

Figure 3-10 presents the wet re-compaction traces for the CFM compaction test series. As with the CSM, each wet re-compaction curve appears to stem from the main wet unloading trace (the dashed red line). All of the traces also seem to converge to a point around 65000 Pa and 24% volume fraction. When looking beyond that convergence point, there is a clear trend relating the final $V_f$ to the initial compaction stress; the lower the initial compaction stress, the higher the final $V_f$ is achieved.
3.2.4 Stress/Fibre Volume Fraction Relationship

3.2.4.a Modelling the Dry Compaction, Main Wet Compaction and Main Wet Unloading

To fit the experimental data using simple empirical relationships, the data were first divided to form three non linear elastic models: dry compaction, main wet unloading and main wet compaction. It was found that a power law (3-2) as described by Robitaille [53, 54] was an effective way of characterising the relationship between stress and fibre volume fraction. This power law can be easily inverted and differentiated, and provides a reasonable fit to the experimental data:
Material Characterisation

\[ V_f = V_{f0} \cdot \sigma_f^B, \quad (3-2) \]

where \( V_{f0} \) and \( B \) are parameters determined experimentally. The ability to inverse and differentiate this equation is important to be able to calculate the fluid pressure from the \( V_f \) and use it in the flow calculation as described in Section 2.2.2.

![Graph showing example fitting of experimental compaction trace](image)

**Figure 3-11:** Example fitting of experimental compaction trace. The application of three curves is compared to application of a single power law curve.

This model had been developed for reinforcement compaction, and provides a fairly good fit to the experimental data in the compaction cases. However, in the unloading case, the model exhibited significant deviation from the experimental trace. To obtain a closer fit to the experimental data over the complete \( V_f \) range, the experimental compaction and unloading traces were interpolated in three overlapping sections. Figure 3-11 presents an example of
this approach, comparing the fitting of the wet unloading data of the CSM by a single power law and by three overlapping power laws. The model works by selecting the minimum of the $V_f$ given by the three power laws for any given compaction stress as when going from a lower stress interval to a higher one, the $V_{f0}$ term increases and the B term decreases. It is therefore not necessary to calculate the domain of application of each section. A macro has been written within Microsoft Excel to optimise the selection of the sections to interpolate. This macro minimises the fitting error as well as the change of gradient between the interpolated curves. The main wet unloading (unloading to 0.01 bar), and main wet compaction (compaction from 0.01 to 1 bar) experimental traces were interpolated following this approach. It was found that the single power law approach provided sufficient accuracy for the dry compaction curve.

Each material requires therefore 14 parameters for the characterisation of the dry compaction, main wet unloading and main wet compaction behaviour. This number of parameters may seem large but it should be noted that all of them can be quickly determined from one single compaction test. The reader should note that additional tests are still required to determine the wet re-compaction behaviour.

<table>
<thead>
<tr>
<th></th>
<th>$V_{f0}$</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry Compaction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1447</td>
<td>0.1042</td>
</tr>
<tr>
<td><strong>Main Wet Unloading</strong></td>
<td>0.191851</td>
<td>0.085056</td>
</tr>
<tr>
<td></td>
<td>0.286561</td>
<td>0.046089</td>
</tr>
<tr>
<td></td>
<td>0.3594</td>
<td>0.025126</td>
</tr>
<tr>
<td><strong>Main Wet Compaction</strong></td>
<td>0.1408</td>
<td>0.1106</td>
</tr>
<tr>
<td></td>
<td>0.1515</td>
<td>0.1033</td>
</tr>
<tr>
<td></td>
<td>0.1746</td>
<td>0.0898</td>
</tr>
</tbody>
</table>
Table 3-3: Parameters for the CFM reinforcement.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{f0}$</td>
<td>$B$</td>
</tr>
<tr>
<td>Dry Compaction</td>
<td></td>
</tr>
<tr>
<td>0.024236</td>
<td>0.190727</td>
</tr>
<tr>
<td>Main Wet Unloading</td>
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</tr>
<tr>
<td>0.038703</td>
<td>0.6611</td>
</tr>
<tr>
<td>0.07417</td>
<td>0.105308</td>
</tr>
<tr>
<td>0.113266</td>
<td>0.168256</td>
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<tr>
<td>Main Wet Compaction</td>
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<tr>
<td>0.28012</td>
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</tr>
<tr>
<td>0.29449</td>
<td>0.187107</td>
</tr>
</tbody>
</table>

### 3.2.4.b Modelling Re-Compaction

Each experimental re-compaction trace appears to have a different starting and ending point (See Figure 3-8 and Figure 3-10). However to be of any use any proposed model should be able to replicate the family of wet re-compaction traces by inputting only two variables: the initial compaction stress and the current compaction stress. The aim has been to find a set of equations that will fit any of the experimental re-compaction traces by only changing the value of the initial compaction stress. Figure 3-12 presents an example of a re-compaction trace and the applied model and also illustrates some key stress parameters used to construct the model.

It was found that the re-compaction of the partially unloaded preforms could be empirically interpolated from the main wet unloading and main wet compaction models as follows:
Material Characterisation

\[
V_{f_R} = \begin{cases} 
(1 - A) \cdot V_{f_U} - A \cdot V_{f_L}, & \sigma^* < \sigma_c \\
B \cdot V_{f_U} + \left(1 - \frac{1}{B} \cdot V_{f_U} + \left(1 - \frac{1}{B^2} \cdot V_{f_L}ight)ight) \cdot V_{f_L}, & \sigma^* \geq \sigma_c
\end{cases}
\]  

(3-3)

with \( A = \frac{(\sigma_c - \sigma_f)}{(\sigma_c - \sigma^*)} \cdot \frac{\sigma_f - \sigma^*}{\sigma_f} \) and \( B = \frac{\sigma_{\text{max}} - (\sigma_f - \sigma^*)}{\sigma_{\text{max}}} \)

where \( \sigma^* \) is the compaction stress on the reinforcement at the start of re-compaction, \( V_{f_R} \) the volume fraction during re-compaction, \( V_{f_U} \) the volume fraction following the main wet unloading trace, \( V_{f_L} \) the volume fraction following the main wet compaction trace, \( \sigma_c \) is the compaction stress at which the main wet compaction and unloading curves are found to intersect, \( \sigma_{\text{max}} \) is the maximum compaction stress applied to the preform, and \( \alpha \) is a constant dependant on the reinforcement architecture and determined from the experiments. If \( \sigma^* < \sigma_c \) the model uses the minimum produced by two approaches to interpolation between \( V_{f_U} \) and \( V_{f_L} \). The first interpolation gave best results at compaction stresses close to \( \sigma^* \), while the second was found to be more accurate as the compaction stress was increased. The model used when \( \sigma^* \geq \sigma_c \) produces good results for the CFM reinforcement and moderate errors for the CSM reinforcement. As the experimental results did not provide any clear trend for the CSM when \( \sigma^* \geq \sigma_c \), it is difficult to refine the model further.

Table 3-4: \( \alpha \) value for the re-compaction of both reinforcements

<table>
<thead>
<tr>
<th></th>
<th>CSM</th>
<th>CFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>80</td>
<td>7</td>
</tr>
</tbody>
</table>
The reader should note that although the determination of the re-compaction behaviour required a large number of tests in this study, this was done to verify the trend. Further determination for new reinforcements could be done with only a couple of re-compaction tests allowing the determination of the coefficient $\alpha$.

![Figure 3-12: Example of the re-compaction model as applied to the CFM.](image-url)
3.3 Reinforcement Permeability

During the resin infusion process, if no distribution media is used, there is not any flow in the through thickness direction. Therefore, only the in-plane permeability needs to be characterised. Due to the high randomness of the fibre orientation in both CSM and CFM reinforcement, the in-plane permeability can be assumed isotropic. Therefore, a steady state flow experiment as described by Umer in [61] can be used to characterise CSM and CFM permeability.

3.3.1 Experimental Setup

![Diagram of permeability measurement setup]

Figure 3-13: Schematic of the permeability measurement setup.
3.3.1.a Bowl and Platen

Figure 3-14: Bowl and top platen used for the permeability measurements.

Due to the large amount of fluid used during the steady state permeability measurements, the two platens used for the compaction experiments were not suitable. For permeability measurement, the lower platen was replaced with an aluminium bowl shaped mould, shown in Figure 3-14. The base of the bowl is a flat disc with an internal diameter of 300 mm and is 45 mm thick, with a 10 mm diameter injection gate in the middle. The walls of the bowl are 20 mm thick and 100 mm high. The top platen is a 210 mm diameter aluminium disc with a thickness of 25 mm.

3.3.1.b Spherical Alignment System

The Spherical alignment unit described in Section 3.2.2.b was again used to ensure the correct alignment of the top and bottom platens. As for the compaction tests, the cavity thickness between the two platens was measured using a laser gauge. To avoid errors due to the presence of oil at the bottom of the bowl, the laser gauge was set to take measurement on the top of the wall.
3.3.1.c Sample Preparation

The samples were prepared in the same manner as for the compaction experiments described in Section 3.2.2.c. Figure 3-15 presents the geometry of the samples; \( r_o \) and \( r_i \) are respectively the outer and inner diameters of the sample and measure 100 mm and 7.5 mm.

![Sample geometry for the permeability experiments.](image)

3.3.1.d Measurement of Flow Rate and Pressure

The permeability of the reinforcement was calculated assuming the fluid flow within the sample follows Darcy’s law, using the Equation developed in [24]:

\[
K = \frac{\mu \cdot Q}{2 \cdot \pi \cdot h \cdot P_{inj}} \cdot \ln \left( \frac{r_o}{r_i} \right),
\]

(3-4)

where \( K \) is the isotropic permeability, \( \mu \) is the fluid viscosity, \( Q \) is the flow rate, \( P_{inj} \) is the injection pressure and \( r_o \) and \( r_i \) are respectively the outer and inner radii of the tested sample (as depicted in Figure 3-15). It is therefore necessary to measure both the flow rate and injection pressure. The pressure was measured by a Gems 1200 series pressure transducer with a range of -103.4 to
1965 kPa located near the injection gate as depicted in Figure 3-13. The flow rate was measured by recording the weight of the pressure pot containing the fluid to be injected, using a Mettler Toledo SB16001 mass balance connected to a computer running LabView.

### 3.3.1.e Procedure

Before a test, each specimen was weighed and the ambient temperature recorded. The weight of the sample enabled accurate calculation of the $V_f$, while the measurement of the temperature allowed accurate determination of the viscosity of the fluid during the test. The sample was then placed in the lower mould, aligning the punched hole with the injection gate. The sample was then compacted to an initial low $V_f$ (0.075 and 0.25 for the CFM and CSM respectively) and some Mobil DTE Vacuoline 547 oil was injected to fully saturate the sample. These initial $V_f$ values were chosen as just slightly higher than the $V_f$ of the reinforcement under no compaction stress. The sample was then compacted to a series of decreasing cavity thickness at a rate of 5 mm.min$^{-1}$. At each target cavity thickness, the thickness was held constant for four minutes. After waiting one minute to allow for some relaxation and reorganisation of the sample, the injection gate was opened and a constant flow was established. The flow rate and pressure were then recorded over a period of one minute.

The target thicknesses were selected to give a range of $V_f$ comparable to that experienced during the compaction experiments. The thicknesses were estimated from the reinforcement nominal surface weight following Equation (3-5):

$$h = \frac{M \cdot N}{\rho \cdot V_f},$$

(3-5)

where $M$ is the surface weight of the reinforcement and $N$ is the number of layers. The actual $V_f$ was calculated afterwards using Equation (3-1) and the
measured laser gauge data. The target $V_j$’s for each reinforcements are given in Table 3-5.

<table>
<thead>
<tr>
<th>CSM</th>
<th>CFM</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.5</td>
<td>0.3</td>
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</tbody>
</table>

3.3.2 Results

3.3.2.a Chopped Strand Mat

Figure 3-16 presents the results of three permeability tests for the CSM reinforcement. As expected the results appears relatively linear when the permeability is plotted on a logarithmic scale.
3.3.2.b Continuous Filament Mat

Figure 3-17 presents the results of three permeability tests for the CFM reinforcement. Once again, the results appear relatively linear when the permeability is plotted on a logarithmic scale.
3.3.3 Permeability/Fibre Volume Fraction Relationship

The Carman-Kozeny Equation, or one of its variants such as Equation (3-6), is often used to relate experimental permeability and $V_f$ data:

$$K = C \left(1 - \frac{V_f}{V_f^n}\right)^{n+1}$$

where $C$ and $n$ are parameters determined from experiment.

Another empirical model commonly used applies an exponential fit to the experimental values following Equation (3-7). This method provides good accuracy of fit with much easier determination of the coefficients, and was therefore chosen over the Equation (3-6) for the rest of the study. However, the choice of the modified Carman-Kozeny Equation has still been made available in the simulation program presented in Chapter 5.

$$K = a \cdot e^{V_f^b}$$
Material Characterisation

$a$ and $b$ being determined from experiment. These parameters for the CSM and CFM reinforcements are presented in Table 3-6.

Table 3-6: Parameters of the permeability equation for the two reinforcements.

<table>
<thead>
<tr>
<th></th>
<th>CSM</th>
<th>CFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>2.5x10⁻⁸</td>
<td>1.3x10⁻⁸</td>
</tr>
<tr>
<td>$b$</td>
<td>-12.55</td>
<td>-12.61</td>
</tr>
</tbody>
</table>

3.4 Fluid Behaviour

The use of Darcy’s law and in it the dynamic viscosity term ($\mu$) implies that the fluid is Newtonian and incompressible. However, non-Newtonian fluid modifications of Darcy’s law exist, such as that proposed by Liu et al. in [122]. A Newtonian fluid is characterised by a linear relationship between shear stress and shear strain rate. The viscosity of Newtonian fluids depends only on its composition, the temperature and the pressure, and not on the forces acting upon it. During the RI process, the viscosity of the fluid is time dependant as the components of the thermoset resin are reacting during polymerisation. Leroy [123] studied the rheological behaviour of a catalysed polyester resin during the whole polymerisation process and found that the resin was acting as a Newtonian fluid up to a degree of cure of 45%, after which it had characteristics of a viscoelastic fluid until gelling (at around 50% degree of cure).

For the simulation developed in this thesis, the fluid will be assumed to be always Newtonian, which is reasonable during filling and the majority of post-filling. The simulation could easily be adjusted to account for the change of viscosity of a curing resin but would still need the Newtonian assumption.

3.4.1 Resin Cure Kinetics

During the LCM manufacturing processes, a liquid resin is impregnated through a dry reinforcement. Over time, the components of the resin react with
each other to polymerise and solidify the material. The polymeric matrix goes from a liquid state to a solid state. It is important in order to understand and simulate the RI process, to know and be able to model the polymerisation of the resin and how it affects its viscosity. Extensive research has been ongoing to understand the kinetics of polymerisation and its effect on the rheological properties of the resins [123-128]. However these are not treated in this study that concentrates on the reinforcement characterisation and the coupling between fluid flow and reinforcement compaction.

3.4.2 Viscosity Measurement

Figure 3-18: Rheometer used for the fluid characterisation tests.

3.4.2.a Procedure

To study the flow behaviour of the fluids employed, a *Physica UDS200* rheometer (Figure 3-18), was used with a cone and plate setup. The shallow cone used has a diameter of 25 mm and an angle of 1°. The distance between the cone and plate was set to 0.05 mm. For each test, a virgin sample of approximately 5 ml was placed in the middle of the plate. The cone was then
lowered to the measuring position and the excess fluid overflowing from under the cone was wiped clear.

Before measuring the viscosity, it must first be proven that the test fluids as well as the resin have a Newtonian behaviour. For this purpose, the strain was ramped while maintaining all other parameters constant. The angular frequency was maintained at 10 Hz and the strain was ramped between 0.01 to 100%. The fluids were then tested over a range of frequencies to determine the most stable measuring parameters. The amplitude was set to 5% of strain, and the frequency was ramped from 1 to 100 Hz.

After verifying that the fluids had a Newtonian behaviour, the fluids were characterised as a function of temperature. The strain was set to 55% and the frequency of oscillation set to 25 Hz. The temperature was ramped from 10 to 40°C.
3.4.2.b Results

Figure 3-19: Measured relation between shear stress and strain rate for the various test fluids.

Figure 3-19, presents the results of one such test, in this case the temperature was maintained constant at 30°C. The reader should note that the Mobil DTE AA oil was a predecessor of the Mobil Vacuoline 547, the producer having changed the name during the period of this study. From Figure 3-19, the stress-strain relationships for the fluids considered appear linear, the curves passing through the origin. The fluids therefore appear to have a Newtonian behaviour.

Figure 3-20 presents the evolution of the viscosity with temperature. It can be seen that in the range tested here, the viscosity is highly dependant on the temperature. This demonstrates the importance of accurately controlling, or at least measuring, the temperature of the resin and mould during the infusion process. A change of a few degrees will significantly affect the viscosity of the fluid, and therefore the fill time and post-filling behaviour during manufacturing. It can be observed from Figure 3-20 that the behaviour of the Mobil DTE Light and Heavy did not change with the two different batches purchased. However, despite claims from the supplier, there was a small difference of viscosity
between the *Mobil DTE AA* that was first supplied and the *Mobil DTE Vacuoline 547* purchased later on.

![Graph showing viscosity versus temperature for various test fluids](image)

Figure 3-20: Variation of the viscosity as a function of the temperature for the various test fluids.

### 3.5 Conclusion

This chapter has covered the characterisation of the materials used during this study. It was chosen to model the reinforcement compaction using macro-scale models. A new set of compaction and re-compaction models were developed in order to characterise the reinforcements using only elastic component models. The models developed have showed good agreement with the characterisation data for two different random mat glass fibre reinforcements. The permeability of these reinforcements was also characterised as a function of $V_f$.

The fluid viscosity was characterised, and the significant influence of temperature was demonstrated. This demonstrates the potential for the use of temperature variations, either locally or globally, as a potential means of controlling the resin infusion process. As this work focuses on complex coupled
reinforcement compaction and resin flow, for the sake of simplicity, it was decided not to include the effect of cure kinetics on resin viscosity in the scope of this study.
After having characterised the materials used during this study, in the previous chapter, it is necessary to collect some experimental data to be able to compare and validate the simulation being developed. In the resin infusion process, with the use of clear vacuum bag, it is easy to visually track the progression of the flow front. However, to compare with simulation, more experimental data is required, especially for the post filling stage as the flow front does not evolve anymore once it reaches the vent. The fluid pressure and pressure gradient inside the laminate are key parameters related to the application of Darcy’s law and should therefore be monitored. As the vacuum bag provides no rigidity, the laminate properties are constantly evolving during the process; it is therefore desirable to monitor the variations in the local reinforcement permeability. To compare with the simulation it can also be useful to measure the rate of fluid flow into the cavity as well as the total amount of fluid injected.

In the first part of this chapter, the experimental setup developed to monitor the RI process will be presented. This part will include development of the moulds, use of sensors and the stereophotogrammetry technique developed to monitor the laminate thickness variations. The second part of the chapter will provide experimental results using the monitoring system developed. First a series of preliminary test will provide some information on the influence of
different factors on filling and post-filling, as well as on the variability of the process. Then a single RI experiment will be analysed using the monitoring tools developed in this chapter as a demonstration of the capabilities of the setup.

4.1 Development of the Experimental Setup

4.1.1 Moulds design

4.1.1.a Temperature Controlled Table.

Two moulds have been used over the course of the study presented in this thesis. First a 1200 mm by 2400 mm temperature controlled infusion table was
employed. To increase the rigidity while keeping the weight reasonable, the table was constructed with a sandwich structure having a 5 mm thick aluminium sheet at the mould surface, a 50 mm PVC foam core, and a 3 mm thick sheet of aluminium as the lower skin. Aluminium was chosen for the skins as it is reasonably lightweight and also provides good heat conductivity to ensure a more homogeneous temperature distribution on the mould. The PVC foam core, as well as providing a light core for increased thickness, also provided an insulating layer to prevent heat loss from the underside of the mould.

To regulate the temperature, a copper tube track runs just below the top aluminium sheet, circulating water supplied by a Boe-Therm Temp 95 vac thermolator able to supply water from 20° to 90°C. To decrease the pressure drop along the track and allow heating up of only one half of the table, the track was divided in two as depicted in Figure 4-2. The temperature is monitored using thermocouples embedded in the mould and connected to a computer running LabView. This computer then controls the thermolator. The infusion table is able to run at temperatures between 20° and 50°C. On each side on the mould along the length, an aluminium extruded profile 60x30 Light from ITEM (as depicted in Figure 4-3) was embedded between the two skins. These aluminium profiles, as well as providing added longitudinal rigidity to the table, are also used for fixation points for the laminate thickness monitoring system. To provide a good surface finish and an easier release when moulding with thermoset resins, the upper mould surface was coated with a black urethane gelcoat (Devoe – Devthane 379 supplied by Altex Coatings) increasing surface hardness. The black gelcoat also provides better contrast to track the flow front as the white glass reinforcement becomes clear as the preform is saturated.
Figure 4-2: Schematic description of the temperature controlled table.

On one half of the mould, as seen in Figure 4-2, three holes have been drilled along the width and equipped with pressure transducer fittings to enable measurement of the fluid pressure within the laminate. The pressure transducer used in this study are BTE6001A4-FL from Farnell, these pressure transducers allow measurement from 0 to 1 bar absolute, and utilise a stainless steel diaphragm allowing for use with thermoset resin.
4.1.1.b Post-Filling Study Mould.

A second mould was developed later on to study with more precision the phenomenon happening during the post-filling stage of resin infusion. This mould was designed to produce a smaller part, and have a higher density of pressure transducers. The mould was built from a 530x300 mm aluminium plate with a thickness of 32 mm. This second mould is presented in Figure 4-4 and described below. The full technical drawings can be found in Appendix A.
It was observed that the flexible tube and distribution media used at the inlet during early experimentation can act as a fluid reservoir during post-filling, providing a small but non negligible flux of fluid into the preform after the clamping of the inlet. It was therefore decided to create a non deformable inlet system embedded in the mould. The inlet tube goes from the inlet pot to a shut-off valve connected to a T junction at the bottom of the mould. On the other end of the T junction a pressure transducer is connected to record the inlet pressure. The third end of the T junction is connected to the bottom of the mould. The details of the T junction connection can be seen in Figure 4-5. From there the fluid path leads up through the mould and arrives in a 3 mm wide 180 mm long and 8 mm deep channel that serves as an inlet. Seven pressure transducer fittings were machined on the bottom of the mould (see Appendix A). The first pressure transducer hole was placed 35 mm from the inlet, then the transducers are spaced 55 mm from each other. 35 mm from the seventh transducer fitting, a 10 mm diameter hole was drilled as a vacuum gate and the same type of T junction connection was used to monitor the fluid pressure at the vent. The pressure transducers used with this mould are the same 6001A4-FL used with the temperature controlled table.
4.1.2 Monitoring Fluid Flow Rate

The fluid flow rate is measured by monitoring the weight of the resin pot. The pot is placed on a Mettler Toledo SB16001 weighing scale (pictured in Figure 4-6) connected to a computer running LabView. Through this the mass flow rate into the laminate can be calculated with a frequency of 1 Hz.
4.2 Monitoring Laminate Thickness Variation

4.2.1 Review of Previously Applied Methods

The different methods used to monitor thickness variation have been outlined in Section 2.1; this section will demonstrate the motivations for the choice of thickness monitoring system developed in this thesis. As shown in Chapter 3, local laminate $V_f$ is highly dependant on the compaction response of the reinforcement. For low compaction stresses particularly, a small variation in the compaction stress will result in significant variation of the $V_f$ and therefore of the laminate thickness. It was therefore decided to eliminate all contact measurement methods.

In previous RI studies at the University of Auckland, the laminate thickness was monitored using laser gauges [38]. However, problems caused by the uneven and reflective surface of the plastic bag resulted in unacceptable noise levels. The noise level could be decreased by applying some masking tape on
the vacuum bag at the measured point. Figure 4-7 presents the measurement recorded during three repeats of the same test, a radial infusion of mineral oil through a preform composed of 12 layers of biaxial stitched glass fabric EB800-1270 with a superficial weight of 825 g/m² supplied by High Modulus. The measurements were taken 100 mm from the inlet using a Banner LG10A65PU laser gauge. For each test, there is an initial dip in thickness just after the passage of the flow front. Beyond this time the four traces exhibit quite different and puzzling behaviour. The ability to interpret this data is also severely limited as measurement is completed at a single point. But the various behaviours exhibited could be due to variation whether the measurement is taken on top of a tow or between tows, and also to the fact that tows can move with the lubrication effect created by the arrival of the fluid. These initial measurements did, however, demonstrate that thickness changes were significant enough to influence local reinforcement permeability, therefore emphasizing the need for more extensive measurements.
Figure 4-7: Example of laminate thickness measurement using laser gauges; 
a) experimental setup and b) results.

In [42], Li et al. used a 3D laser scanner for measuring the laminate thickness variation during the infusion process. However, given the first initial results with laser gauges and the cost of such equipment, this solution was not explored. Instead it was decided to develop a system similar to that developed
by Andersson in [41], but using cheaper general purpose digital cameras rather than CCD-cameras. The method and software were developed in collaboration with the Communication and Information Technology Research (CITR) centre of the University of Auckland. Work at the CITR was performed by Yizhe Lin under the supervision of Associate Professor John Morris.

4.2.2 Theory of Stereophotogrammetry

The thickness measurement technique developed here is based on speckle photogrammetry [41, 129, 130], the idea being to compare a pattern on an object surface before and after deformation. The stereo version of this technique allows for out-of-plane deformation measurement, and reduces problems with perspective errors. Before deformation, a pair of reference images was taken by a pair of cameras and a set of correspondences was established. During deformation, two sequences of images were taken. The relative displacements to the reference images were calculated on a left-left and right-right comparison basis. Having collected all the initial states and the displacement vectors, the 3D deformations were calculated by triangulating corresponding pairs formed by their initial positions plus displacement vectors.

4.2.2.a Matching of the Measurement Points

The technique applied here records only the displacement vector of the vacuum bag covering the preform. To extract the 3D data out of a pair of 2D images requires a triangulation calculation. For triangulation, the initial coordinates in the left and right reference images must be established.

Since the focus is on thickness variation and laminate stacking is uniform across the surface, the initial vacuum bag surface can be approximated as a plane due to its large dimension as compared to the diameter of the fibre tows. Thus correspondences at the initial stage can be approximated as a planar homography, \( H \), a 3x3 matrix:
\[ x' = Hx, \quad (4-1) \]

where \( x \) and \( x' \) are a pair of corresponding points in the left and right images respectively. Given coordinates of at least four pairs of corresponding points, the planar homography can be found by direct linear transformation. Once the planar homography is known, a set of points \( P_{i,j} \) is chosen in the left image and the corresponding points are determined in the right image, it is at these points that the displacements are measured. Figure 4-8 shows a pair of images with 200 measurement points superimposed on the laminate. The density of the measurement points repartition can be increased or decreased as required.

![Figure 4-8: Example of points registration on a pair of a) left and b) right images.](image)

### 4.2.2.b In-Plane Displacement Measurement

Given a unique pattern on an object surface, the corresponding region in a subsequent image can be found by cross correlation of the original pattern with the subsequent image. Consider matching a pattern of greyscale or RGB values \( w(x,y) \) of size \( J \times K \) pixels in an image, with \( f(x,y) \) of size \( M \times N \) pixels in the subsequent image, \( x \) and \( y \) being the pixel coordinate in each individual image. The correlation between \( w(x,y) \) and \( f(x,y) \) is:

\[
c(s,t) = \sum_{x=0}^{J-1} \sum_{y=0}^{K-1} f(x,y)w(x-s,y-t), \quad (4-2)
\]

where \( s = 0, 1, 2, \ldots, M-1, \ t = 0, 1, 2, \ldots, N-1 \). The position of the maximal value in \( c(s,t) \) indicates where \( w(x,y) \) matches \( f(x,y) \). The correlation can be
computed in the frequency domain if \( f \) and \( w \) have the same size (i.e. when \( M=J \) and \( N=K \)). Then:

\[
f(x, y) \circledcirc w(x, y) \leftrightarrow F^*(u, v)W(u, v),
\]

where \( f(x, y) \circledcirc w(x, y) \) denotes the correlation between \( f(x,y) \) and \( w(x,y) \), and \( F(u,v) \) and \( W(u,v) \) are the Fourier Transforms (FT) of \( f(x,y) \) and \( w(x,y) \).

Equation (4-4) shows that the correlation in the spatial domain can be obtained by taking the inverse transform of \( F^*(u,v)W(u,v) \) in the frequency domain:

\[
c(s,t) = F^{-1}\{F^*(u,v)W(u,v)\},
\]

where \( F^{-1} \) is the inverse FT operator. In general the translation will be non-integral, a 2D parabola plotted to the surrounding nine points to estimate a sub-pixel translation value. [131-133]

The random error in locating the correlation peak is [134, 135]:

\[
e = k\zeta \sqrt{\frac{1-\delta}{\delta}},
\]

where \( \delta \) is the Yamaguchi correlation factor [134], \( \zeta \) is the average speckle size (size of the dots of white paint), and \( k \) is a function of \( \zeta \) and the inverse of the pattern size. The accuracy drops quickly as the correlation drops. If there is a large displacement between two fields, the correlation function will have a smeared out peak because of the decreased correlation (less overlapping area). In such cases, for the biggest possible overlapping area, the position of the window will be shifted to the new position until the integral translation is zero. The sub-pixel peak position is then estimated after this shift; this estimation has a precision of \( 1/100 \)th of a pixel. Centering the patterns on the points \( P_{ij} \) enables mapping of the displacement of the \( P_{ij} \) in both the left and right image sequence, and subsequent calculation of the image coordinates of \( P_{ij} \) in every image.
### 4.2.2.c Deformation Calculation

Once the image coordinates of the points $P_{ij}$ in the initial and following images are known, normal stereophotogrammetry and triangulation techniques are used to determine point positions in the global coordinates $(X,Y,Z)$ out of the coordinates $(x_L, y_L)$ and $(x_R, y_R)$ of that point in the left and right image respectively. With calibrated stereo cameras, the position of a scene point can be obtained by intersecting two rays formed by the corresponding points in the left and right images (see Figure 4-9). From calibration, the distance $b$, separating the optical centres $O_L$ and $O_R$ of the left and right camera respectively, is calculated as well as the angles $\Phi_L$ and $\Phi_R$ between the baseline and the optical axes of respectively the left and right camera. The optical axes intersect at the fixation point $\Omega$. A point $P(X_P, Y_P, Z_P)$, appears at $(x_L, y_L)$ in the left camera image and $(x_R, y_R)$ in the right camera image. If global coordinates are referenced to an origin, $O_w$ (mid-point of the baseline joining the two camera optical centres) and axes $X$, $Y$ and $Z$ as shown in Figure 4-9, then the coordinates of the point $P$ are:

$$X_P = \frac{b}{2} \left( \frac{f \tan \varphi_R + x_R}{f \tan \varphi_L + x_L} \right) \left( f - \tan \varphi_L x_L \right) + \left( \frac{f \tan \varphi_L + x_L}{f \tan \varphi_R + x_R} \right) \left( f - \tan \varphi_R x_R \right)$$

$$\left( f \tan \varphi_L + x_L \right) \left( f - \tan \varphi_R x_R \right) - \left( f \tan \varphi_R + x_R \right) \left( f - \tan \varphi_L x_L \right), \quad (4-6)$$
\[
Z_p = -\left(\frac{b}{2} + X_p\right) \frac{f \tan \varphi_L + x_L}{f - \tan \varphi_L x_L},
\]
(4-7)

\[
Y_p = \frac{Z}{f \sin \varphi_L} y_L,
\]
(4-8)

where \( f \) is the focal length [136]. For the speckle stereophotogrammetry technique applied here, the initial points \( P_{i,j} \) are arbitrarily chosen and defined as being at \( Z = 0 \). The positions of the points after deformation are calculated compared to the initial map. In other words, the system can only extract laminate thickness variation instead of actual thickness. The initial laminate thickness was measured prior to the filling stage using a dial gauge.
4.2.3 Development of the Setup

4.2.3.a Rig Construction

Using the stereophotogrammetry system developed here requires the acquisition of two similar digital cameras. With a measurement precision of 1/100th of a pixel, the accuracy of the thickness measurement depends on the resolution of the camera and the size of the measured area. It is possible to increase the resolution of the measurement by either using higher resolution cameras or by reducing the measured area by moving the cameras closer to the subject. The choice of the camera was therefore a result of the choice of measured area and the minimum acceptable resolution, while also trying to reduce the cost of the setup. The Canon EOS 20D with a resolution of eight mega-pixels was chosen as a result. The advantage of the Canon camera over competing brands was also a more readily available Software Development Kit to be able to modify the existing remote control system enabling the camera to be controlled from the computer.
Every camera lens creates a varying amount of distortion to the recorded image, especially around the edges. The amount of distortion increases as the focal length decreases and is also higher for a zoom lens than for a fixed focal length. To minimise the deformation from the camera lenses, each camera was fitted with an *EF 50mm f/1.8 II* fixed focal length lens. This lens choice was made as a trade off between the amount of distortion created by shorter focal length, and the necessity to keep the camera at a reasonable distance from the measured surface while enabling measurement on the whole length of the laminate. These lenses have a minimum aperture of f/22 enabling to keep focused on objects at a wide range of distances. This characteristic is important to enable the camera to be oriented with a larger angle ($\Phi$ in Figure 4-9). The lenses have a horizontal angle of view of 40°. From this characteristic, the distance between the camera and the measurement surfaces can be calculated by triangulation; to enable measurement over a width of 800 mm with a baseline between the cameras of 1020 mm, the baseline axis must be positioned 1800 mm away from the measured surface.

The frame built to hold the camera must therefore permit to hold the camera 1800 mm high over the infusion table; it must also be sturdy and not allow for too much vibration. Excessive vibration in the frame will decrease accuracy of measurement by moving the camera relatively to the measured surface. For this purpose the main frame is built with *60x60 Heavy* aluminium profiles (as pictured in Figure 4-11a). These profiles provide a light and sturdy structure, composed of two vertical profiles 2000 mm long, and one 1200 mm long horizontal one able to slide along the vertical mounts. To increase the rigidity, four set of braces were installed between the table and the vertical mount, and a pair of braces was installed between the vertical mount and the horizontal profile holding the cameras, as seen in Figure 4-1, all braces being made of *30x30 aluminium extrusion* (as pictured in Figure 4-11b).
Figure 4-11: Details of the Aluminium extrusion profiles: a) 60x60; and b) 30x30.
To secure the camera onto the mounting frame, special mounting plates, shown in Figure 4-12, were designed and built. The mounting plates work as a pair, one attaching to the mounting frame and the other attaching to the camera. The plate attached to the frame is secured by four M6 bolts screwed onto special nuts running in the grooves of the aluminium profile. To provide a good hold of the camera, both the tripod socket and pin hole are used. A special pin mounted on a circular slot can be secured in any position to allow precise orientation of the camera. Each plate had holes drilled to allow room for the screw head coming out of the other plate. The plates are secured together using four M4 screws and butterfly nuts, one on each corner as depicted in Figure 4-13.
4.2.3.b Control of the Cameras

Each camera is connected via USB2 to a different computer as the communication standards of the Canon EOS 20D does not allow for a single computer to control more than one camera at once. The EOS Capture v1.2.0.7 program supplied by Canon, allows remote control of the camera settings and taking of pictures from the computer. This program also allows pictures to be taken at a set time interval; however there is no possibility of synchronising the image acquisition between the two cameras and it would be very hard to correlate the thickness data with the pressure or flow rate data as the sets of data are acquired completely independently. Instead the UCSCCanonRC v1.0 developed at the University of California Santa Cruz and modified by Associate Professor John Morris from the Communication and Information Technology Research (CITR) of the University of Auckland was used. The modification
enabled the program to capture an image on reception of a broadcasted signal generated by the LabView program capturing the pressure and flow data.

4.2.3.c Software Implementation

4.2.3.c.i Data Acquisition

Figure 4-14: Schematics of the data acquisition setup.

Figure 4-14 presents the schematics of the data acquisition setup; two computers were required for the acquisition setup. One computer was used to acquire the temperatures, pressures and mass of the resin pot data, as well as control one of the cameras. The other computer was networked to that first one and used only to control the second camera. The temperature and pressure data were acquired using a National Instruments NI SCXI1000 box equipped with a NI SCXI1112 thermocouple input module and a NI SCXI1302 terminal box. The thermocouples embedded in the temperature control table were connected to the NI SCXI1112 thermocouple input module, while the SCXI1302 terminal box was used for the input of the pressure transducers data as well as an output to control the thermolator. The mass balance was connected through the serial port, while the camera was connected through a USB2.0 port. A
LabView application was created with different modules to acquires, and process the data as well as control the thermolator and cameras.

A first module evaluates the temperature given by the thermocouple embedded in the temperature controlled table and compares the averaged value to the desired temperature; the temperature setting of the thermolator is then updated in function of that result. The averaged temperature is also recorded in an output file. Another module was created to measure the output of the pressure transducers as well as the reading of the mass balance and write those data in the output file. The last module was created to broadcast a signal at a set interval and write it in the output file to have a time stamp of each picture taken. That broadcasted signal can be received simultaneously on both computer and triggers the UCSCCanonRC to capture an image from the cameras. Due to the time to transfer the image data from the camera to the computer, the maximum rate of acquisition was set to a maximum of one image per five seconds to ensure a smooth transfer.

4.2.3.c.ii Image Correlation

The image correlation software was implemented in C++ by Mr Yizhe Lin and John Morris from CITR at the University of Auckland, following the principle exposed in Section 4.2.2. This program outputs a map of thickness variation for each pair of image which can then be interpreted in term of $V_f$ and permeability.

4.2.3.d Calibration and Verification Tests

![Figure 4-15: Stereophotogrammetry calibration rig.](image)

A rig has been developed to calibrate the stereophotogrammetry system and verify its accuracy (see Figure 4-15). A steel plate, 290 mm long, 130 mm
wide and 20 mm thick, was cut at a 30° angle at both ends and is painted on the top surface with a high frequency random pattern. A wedge mounted on a linear translation screw is used to raise and lower one end of the plate. A *MITUTOYO ID-C112CE* dial gauge measures displacement of one point on the plate, enabling calculation of the whole surface displacement. An initial series of images were recorded while keeping the plate stationery, in order to determine measurement noise.

![Figure 4-16: Evaluation of the stereophotogrammetry over a flat stationary plate.](image)

Figure 4-16 presents thickness variation along the centreline of the plate, at seven instants over one hour. The maximum standard deviation at any instant is 0.014 mm, the variations being due to a combination of small vibrations in the mounting frame, and unavoidable errors generated during the image recognition process. The observed drift with time is most likely due to thermal contraction in the camera mounting frame. With a thermal expansion coefficient of $2.36 \times 10^{-5} \ 1/\degree C$, a 2°C variation will cause a change of 0.087 mm to the length of the aluminium uprights. To eliminate this effect, a stationary plate was placed in the view field of the cameras during the RI experiments (as seen at the top of Figure 4-8). The thermal drift was monitored and deducted from the measured thickness variation, as part of the standard procedure.
A second test was completed while changing the orientation of the flat plate. Figure 4-17 presents the comparison between the stereophotogrammetry data and position measured using the dial gauge. The average deviation from the theoretical measurement was 0.04 mm.

![Graph](image)

Figure 4-17: Evaluation of the stereophotogrammetry on an angled plate.

Given these results, we will consider an accuracy of ±0.05 mm for the system in this configuration. Reducing the measuring field, by lowering the cameras or using lenses with a longer focal length, would increase the accuracy if required.

### 4.3 Preliminary Experimental Observations

Discussion is presented in this section on observations made during preliminary experiments aimed at evaluating the influence of various parameters as well as finding some of the factors affecting the repeatability of the RI experiments.
4.3.1 Influence of Fluid Viscosity

![Schematic representation of the lay-up for testing the influence of fluid viscosity.](image)

To investigate the influence of the fluid viscosity, infusion tests were performed with different fluids. The preforms tested were 200 mm wide by 250 mm long and composed of 10 layers of CSM (as characterised in Chapter 3). To isolate only the fluid viscosity as a variable, the tests were performed simultaneously with three preforms in parallel on the temperature controlled table. The preforms were individually bagged but the vacuum ports were connected together. The preform were laid up so that on each preform, a pressure transducer (P₁, P₂ and P₃) can measure the fluid pressure 5 mm away from the inlet as shown in Figure 4-18. At both inlet and vent ends of the preform, a 100 mm wide distribution tape (Enkachannel FPF-100) was laid up for even distribution of the resin and vacuum respectively. During pre-filling the vacuum was drawn for 10 minutes, and then released for five minutes before applying vacuum again for five minutes before the start of the infusion.
Two tests were performed with different fluids as presented in Table 4-1. Due to small differences in temperature and maximum achievable vacuum, when comparing between test A and test B, the traces of the tests using Mobil DTE Heavy (preform 3 and 6) as well as the traces of the tests using the Mobil DTE Light (preform 2 and 4) were showing a noticeable disparity when compared together. However, the ratio of fill time as well as the difference of pressure traces between the Mobil DTE Light and Heavy for time normalised to the fill time appeared to be consistent between test A and test B.

### Table 4-2: Fill time comparison for different fluid viscosity.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Approximate Viscosity (Pa.s)</th>
<th>Fill Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.000891</td>
<td>7</td>
</tr>
<tr>
<td>Mobil DTE Light</td>
<td>0.0581</td>
<td>225</td>
</tr>
<tr>
<td>Mobil DTE Medium</td>
<td>0.119</td>
<td>550</td>
</tr>
<tr>
<td>Mobil DTE Heavy</td>
<td>0.195</td>
<td>760</td>
</tr>
</tbody>
</table>

Figure 4-19 presents the evolution of the fluid pressure at a point 5 mm away from the inlet for infusions with four different fluids. To compare these tests despite the very different filling times, Figure 4-20 presents the fluid pressure near the inlet as a function of the time normalised to the fill time for some of the performed tests. For clarity of reading it was decided not to plot the traces of preforms 2 and 3. It can be observed from Figure 4-20 that the distilled water has a very different trace during both filling and post-filling. The viscosity of the distilled water is many orders of magnitude smaller than any of the oil used, the preform was filled in 7 seconds and the pressure at the inlet only reached 910 mbar by the time the flow front reached the vent. Pressure
evolution during post-filling was also significantly faster than with any of the oils used. The trace of the Mobil DTE Light pressure shows very little difference with the other oils during the filling stage but appears to decrease slightly faster than the others during post-filling and achieve a lower pressure after a post-filling time equivalent to six times the fill time. There seems to be very little difference between the traces of the Mobil DTE Heavy and DTE Medium oils for both filling and post-filling.

Figure 4-19: Fluid pressure near the inlet as a function of the injection time for four different fluids.
Figure 4-20: Fluid pressure near the inlet as a function of the relative injection time for four different fluids, the dashed line representing the end of filling.

By following Darcy’s law as proposed in Section 2.2.2 or in [27], all of these traces should perfectly match each other. The disparity between these experiments and the predicted results provided a small hint that there is a small but real deviation from Darcy’s law influenced by the fluid viscosity especially during the post-filling stage of the RI process.
4.3.2 Influence of Preform Length

To evaluate the influence of the preform length a similar type of test as presented in Section 4.3.1 was performed but varying the preform length and using the same test fluid *Mobil DTE Heavy* for all experiments. Three preform lengths were tested, 200, 400 and 600 mm as depicted in Figure 4-21, the *Enkachannel FPF-100* distribution tape was again used at both the inlet and vent.

Table 4-3: Fill time for infusion with three different lengths.

<table>
<thead>
<tr>
<th>Preform Length (mm)</th>
<th>Fill Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>725</td>
</tr>
<tr>
<td>400</td>
<td>1640</td>
</tr>
<tr>
<td>600</td>
<td>3650</td>
</tr>
</tbody>
</table>
Figure 4-22: Fluid pressure near the inlet as a function of the relative injection time for three different preform lengths.

Figure 4-22 presents the evolution of the fluid pressure over the pressure transducers during the experiment. The pressure traces overlap relatively well and the fill time appears to increase as a function of the square of the preform length as predicted by the theory proposed in Section 2.2.2 and in [27]. To evaluate the effect of the preform length on the post-filling stage, the pressure transducers reading are plotted against the relative time in Figure 4-23. It can be observed that the longer the preform, the slower the drop of pressure during post-filling. After a time equivalent to 7 times the fill time the pressures are still not fully settled. The residual pressure left after post filling was also larger in the longer preform. This seems to indicate a deviation from Darcy’s law influenced by the pressure gradient.
4.3.3 Other Factors Influencing the Repeatability

Amongst the factors influencing the repeatability of the process, the temperature and vacuum level are the most obvious. But also critical is the placement of the inlet and vent relative to the preform. A slight increase of the distance between vent and preform can dramatically affect the bleeding of the resin during post-filling as will be presented in Chapter 6, while the distance between inlet and preform will affect the fill time dramatically if no distribution medium is used.

When the vacuum is applied to the cavity, the bag may create a bridge between the edges of the preform and the mould, creating a small gap that will
procure a path of least resistance to the flow that will therefore race along that edge. This phenomenon known as race-tracking can also occur around ribs or inserts or any irregularity in the preform. The presence of race-tracking along the edges of the preform or following folds in the vacuum bag can alter the progression of the flow front by drawing more resin through the least resistance path. Race-tracking can also affect the final quality of the composite especially if two fronts join entrapping some unsaturated part of the preform causing dry spots or increased porosity [12, 137-139].

Another important factor that has been observed is the position of the vent tube. If the vent tube goes up somewhere between the vent port and resin trap, a pool of fluid tends to form in the tube that will result in an increased pressure at the vent port. Once the fluid reaches the top of that pool, it overflows towards the resin trap a small quantity at a time. This results in sudden drop of fluid pressure at the vent port that can be traced a long way into the preform. This phenomenon is responsible for the ‘steps’ observed close to the inlet during post-filling in Figure 4-20 and Figure 4-23.

4.4 Analysis of a Sample Resin Infusion Experiment

In this section, the data acquired from an infusion experiment performed on the post-filling study mould presented in Section 4.1.1.b, will be analysed as a demonstration of the RI monitoring setup presented in this chapter.

4.4.1 Experimental Parameters

The preform used in this experiment was composed of 10 layers of the Chopped Strand Mat characterised in Chapter 3. The preform was cut into a rectangle 380 mm long and 200 mm wide. After aligning one end of the preform with the inlet groove on the mould, a piece of distribution tape Enkachannel FPF-100 was laid up against the other end of the preform to connect the preform to the vent. Some tacky tape was applied on the sides of the preform to maintain it in position as well as limit the occurrence of race tracking due to bridging of the vacuum bag. The preform and distribution tape were then
covered with one layer of peel ply. The cavity was then sealed with a vacuum bag previously painted with a highly random speckle pattern. Two 20 mm wide strips of bag were left unpainted at the sides of the preform to monitor the progression of the flow front. Once the cavity was properly sealed, vacuum was applied through the vent. The cavity was then left under vacuum for 10 minutes to check for any leak and apply a first dry compaction to the preform. After 10 minutes, the vacuum was released and the preform was left to settle uncompressed for 5 minutes. Vacuum was then applied again and the preform was left under vacuum for another 5 minutes to allow for any creep to occur. The picture acquisition was started at that moment, and the initial thickness measured at the centre of the preform using a MITUTOYO ID-C112CE dial gauge. The inlet gate was then opened to start the infusion. Once the fluid reached the end of the preform, the inlet gate was closed and the fluid pressure left to equilibrate during post-filling. Full vacuum (~3.5 mbar) was applied at the vent during both filling and post-filling stages.

Establishing a line infusion and using a preform with no distribution media meant that the flow during the experiment is purely 1D along the length of the preform. Apart from a very short length at the inlet, there should be no flow in the through thickness direction or in the width direction. This one-dimensional assumption is necessary to compare these experimental results to the 1D finite element simulation developed and presented in Chapter 5.
4.4.2 Flow Front Progression

Figure 4-24: Evolution of the flow front during the RI experiment.

Using the pictures acquired for the stereophotogrammetry measurement it is possible to measure the progression of the flow front in the two viewing strips left unpainted. Measurement of the flow front position was made using a code developed in Matlab in collaboration with Ming Gan, and presented in Appendix C, making use of the built in image processing library. The optical properties of the saturated preform being quite different from the unsaturated part, the filled portion can easily be identified by using an appropriate thresholding and binarisation. The size of the saturated portion can then be easily measured.

The flow front position was correlated with the time through the time stamp of image acquisition in the LabView output file. The progression of the flow front is plotted in Figure 4-24. It can be observed that the fill time appears proportional to the square of the filled length in agreement to the analytical solution proposed by Correia et al. [27]. The fill time for this experiment was 1187 seconds.
4.4.3 Flow Rate into the Preform

From monitoring the mass of the resin pot, it is possible to calculate the rate of fluid flow into the laminate, which is plotted in Figure 4-25. The total amount of fluid infused into the laminate can also be calculated; however there is no measurement of the amount of fluid extracted during the post-filling stage. In the experiment presented in this section, the preform had a mass of 348.3 g and 175 g of *Mobil DTE Heavy* oil was injected to fill the preform.

![Figure 4-25: Flow rate into the cavity during the RI experiment.](image-url)
4.4.4 Laminate Properties

Figure 4-26: Map of laminate thickness at four instants during the RI process. a) Just prior to filling (t=0 s); b) when flow front reaches half of the preform (t=349 s); c) at the end of filling (t=1187 s); and d) at the end of post-filling (t=12000 s).

Figure 4-26 presents sample maps of laminate thickness obtained through stereophotogrammetry measurement at four different instants during the RI process. In Figure 4-26b, the position of the flow front is marked by the dashed yellow line; no thickness reduction can be detected at the flow front in this experiment. It can be observed on these figures that most thickness change occurs near the inlet and on the inlet half of the preform. At the end of filling the thickness at the inlet is about 55% larger than at the vent.
Figure 4-27: Evolution over time of the thickness along the length of the preform, averaged across the width of the mould.

As the flow through the laminate is purely 1D, it is possible to present the evolution of the laminate properties along the length of the mould in a single graph by averaging the desired property across the width of the preform. Figure 4-27 presents the evolution of thickness along the mould during the filling and post-filling stages. Through knowledge of the laminate thickness, the local $V_f$ can be calculated using Equation (3-1). Figure 4-28 presents the evolution of the $V_f$ during the experiment. Knowledge of $V_f$ distribution in time can then be used to infer the resulting variation in reinforcement permeability. Figure 4-29 presents the evolution of the reinforcement permeability, as calculated using Equation (3-7) and the permeability characterisation parameters established in Section 3.3 for the CSM.

The format of Figure 4-27 to Figure 4-29 allows to quickly evaluate the evolution of the desired parameter in both time and position throughout the process. These figures clearly show that most of the thickness and $V_f$ changes
occur in the inlet half of the mould. At the end of filling, thickness near the inlet reduces very quickly. As post-filling progresses, the rate of reduction falls. From Figure 4-29, it can be seen that there is a rather large variation of permeability on the inlet half of the preform. At the end of filling, the permeability is about five times larger at the inlet than at the vent, and the first third of the preform has a permeability more than double than that at the flow front. Throughout the filling, there is a significant permeability increase on the first third of the saturated portion of the preform.

Figure 4-28: Evolution over time of the $V_f$ along the length of the preform, averaged across the width of the mould.
Figure 4-29: Evolution over time of the permeability along the length of the preform, averaged across the width of the mould.
4.4.5 Fluid Pressure

Figure 4-30: Evolution of the fluid pressure along the preform during a RI experiment.

Through the pressure transducers embedded in the mould, it is possible to follow in real time the evolution of the fluid pressure inside the laminate at five discrete locations. Figure 4-30 presents the evolution of the fluid pressure in the laminate during the RI experiment. After a time equivalent to ten times the fill time, there does not appear to be any more change in pressure over time but a small pressure gradient subsists inside the laminate. Figure 4-31 presents the pressure distribution in the laminate at various times during post-filling. It can be clearly seen that as the time progresses, the rate of pressure changes decreases until being negligible. It can also be noted that as opposed to 1D flow in an RTM situation, the pressure distribution along the length of the preform at the end of filling is not linear.
Using data generated by the stereophotogrammetry system it is also possible to relate the fluid pressure and laminate thickness evolutions in time, as presented in Figure 4-32. It can be observed that very little thickness changes happen over the pressure transducers closest to the vent (P6 and P7). As would be expected by consideration of the compaction model developed in Chapter 3, very small fibre volume fraction changes occur unless fluid pressure exceeds 40000 Pa (i.e. there is very little change in reinforcement compaction while the compaction pressure is superior to 60000 Pa). At the centre point of the preform the thickness only rises from 3.7 mm to 3.8 mm during filling (equivalent to a 2.7% increase), while at the location P1 the thickness rises from 3.7 to 5.2 mm (a 40% increase). This increase in thickness results in an
increasing permeability; at P1 the permeability has increased by 445% by the end of filling, at P2 the increase is 146%, and at P4 permeability increases by only 17%. This large increase of thickness and permeability will have a significant influence on the flow during filling as was demonstrated in [140]. During post-filling, the fluid pressure and laminate thickness initially drop fairly rapidly, but then the rate of reduction slows down, until the pressures stabilise after a post-filling period of about 20 times the fill time (~21000 s of post-filling). When following the fluid pressure at P1, at the end of filling the pressure is about 98000 Pa. After a time equivalent to the fill time, that pressure is 48000 Pa; the fluid pressure is about 24000 Pa after a time equivalent to three times the fill time. It can be noticed that after 10000s, despite the fluid pressure being higher near the inlet than at the vent, the thickness is slightly smaller at the inlet than at the vent. This observation would be in contradiction with an elastic model of reinforcement compaction, but is qualitatively in accordance with the interpolated re-compaction model, developed in Chapter 3. This model takes into account the loading history of the reinforcement.
Figure 4-32: Evolution of the fluid pressure (a) and laminate thickness (b) over the different pressure transducers during the RI experiment.

Being able to relate fluid pressure and laminate thickness at specific points allows the study of the compaction behaviour, and for comparison to the model
developed in Chapter 3. Figure 4-33 presents such a comparison. It is apparent from this figure that the wet reinforcement unloading happening over transducer P1 (35 mm away from the inlet) does not exactly follow the unloading model obtained through the compaction test in the Instron. However, the model appears to provide a relatively good fit to the traces obtained at P2 and P4. This discrepancy could possibly be explained by differences in loading rates; at the inlet the fluid pressure rises very rapidly to 1.0 bar, while further along the preform the rise of fluid pressure is much slower. Therefore, the deformation rate for the reinforcement is varying along the length of the preform. The reinforcement compaction model developed in this thesis is based on elastic models and therefore cannot account for these viscoelastic effects. It can be argued that the deviation from the proposed model is relatively small and only occurs very close to the inlet, and the model is therefore acceptable for use in a simulation of the RI process with the CSM reinforcement.

Looking at the traces during post-filling, the difference between the unloading and re-compaction traces is in relatively good accordance to the re-compaction model developed in Section 3.2.4. While the compaction model developed in Chapter 3 does not provide a perfect fit to the compaction behaviour exhibited during the RI experiment, it is in qualitative agreement, and provides reasonable quantitative estimations of the reinforcement behaviour during the infusion process.
4.5 Conclusion

In this chapter, the resin infusion monitoring setup was presented. A stereophotogrammetry technique was developed to provide full field laminate thickness measurements, and this has been coupled with measures of fluid pressure, flow front position, and mass of fluid injected. The results of a single infusion experiment were analysed as a demonstration of the capabilities of this setup.

Simple studies were presented on potential causes of process variability. From the experimental observations, the evidence of a small deviation from
Darcy’s law and the existence of a residual pressure gradient at the end of the process were pointed out.

The reinforcement compaction behaviour characterized using an Instron testing machine and modelled in Chapter 3 was compared to experimental observations of the RI process. The proposed model appears to provide a reasonable qualitative and quantitative fit to the experimental data.

The RI monitoring setup was used to validate the compaction model developed in the previous chapter and could be used as an alternative method of characterising the reinforcement compaction behaviour.
In the composites manufacturing industry, the use of numerical simulation is increasing constantly. As the properties of composite materials can be tailored to the designed application, structural finite element analysis is widely used to predict the stresses in the part and optimize the fibre orientation and placement to attain the desired mechanical properties and minimize weight. But simulation is not limited to structural modelling; numerical techniques can also be used to simulate the manufacturing process, helping a manufacturer to create new products without long and costly trial and error process development.

This chapter will present the development of a 1D transient finite element simulation of the RI process. In a first part, the development of a 1D RTM and I/CM simulation will be presented as first steps towards the RI simulation. Then the implementation of various parts of the simulation will be presented before comparing the final implementation of the simulation with the experiment presented in Section 4.4.

5.1 Galerkin Finite Element method

This section will briefly describe the fundamentals of the Finite Element Method (FEM) used to build a one dimensional model of the LCM processes.
The finite element method is used to find numerical approximate solutions of complex differential equations by dividing the domain of application into smaller elements and approximating the complex equation by simpler equations over each element [141].

### 5.1.1 Approximation of the Variables

In this thesis, it was chosen to use one dimensional linear elements, meaning that each variable is approximated using linear shape functions over an element. A shape function is a function defined only inside each element which is used to interpolate the values of a variable inside an element as a function of the known value at the nodes and the position inside the element in local coordinates. The linear shape functions are expressed in local coordinates as:

\[
N_1(\xi) = \frac{1 - \xi}{2} \quad \text{and} \quad N_2(\xi) = \frac{1 + \xi}{2}, \quad (5-1)
\]

and the transformation from global to local coordinates follows the following Equations:

\[
x = \frac{1 - \xi}{2} x_i + \frac{1 + \xi}{2} x_{i+1}, \quad \xi = \frac{2(x - x_i)}{x_{i+1} - x_i} - 1, \quad \frac{d\xi}{dx} = -\frac{2}{x_{i+1} - x_i} = \frac{2}{L}. \quad (5-2)
\]

Each variable is expressed using trial functions, that use the discrete values at each node of the finite element mesh and the shape functions to obtain a continuous representation over the whole domain. For example the fluid pressure is expressed as:

\[
P \approx P_i N_1 + P_{i+1} N_2. \quad (5-3)
\]
5.1.2 Formulation Process

Each of the LCM processes have different governing equations, therefore the final formulation of the models will differ. However in each case, the formulation is derived from the same steps defined here.

The strong formulation of the governing Equation is expressed over the domain \([x_i, x_{i+1}]\) as:

\[
I = \int_{x_i}^{x_{i+1}} G(u) \omega(x) \, dx = 0,
\]  

where \(G(u)\) is the governing Equation (\(u\) being the variable to be evaluated), and \(\omega(x)\) is the weight function. In the Galerkin finite elements method, the weight functions are the shape functions. There is therefore for each element a pair of equations, one for each shape function.

If a derivative of order two or greater is present in the strong formulation, a weak formulation is obtained by integrating by parts the terms of order greater than two until only first derivatives are present.

The variables in the weak formulation are then replaced with their corresponding discretised approximation (5-3). The pair of equations (one for each shape function) are then transformed into the local coordinates and integrated. The resulting linear equations are then split into different parts to create elemental matrices. Solving the governing Equation of the VARTM for the thickness results in:

\[
\overline{K}^{(h)}_{el} + \overline{C}_{el} \frac{\partial \bar{h}}{\partial t} = \overline{F}^{(h)}_{el},
\]  

where \(\overline{K}^{(h)}_{el}\) is the element stiffness vector, \(\overline{C}_{el}\) is the element capacitance matrix, \(\overline{F}^{(h)}_{el}\) is the element force vector, and \(\bar{h}\) is the vector of laminate thickness values associated with the element. The elemental matrices are then
assembled into global matrices by overlapping the elemental matrices with common nodes.

5.1.3 Implicit Solution Method

An implicit method is used by applying a backward difference approximation:

\[
\frac{\partial h}{\partial t} \approx \frac{h(t) - h(t - \Delta t)}{\Delta t}.
\]

(5-6)

The current thickness values \( h(t) \) are estimated from the previous time step, and an iterative approach has been taken to refine the solution. Eqn. (5-5) can then be expressed as:

\[
\begin{pmatrix}
K(h(t)) + C \left( \frac{h(t) - h(t - \Delta t)}{\Delta t} \right)
\end{pmatrix}
= F(h(t)),
\]

(5-7)

where \( \vec{h}(t) \) and \( \vec{h}(t - \Delta t) \) are the vectors of laminate thickness throughout the filled part of the mould at time \( t \) and \( t - \Delta t \) respectively. The estimated error is the residual, \( R(\vec{h}(t)) \), calculated from:

\[
R(\vec{h}(t)) = C(\vec{h}(t) - \vec{h}(t - \Delta t)) + \Delta t (\vec{K}(\vec{h}(t)) - \vec{F}(\vec{h}(t))).
\]

(5-8)

To minimise the residual at each time step, the Newton-Raphson algorithm is used.

\[
\begin{pmatrix}
K(\vec{h}^{i-1})
\end{pmatrix} \cdot \Delta \vec{h}^i = -R(\vec{h}^{i-1}),
\]

(5-9)
The matrix $\bar{K}_r$ is the tangent matrix, $i$ is the iteration number and $\bar{h}^i$ is the vector of thickness distribution at iteration $i$. For the first iteration, the thickness distribution is assumed equal to the thickness distribution at the previous time step. This algorithm is run iteratively until the residual reaches the desired precision.

### 5.1.4 Boundary Conditions

Three types of boundary conditions are applied to the models presented. In all cases, prescribed pressure or prescribed flux can be assigned to the inlet node, and prescribed vacuum pressure is applied to the flow front node. For prescribed pressure, the row of the boundary node in the tangent matrix is replaced with its corresponding row off the identity matrix, and the right hand side vector’s corresponding row is replaced by the prescribed pressure. For prescribed flux, the pressure gradient at the boundary is evaluated through Darcy’s law and substituted into the right hand side vector without changing the tangent matrix.

For the RI process, at every node, the outside atmospheric pressure is combined with the inside cavity pressure to evaluate the compaction stress on the fibres. This physical boundary condition is therefore treated as a loading condition to calculate volume fraction and permeability. In the RI process, the pressure drop in the inlet tube might need to be taken into account in cases where a large flow rate is drawn through a tube of small diameter.

### 5.2 RTM Simulation

#### 5.2.1 Solution Method

In the RTM process, the resin is injected into a rigid closed mould. The cavity thickness does not vary with time. For the RTM simulation, the post-filling was not addressed as it is considered trivial due to the use of a rigid mould. The continuity Equation (2-14) is therefore equivalent to:
\[
\frac{\partial}{\partial x}\left( \frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} \right) = \frac{\partial h}{\partial t} = 0 . \tag{5-10}
\]

In this simulation it will also be assumed that the cavity thickness does not vary spatially.

\[
\frac{\partial h}{\partial x} = 0 . \tag{5-11}
\]

As a consequence, the \( V_f \) and permeability are also constant in time and space. The governing Equation (5-10) can therefore be rewritten as:

\[
\frac{\partial^2 P}{\partial x^2} = 0 . \tag{5-12}
\]

In accordance to the simplifications of Equations (5-10) and (5-11), the volume-averaged velocity expressed in Equation (2-19) can be simplified to the exact formulation of Darcy’s law:

\[
q_s = -\frac{K_{xx}}{\mu} \frac{dP}{dx} , \tag{5-13}
\]

As the governing Equation for the RTM (5-12), does not depend on time, a quasi-static method will be used. For each time step, the system is considered at equilibrium.

Using the Galerkin finite elements method, the strong formulation of Equation (5-12) is:

\[
I = \int_{x_i}^{x_f} \left( \frac{d^2 P}{dx^2} \omega(x) \right) dx = 0 . \tag{5-14}
\]

and integrating by parts gives the weak formulation:

\[
\int_{x_i}^{x_f} \left( \frac{dP}{dx} \frac{d\omega}{dx} \right) dx = \left[ \frac{dP}{dx} \omega(x) \right]_{x_i}^{x_f+1} . \tag{5-15}
\]
Discretising the pressure gives:

\[
\int_{x_i}^{x_{i+1}} \left( P_i \frac{N_1}{dx} + P_{i+1} \frac{N_2}{dx} \right) dN_j \, dx = \left[ \frac{dP}{dx} N_j \right]_{x_i}^{x_{i+1}} .
\]  

(5-16)

Transposing into local coordinates gives:

\[
\int_{\xi_i}^{\xi_{i+1}} \left( P_i \frac{N_1}{d\xi} L + P_{i+1} \frac{N_2}{d\xi} L \right) dN_j \, d\xi = \left[ \frac{dP}{d\xi} N_j \right]_{\xi_i}^{\xi_{i+1}} .
\]  

(5-17)

So for each shape function:

\[
j=1:
\]

\[
\frac{1}{2L} \left( P_i - P_{i+1} \right) \int_{\xi_i}^{\xi_{i+1}} d\xi = - \frac{dP}{dx} \bigg|_{x_i} ,
\]

\[
(5-18)
\]

\[
j=2:
\]

\[
\frac{1}{2L} \left( P_{i+1} - P_i \right) \int_{\xi_i}^{\xi_{i+1}} d\xi = \frac{dP}{dx} \bigg|_{\xi_{i+1}} ,
\]

The elemental matrices are obtained by integrating Equation (5-18):

\[
\mathbf{K}_{el} = \frac{1}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \text{ and } \mathbf{F}_{el} = \begin{bmatrix} - \frac{dP}{dx} \bigg|_{x_i} \\ \frac{dP}{dx} \bigg|_{\xi_{i+1}} \end{bmatrix}
\]

(5-19)

This results in the linear system of Equation (5-20); \( \mathbf{P} \) being the vector of pressure along the mould. It should be noted that the alternating sign in the elemental right hand side matrix, will result in overlapping points cancelling each other in the global matrix.

\[
\mathbf{K}_{el} \mathbf{P} = \mathbf{F},
\]

(5-20)
The computational method implemented for simulating the RTM process is detailed in Figure 5-1. At each step, the time step is calculated as the time required to fill the element adjacent to the flow front, considering the calculated flow front velocity at the start of the time step. To start the simulation, the first element is considered full and the initial time is calculated backwards by estimating the time required to fill the first element considering the flow front velocity calculated when the fluid has saturated the first element.

![Figure 5-1: Flow chart of the RTM simulation.](image)

5.2.2 Material Data

5.2.2.a Compaction Behaviour

As opposed to the RI, the driving factor for the reinforcement compaction is the laminate thickness, or $V_f$. The $V_f$ is imposed and the resulting compaction stress is calculated. Two non linear elastic laws were created, one for dry
compaction and one for wet compaction. The elastic laws were fitted to compaction tests performed by Mr. Andrew Walbran, using fifth order polynomial fitting [142].

5.2.2.b Permeability

The permeability was calculated as a function of \( V_f \) in the same manner as presented in Section 3.3.

5.2.3 Results

5.2.3.a Analytical Solution

5.2.3.a.i Constant Inlet Flow Rate

In the constant flow rate case, a constant flow is forced through the inlet. This method allows for a fast injection but can result in very large fluid pressure at the inlet as the dimension of the part to inject increases.

If \( Q_{\text{inlet}} \) is the constant flow rate at the inlet and \( A_{\text{inlet}} \) is the cross section area at the inlet, then:

\[
q = \frac{Q_{\text{inlet}}}{A_{\text{inlet}}}. \tag{5-21}
\]

Using Equation (2-19) to relate the volume averaged velocity to the flow front velocity:

\[
v = \frac{dx_f}{dt} = \frac{q}{\phi \phi A_{\text{inlet}}} = \frac{Q_{\text{inlet}}}{\phi A_{\text{inlet}}}, \tag{5-22}
\]

integrating (5-22) over the time leads to:

\[
x_f = \frac{Q_{\text{inlet}}}{\phi A_{\text{inlet}}} t + C_i. \tag{5-23}
\]

At \( t=0, x_f=0 \) therefore:
\[ x_f = \frac{Q_{inlet}}{\phi A_{inlet}}. \quad (5-24) \]

There is a linear relationship between the time and the flow front position. The time required to fill a mould of length \( l \) is then:

\[ t_{fill} = \frac{\phi A_{inlet}}{Q_{inlet}} l. \quad (5-25) \]

### 5.2.3.a.ii Constant Inlet Pressure

In the constant inlet pressure case, the fluid is injected under constant pressure \( P_{inlet} \) at the inlet, while the pressure at the flow front is also constant and equal to the pressure at the vent \( P_{vent} \) (usually vacuum or atmospheric pressure). This technique allows for smaller tooling forces but the fill time can dramatically increase with larger preforms.

Using the RTM governing Equation (5-12); Darcy’s law (Equation (2-13)) can be rewritten as:

\[ q_x = -\frac{K_{xx}}{\mu} \left( \frac{P_{vent} - P_{inlet}}{x_f} \right); \quad (5-26) \]

Using Equation (2-19) to relate the volume averaged velocity to the flow front velocity results in:

\[ v = \frac{dx_f}{dt} = \frac{q_x}{\phi} = \frac{K_{xx}}{\phi \mu} \left( \frac{P_{vent} - P_{inlet}}{x_f} \right); \quad (5-27) \]

This leads to:

\[ \int x_f dx_f = \frac{K_{xx}}{\phi \mu} \left( P_{vent} - P_{inlet} \right) dt. \quad (5-28) \]

At \( t=0, x_f=0 \) therefore (5-28) can be solved as:
\[ x_f ^2 = -\frac{2K_{xx}}{\phi \mu} \left( P_{\text{vent}} - P_{\text{inlet}} \right). \]  

(5-29)

The fill time for a mould of length \( l \), can therefore be calculated as:

\[ t_{\text{fill}} = \frac{\phi \mu}{K_{xx} \left( P_{\text{vent}} - P_{\text{inlet}} \right) 2} l^2. \]  

(5-30)

### 5.2.3.b Simulation Results

Only the constant inlet pressure case will be presented here. In the constant flow rate case, the progression of the flow front is simply linear with time.

To evaluate the performance of the RTM simulation, a test case of an 800 mm long preform composed of 10 layers of the CSM reinforcement studied in Chapter 3, and placed into a mould with a thickness of 3.63 mm. The injection pressure is set at 100000 Pa and the vent pressure at 470 Pa. The calculated volume fraction and permeability of the preform as well as the injection parameters are given in Table 5-1.

<table>
<thead>
<tr>
<th>( V_f )</th>
<th>( \phi )</th>
<th>K_{xx} (m²)</th>
<th>( \mu ) (Pa.s)</th>
<th>( P_{\text{inlet}} ) (Pa)</th>
<th>( P_{\text{vent}} ) (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4805</td>
<td>0.5195</td>
<td>4.681x10^{-11}</td>
<td>0.365</td>
<td>100000</td>
<td>470</td>
</tr>
</tbody>
</table>

Figure 5-2 presents the flow front progression as calculated by the simulation together with analytical calculation. The mesh consisted of 100 elements of equal size, the number of elements being determined after testing the convergence of the simulation results. Apart from the first few time steps, the error in the simulation is approximately 2.3% in the calculation of the flow front position compared to analytical results. The fill time calculated through the simulation is \( t_{\text{fill}} = 12965 \) s, while the analytical solution gives \( t_{\text{fill}} = 13023 \) s, representing an error of 0.45%.

Figure 5-3 presents the pressure distribution calculated during the simulation, each line representing a different time step. The pressure distribution is linear in the saturated part as expected, following Equation (5-12).
Figure 5-2: Evolution of the calculated flow front for the RTM case.

Figure 5-3: Pressure distribution during the RTM process with constant injection pressure.
5.3 I/CM Simulation

5.3.1 Solution Method

The mould filling process for I/CM can be divided in two parts as described in Figure 1-6, first the injection stage which can be modelled using an RTM solution, provided there is no gap between the top mould and the preform. After injection, during the final compaction, the flow is driven by the closing of the mould and squeezing of the saturated preform. The temporal variation of the mould and preform must be taken into account. For this simulation the assumption of no spatial variation will be conserved:

\[
\frac{\partial h}{\partial x} = 0. \tag{5-31}
\]

Combining Equations (2-12 and 2-13) leads to the I/CM governing Equation:

\[
\frac{K_{xx}}{\mu} \frac{\partial^2 P}{\partial x^2} = \frac{1}{h} \frac{dh}{dt}. \tag{5-32}
\]

As the permeability does not vary spatially (5-31), Equation (2-19) leads to the formulation of the volume average velocity at the flow front:

\[
q_i = -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} + (x_c - x) \left( \frac{1}{h} \frac{dh}{dt} \right). \tag{5-33}
\]

Different compression methods are available for the compaction phase of I/CM, prescribed velocity of the B side mould or a prescribed applied force on the tool. In this preliminary simulation, only the constant B side mould velocity will be evaluated as it is the only method allowing for a simple analytical calculation of the fill time to compare with the simulation.

Using the Galerkin finite elements method, the strong formulation of the I/CM governing Equation (5-32) is:
\[ I = \int_{x_i}^{x_{i+1}} \left( \frac{d}{dx} \left( K_{xx} \frac{dP}{dx} \right) - \frac{1}{h} \frac{dh}{dt} \right) \phi(x) dx = 0, \quad (5-34) \]

The full development of the solution process is detailed in Appendix B-1. The linear system of Equations to solve is expressed as:

\[ \text{KE}_n = \text{F}, \quad (5-35) \]

The elemental matrices used to produce the system of Equations (5-35) can be expressed as follows:

\[ \text{KE}_{el} = \frac{K_{xx}}{\mu L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \quad \text{and} \quad \text{F}_{el} = \begin{bmatrix} -K_{xx} \frac{dP}{dx} |_{x_i} & -L \frac{\dot{h}}{2h} \\ \frac{1}{h} \frac{dh}{dt} & \frac{2}{h} \end{bmatrix} + \begin{bmatrix} -K_{xx} \frac{dP}{dx} |_{x_i} & -L \frac{\dot{h}}{2h} \\ \frac{1}{h} \frac{dh}{dt} & \frac{2}{h} \end{bmatrix}. \quad (5-36) \]

It should be noted that when building the global right hand side matrix, the \( \frac{dP}{dx} \) terms cancel at overlapping points, but the B side mould velocity term adds up.

The computational method implemented for simulating the I/CM process is detailed in Figure 5-4. This is a quasi-static solution process; at each step the time step is calculated as the time required to fill the element adjacent to the flow front considering the calculated flow front velocity at the start of the time step.
5.3.2 Results

5.3.2.a Analytical Solution

Instead of analytically solving the I/CM governing Equation which is a non-linear partial differential equation, the fill time for the I/CM is calculated using the conservation of mass. During the compaction phase of the I/CM, the inlet is closed and there is no resin flux in or out of the mould. Both the resin and reinforcement are supposed incompressible; therefore the volume of resin at any time is equal to the volume of resin at the start of the compaction phase:

\[ V_{\text{resin}} = \phi_0 x_f = \phi_0 h_0 x_0, \]  

(5-37)

where \( \phi_0, h_0 \) and \( x_0 \) are the porosity laminate thickness and flow front position at the start of the compaction phase.

The height of the mould at time \( t \) can be expressed as:

\[ h(t) = h_0 + \dot{h}t. \]

(5-38)

Using Equation (2-5) to relate porosity and \( V_f \), Equation (5-37) can be expressed:

\[ V_{\text{resin}} = \left(1 - \frac{h_0}{h_0 + \dot{h}t} V_f \right) \left(h_0 + \dot{h}t\right) x_f, \]

(5-39)

The fill time for a mould of length \( l \) is therefore:

\[ t_{\text{fill}} = \frac{h_0 (1-V_f)}{\dot{h} l} (x_0 - l), \]

(5-40)

The pressure in the laminate can also be determined analytically by integrating Equation (5-32) twice over \( x \):
and the constant C1 and C2 can be calculated through the boundary conditions with the pressure equal to the vacuum pressure at the flow front and no flow at the inlet. Therefore:

\[
P(x) = \frac{\dot{h}}{2h} \frac{\mu}{K_{xx}} x^2 + C_1 x + C_2.
\]  

(5-41)

5.3.2.b Simulation Results

To evaluate the performance of the simulation, again a test case of an 800 mm long preform composed of 10 layers of the CSM. The final part shall have the same thickness as for the RTM case (3.63 mm) but at the time of injection the mould is only partially closed to leave a cavity thickness of 5.052 mm. The injection pressure is set at 100000 Pa and the vent pressure at 470 Pa. Once the required amount of fluid has been injected into the preform, the mould is then closed at 0.3 mm/min to the final cavity thickness of 3.63 mm. The material and process parameters are given in Table 5-2.

Table 5-2: Material parameters for the I/CM simulation.

<table>
<thead>
<tr>
<th>(V_f) (at injection)</th>
<th>(\phi) (at injection)</th>
<th>(K_{xx} (m^2)) (at injection)</th>
<th>(\mu ) (Pa.s)</th>
<th>(P_{inlet} ) (Pa)</th>
<th>(P_{vent} ) (Pa)</th>
<th>(\dot{h} ) (m.s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.345</td>
<td>0.655</td>
<td>2.538x10(^{-10})</td>
<td>0.365</td>
<td>100000</td>
<td>470</td>
<td>5.0x10(^{-6})</td>
</tr>
</tbody>
</table>

Figure 5-5 presents the evolution of the flow front position during the proposed I/CM simulation along with the analytical results. As in the precedent RTM case, the mesh consisted of 100 elements of equal size, the number of elements being determined after testing the convergence of the simulation results. The flow front progression can be divided in two parts, the first part representing the injection phase and the second part, the compaction phase. In the compaction phase the closing speed of the mould stays constant, the flow front velocity increases when the saturated portion of the preform increases, the rate of volume change of the cavity remains constant but the \(V_f\) is increasing,
resulting in an exponentially decreasing porous volume for the resin to fill. The fill time for this process is $t_{\text{fill}} = 1273.5$ s which is more than ten times faster than the RTM process for the same part.

Figure 5-6 present the pressure distribution along the preform during the I/CM process. Each line represents one time step, the pressure during the injection part is much smaller (about 250 times smaller) than during the compression part of the process.

![Graph showing the flow front position over time](image)

Figure 5-5: Evolution of the calculated flow front for the I/CM case.
5.4 Resin Infusion Simulation

The resin infusion process utilises much simpler tooling than the RTM and I/CM. However, the analysis of the process is much more complicated. As the vacuum bag provides no rigidity, the laminate properties can vary in time and in space. It should also be noted that at the end of filling, a gradient of pressure and laminate thickness remains in the mould. Once the inlet is closed, the excess fluid present close to the inlet flows towards the vent as a result of the pressure gradient and the atmospheric pressure compacting the preform. The simulation presented here was therefore designed to try to model the fluid flow and reinforcement properties during both the filling and post-filling stages of the RI process.

5.4.1 Solution Method

The mathematical formulation of the resin infusion process is detailed in Section 2.2. The strong formulation of Equation (2-14) is:
\[
I = \int_{x_i}^{x_f} \left( \frac{d}{dx} \left( \frac{K \sigma}{\mu} \frac{dP}{dx} \right) - \frac{d\eta}{dt} \right) d\sigma(x) dx = 0, \quad (5-43)
\]

The full development of the solution process is presented in Appendix B-2 and the implicit Newton-Raphson algorithm can be used to solve the Equation (5-44) iteratively.

\[
\mathbf{R}(\bar{h}(t)) = \mathbf{C}(\bar{h}(t) - \bar{h}(t-\Delta t)) + \Delta \mathbf{K}[\bar{h}(t)]. \quad (5-44)
\]

A summary of the simulation procedure is given in the flow chart of Figure 5-7. As the reinforcement compaction behaviour is assumed to be elastic as stated in Chapter 4, the pre-filling stage of the simulation is of minor importance. The laminate properties at the end of pre-filling and in the dry portion of the preform are those of the dry reinforcement under a load equivalent to the atmospheric pressure minus the vacuum pressure. The initial conditions are calculated with the first element filled, the quasi-static height profile and flow rate being determined in that region. Using the fluid velocity at the flow front, the flow front is updated and the Newton-Raphson algorithm is used to calculate the new temporary properties of the saturated part of the preform. The convergence test for the algorithm is based on the percentage of thickness variation; this allows limitation on the differences between two consecutive time steps but enables increases in the time step for a faster solution during periods in which little changes happens. If the algorithm converges in less than a specified upper limit on iterations, the time step is advanced and the pressures and preform properties are updated. Otherwise the values at the beginning of the time step are retrieved and the solution is evaluated for a smaller time step.

The filling stage is complete once the flow front reaches the specified position, or alternatively once a specified quantity of fluid is injected. Once the end of filling condition is achieved, the boundary conditions are changed to those of post-filling. The iterative process remains the same as for the filling stage. If the flow front reaches the end of the mesh, the amount of resin
evacuated is calculated from the flow out of the last element. The simulation is set to run for a given time period (or post-filling time period), typically comparable to the gel time of the applied resin system.
Figure 5-7: Flow chart of the RI simulation.
5.4.2 Boundary Conditions

The method of applying boundary conditions to the finite element model was described in Section 5.1.4. During the filling part of the RI process, the resin pot is left open at atmospheric pressure. In the inlet tube, a noticeable head loss can happen depending on the magnitude of the fluid flow rate. From experiments using CSM reinforcement, the pressure at the inlet appeared to reach a constant level almost instantly; however when using CFM reinforcement, which has a much higher permeability, the pressure at the inlet was shown to rise gradually as the flow rate decreased. To obtain an accurate simulation of the RI process it is therefore desirable to be able to account for the flow dependant loss of pressure in the inlet tube. The pressure at the inlet can be expressed as:

\[
P_{\text{inlet}} = P_{\text{atm}} - (\rho g \Delta z) - \Delta P,
\]

with \(\rho\) the density of the fluid, \(g\) the acceleration of gravity, \(\Delta z\) the height difference between the surface of the resin in the pot and the inlet port, and \(\Delta P\) the flow dependant loss of pressure along the inlet tube.

The major pressure loss \(\Delta P_{\text{major}}\) along a circular tube can be calculated as:

\[
\Delta P_{\text{major}} = \lambda \frac{\rho V^2}{2} \frac{L_{\text{tube}}}{D_{\text{tube}}} = \lambda \frac{\rho Q_{\text{tube}}^2}{2 S_{\text{tube}}^2} \frac{L_{\text{tube}}}{D_{\text{tube}}},
\]

with \(V\) the average speed of the fluid, \(L_{\text{tube}}\) the length of the tube, \(D_{\text{tube}}\) the diameter of the tube, \(S_{\text{tube}}\) the cross section of the tube, \(Q_{\text{tube}}\) the flow rate in the tube and \(\lambda\) a dimensionless coefficient of linear pressure drop [114]. For a laminar flow, this coefficient \(\lambda\) is equal to:
where $R_d$ is the dimensionless Reynolds number. Combining (5-46) and (5-47) results in:

\[
\Delta P_{\text{major}} = 16\mu\frac{Q_{\text{tube}}}{\pi D_{\text{tube}}^4} \cdot \frac{L_{\text{tube}}}{\Delta \rho}.
\]

In the flow conditions experienced during the tests presented in this thesis, the minor losses do not have a significant effect on the total pressure loss through the tube. The pressure at the inlet port can therefore be calculated as:

\[
P_{\text{inlet}} = P_{\text{atm}} - (\rho g \Delta \zeta) - 16\mu\frac{Q_{\text{tube}}}{\pi D_{\text{tube}}^4} \cdot \frac{L_{\text{tube}}}{\Delta \rho}.
\]

To calculate the pressure at the inlet therefore requires to know the flow rate through the tube $Q_{\text{tube}}$, which is equal to the flow rate into the first element of the mesh $Q_{\text{in}}$, which in turn is dependant on the inlet pressure. An iterative method is therefore used to calculate the inlet pressure during the filling part of the simulation.

At each time step, the inlet pressure is first set to the pressure at the previous time step. The flow equations are solved and the flow rate in the first element $Q_{\text{in}}$ is calculated and compared to the flow rate in the inlet tube $Q_{\text{tube}}$ resulting from the pressure difference between inlet and atmospheric pressures. If the difference between $Q_{\text{tube}}$ and $Q_{\text{in}}$ is higher than a threshold limit, the inlet pressure is updated accordingly and the flow equations are solved again. The time step is only validated and incremented once the flow rates difference is below the threshold.
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Figure 5-8: Calculation of the flow rates inside the inlet tube and into the preform to determine the inlet pressure.

However this method of calculating the inlet pressure proved very computationally expensive and somehow unstable. Another solution has been employed including the inlet tube in the mesh. The equivalent permeability of the tube was calculated from the tube geometry and an infinitesimal volume fraction was entered, the tube was considered rigid and its characteristics independent of the pressure. Through this method, the simulation was able to run much faster.

During post-filling, the inlet is clamped off, therefore there is no flow in or out at the inlet. In a typical infusion process, due to the use of flexible tubing at the inlet, there can be some residual flow caused by squeezing of the tube when the internal fluid pressure drops. However, in the post-filling study mould designed to compare with the simulation, the inlet system is composed of a ball valve and a rigid groove in the mould. There is therefore no possible additional flow into the preform once the inlet is shut.

During filling, the pressure at the flow front is maintained constant and equal to the vacuum pressure (usually between 3 and 5 mbar). The vent pressure might be changed during post-filling to prevent the resin pressure dropping under the boil off pressure which would result in increased porosity in the laminate. Provided the vent system is large enough to allow for unrestricted flow, the pressure at the vent can be considered constant and equal to the applied vacuum pressure.
5.4.3 Meshing and the Floating Node

The simulation developed here is a 1D FEM simulation, the mesh is created using 1D linear elements. In an effort to better simulate the phenomenon happening at the inlet and vent ends of the preform, the inlet channel and distribution tape at the vent are also included in the mesh.

The mould cavity is first discretised using a grid of fixed nodes. Using a transient solution method for the RI process, the time step cannot be forced to result in the flow front filling a full element at each step. To allow for accurate tracking of the flow front without penalising computational performance, a floating node, i.e. a node temporarily placed between two of the fixed grid nodes, is used. The floating node marks precisely the flow front. Figure 5-9 demonstrates the application of the floating node. At the start of time step $n$ the laminate thickness profile is known, and therefore the $V_f$, permeability and fluid pressure along the cavity. The flow front velocity is then calculated from the pressure gradient at the flow front. The new position of the flow front is then approximated, assuming its velocity remains constant throughout the time step. The floating node is then moved to this new position and the laminate thickness profile is calculated using the iterative Newton-Raphson implicit method.
5.4.4 Influence of the Compaction Model

As the simulation presented here accounts for the changes of permeability and changes in thickness as expressed in Equation (2-14), the fill time as well as pressure profile will be highly dependant on the choice of compaction model. Furthermore, during post-filling the flow is driven by the reinforcement compaction, reinforcing the need to choose an adequate model for the reinforcement compaction. This section will present the application of some different compaction models, from simple to the more refined model developed in Chapter 3. In this section the simulated preform is a stack of 10 layers of CSM 380 mm long and 200 mm wide, connected to a 20 mm long and 200 mm wide distribution tape at the vent. The fluid viscosity chosen for these tests is
$\mu = 0.226$ Pa.s. The mesh was divided into 100 elements for the preform and 10 elements for the vent. The condition of convergence for the Newton-Raphson algorithm was set to $\theta = 0.00005$, with $\theta$ defined as the maximum fraction of thickness variation (5-50),

$$\theta = \max \left( \frac{h(t, i) - h(t + \Delta t, i)}{h(t, i)} \right). \quad (5-50)$$

### 5.4.4.a Single Power Law Model

The simplest model to represent the compaction behaviour of a fibrous reinforcement while maintaining a minimum of accuracy would be a non-linear elastic model such as a power law model as suggested by Robitaille and Gauvin [53]. To determine the characteristics of that model from experiment it is necessary to choose some experimental parameters. For example, is the reinforcement in a dry or wet saturated state, or whether the characterisation is done while loading or unloading the sample.

The simplest test to perform is a dry compaction as there is no need to worry about coupling between fibre compaction and fluid flow, or what fluid to use. This test is also relevant to the state of the preform prior to infusion and in the non-saturated part of the preform during filling.

Another solution would be to explore the wet compaction of the reinforcement as presented in [54]. This appears be more relevant as the computation is made over the saturated part of the preform, where the reinforcement is wet and lubricated by the fluid.

As demonstrated in Chapter 3, the wet compaction and wet unloading behaviour of the fibrous reinforcements are quite different. During the filling stage of the RI process, as the fluid pressure increases in the saturated part of the preform, the reinforcement is therefore subject to a wet unloading. Characterising the compaction model through wet unloading tests might therefore provide a more accurate estimation of the fill time [63, 67, 143].
To understand the importance of the compaction model, the three model presented above were tested in a simulation. The characterisation of these three models can be found in Section 3.2.4. Table 5-3 presents the simulated fill times and Figure 5-10 the flow front progression for simulations using the three different power law as a reinforcement compaction model. There is around 30% variation between the two extreme cases.

Table 5-3: Fill time for the three different compaction models.

<table>
<thead>
<tr>
<th>Compaction Model</th>
<th>Fill Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Compaction</td>
<td>742</td>
</tr>
<tr>
<td>Wet Compaction</td>
<td>853</td>
</tr>
<tr>
<td>Wet Unloading</td>
<td>1038</td>
</tr>
</tbody>
</table>

Figure 5-10: Simulated flow front progression using the three different power laws.

These results make good sense when looking at the compaction tests performed in Chapter 3. During the dry compaction, the \( V_f \) is consistently lower than during either wet compaction or unloading, the permeability is therefore higher, leading to a shorter fill time. In the wet compaction tests, the fully
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compacted preform exhibited a higher $V_f$ than in the unloading tests and therefore a lower permeability. However for compaction stresses below 70000 Pa, the $V_f$ is lower in the compaction traces compared to the unloading traces. Therefore using the wet compaction model in the simulation results in a lower permeability at the flow front, but a higher permeability in most of the saturated part of the preform when compared to the wet unloading model. This results in a higher pressure gradient near the flow front when using the wet compaction model (as depicted in Figure 5-11) and therefore finally results in a shorter fill time for the wet compaction model as opposed to the wet unloading model.

![Figure 5-11: Simulated pressure profile for the wet unloading and wet compaction models.](image)

5.4.4.b Three Power Law Model Models

To take into account all the phases of the RI process, it might be more accurate to model the reinforcement behaviour using for each phase a model
that is physically relevant to the compaction experienced by the reinforcement. Therefore a dry compaction model should be used for the pre-filling, a wet unloading model would be used for the filling stage and the post-filling stage would use a wet compaction model for the reinforcement behaviour.

Figure 5-12 presents the evolution of the local volume fraction, at five points corresponding to the position of the pressure transducers utilised in the previous chapter, during the simulation using three power laws in the compaction model (Dry compaction, wet unloading and wet compaction as defined in the previous section and in Section 3.2.4). At the end of filling as the compaction model switches from the wet unloading model, to the wet compaction model, the fluid pressure being kept constant, there is a clear jump in the local $V_f$. This jump results in a sudden increase in the saturated volume and therefore a discontinuity in the amount of fluid present in the mould. If the volume fraction was kept constant, the change of compaction model would have resulted in large jumps in the fluid pressure field.

![Figure 5-12: Evolution of the local $V_f$ at 5 points along the laminate during the RI simulation.](image-url)
It can be seen in Figure 5-13 that the fluid pressure in the laminate gradually raises at the onset of post-filling as a result of the sudden change in laminate property. This raise of pressure is negligible at the inlet, but increases towards the vent.

![Graph showing fluid pressure evolution](image)

**Figure 5-13: Evolution of the fluid pressure at 5 points along the laminate during the RI simulation.**

The expected benefits of using a seemingly more realistic model have been proven to be negated by the discontinuity in the model. For this reason the compaction model presented in Chapter 3 was next implemented.

### 5.4.4.c Interpolated Re-compaction Model

To solve the problem of discontinuity in fluid content and laminate thickness jump at the onset of post-filling, the interpolated model presented in Section 3.2.4.b is used. This model allows for the loading history prior to the compaction happening during post-filling to be taken into account.

Figure 5-14 and Figure 5-15 present the evolution of the local \( V_f \) and fluid pressure respectively at locations corresponding to the five pressure points.
transducers used during the experiment presented in Section 4.4. Using this model, there is no more discontinuity at the onset of post-filling. It can be noticed from Figure 5-14 that the final $V_f$ is varying along the length of the preform. This variation is due to the differences in compaction history along the preform; at the inlet the preform went through a full unloading and reloading cycle, while at the vent the preform was kept under one atmosphere of compaction throughout the process.

![Graph showing the evolution of the local $V_f$ at 5 points along the laminate during the RI simulation.](image)

**Figure 5-14:** Evolution of the local $V_f$ at 5 points along the laminate during the RI simulation.
5.4.5 Modified Darcy’s Law

5.4.5.1 Theory

From experiments presented in this thesis as well as in previous research [38, 112], it appears that the pressure inside the laminate never goes down to vacuum pressure during the post-filling stage of the RI process. The residual pressure appears to be dependant on the distance to the vent, and also on the amount of distribution media over the laminate. However, there is nothing in the conventional version of Darcy’s law that could explain this residual pressure phenomenon.

Upon discussion about those results, Professor Don Nield of the Department of Engineering Science proposed that a constant should be applied to Darcy’s law:

\[ q_x = -\frac{K_{xc}}{\mu} \frac{dP}{dx} + C. \]  \hspace{1cm} (5-51)
As no literature in the field of LCM presented any model of this modification to Darcy’s law, or even mentioned this effect, searches were made in other scientific publications dealing with slow flow through porous media, such as ground water flow or petroleum industry. The paper by Prada [118] already discussed in Section 2.5 proposed the most suitable adaptation of Darcy’s law:

\[
q_x = \frac{-K_{xx}}{\mu} \frac{dP}{dx} - \gamma \left( \frac{K_{xx}}{\mu} \right)^{\lambda}. \tag{5-52}
\]

Modifying Darcy’s law requires redefining the mathematics of the process; the governing Equation for the RI is now:

\[
\frac{\partial}{\partial x} \left( \frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} + h \gamma \left( \frac{K_{xx}}{\mu} \right)^{\lambda} \right) = \frac{\partial h}{\partial t}. \tag{5-53}
\]

The volume averaged velocity is then changed to:

\[
q_x = \frac{-K_{xx}}{\mu} \frac{\partial P}{\partial x} - \gamma \left( \frac{K_{xx}}{\mu} \right)^{\lambda} + \left( \frac{x - x_c}{h} \right) \left( \frac{K_{xx}}{\mu} \frac{\partial h}{\partial x} \right) + \gamma \left( \frac{K_{xx}}{\mu} \right)^{\lambda} \left( \frac{\partial h}{\partial x} - \frac{\partial h}{\partial t} \right). \tag{5-54}
\]

The solution process following the same methodology as for the classic Darcy’s law is presented in Appendix B-3.

**5.4.5.b Determination of the coefficients gamma and lambda**

To determine the coefficients \( \gamma \) and \( \lambda \), one needs to measure the threshold pressure gradient, under which no flow occurs. The threshold pressure gradient needs to be evaluated with a range of fluid mobility values \( (K/\mu) \). In this study, the coefficients were extracted from three RI experiments, measuring the pressure gradient inside the laminate as well as the local permeability and the fluid viscosity, at the end of post-filling once the pressure and thicknesses have stopped changing. The experiments were all performed on 380 mm by 200 mm preforms composed of 6 layers of CFM. The first experiment was performed using the Mobil DTE Heavy oil with the vent directly connected to the preform.
Another experiment was performed in the same conditions but replacing the oil by the Mobil DTE Vacuoline. The last experiment was performed using the Mobil DTE Vacuoline and placing the vent 5 mm away from the preform, using peel ply as a “brake” material between the preform and the vent.

Figure 5-16 presents the plot of final pressure gradients used to determine the coefficients of Prada’s Equation (5-52). For each three experiments, the pressure gradient was calculated at the five pressure transducers embedded in the mould. The Viscosity was calculated by measuring the oil and mould temperatures, and the permeability was calculated through the measurement of the laminate thickness using stereophotogrammetry.

Table 5-4: Coefficients of Prada’s Equation.

<table>
<thead>
<tr>
<th>γ</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1327x10^{-5}</td>
<td>-0.24095</td>
</tr>
</tbody>
</table>

Figure 5-16: Threshold pressure gradient as a function of the fluid mobility.

Further experiments would be useful to better evaluate the terms of this equation. A more specific experimental setup would also be beneficial to better
understand and measure the effect of the threshold pressure gradient. Some possible experimental setup will be further discussed in Chapter 7.

5.4.5.c Results of the simulation using the modified Darcy’s law

When using the modified Darcy’s law, the simulated fill time for the preform is 1047s, which is less than 10s longer than when using the traditional Darcy’s law. The additional term introduced by Prada is only significant on the flow when the pressure gradient is small, therefore it does not affect much the fill time in a common infusion case. However, the use of Equation (5-52) does introduce a limit to the maximum infusible preform length and also affects the post-filling stage by slowing down the pressure decay and preventing the fluid pressure to reduce to the applied vacuum level at the vent.

Figure 5-17 and Figure 5-18 present the simulated $V_f$ and fluid pressure traces respectively at the location of the five pressure transducers when using the interpolated compaction model in association with the modified Darcy’s law as per Prada’s Equation (5-52). It can be noticed in Figure 5-18 that due to the pressure threshold term, there is a pressure gradient remaining in the laminate. The pressure at P1 was equal to 1381 Pa at the end of post-filling while the pressure at P7 was equal to 933 Pa. Due to use of the interpolated re-compaction model, the final $V_f$ also varies along the length of the preform. However, the variation is less pronounced than in the simulation presented in 5.4.4.c due to the existence of the residual pressure gradient.
Figure 5-17: $V_f$ traces obtained through the simulation using Prada’s Equation.
5.5 Convergence and Efficiency of the Simulation

This section presents the convergence tests performed to check the efficiency of the simulation. Two types of convergence have been evaluated. First, as with any finite element simulation, the influence of the number of elements needs to be evaluated. As the presented simulation uses an implicit iteration method, the influence of the precision of the convergence test for each iteration should be evaluated.
The variable chosen to evaluate the convergence of the simulation is the fill time as this value is easily extracted from the simulation, and gives a good estimation of the resulting accuracy. To test the convergence and efficiency of the simulation it was decided to run the simulation using the traditional Darcy’s law and a constant inlet pressure of 99000 Pa, while the vacuum pressure was set at 470 Pa. The preform was composed of 10 layers of CSM 380 mm long by 200 mm wide and the fluid viscosity was set to 0.226 Pa.s. The program was set to simulate a total of 8000 s including pre-filling, filling and post-filling.

Figure 5-19a presents the convergence of the simulation as a function of the number of elements with three levels of tolerance for the convergence criteria of the Newton-Raphson algorithm. It can be noticed that if the convergence criteria is too loose, the simulation does not converge to a set fill time as the number of elements increases. When using a tighter tolerance, the simulation converges to a finite fill time. Using a convergence criterion of $1 \times 10^{-5}$ gives a fill time that converges at 1043 s and is within 2.8% of that result when using 50 elements or more. Figure 5-19b presents the computation time required for the simulation to run for pre-filling filling and post-filling; it can be observed that the computation time increases exponentially as the number of elements increases, and as the convergence tolerance decreases. For a simulation using the tighter convergence criterion of $1 \times 10^{-5}$ and 100 elements, the computation time is 918 s on a computer using a single Pentium 4 CPU with a frequency of 3.20 GHz.
Figure 5-19: Convergence test for the simulation; a) predicted fill time, and b) computation time.
5.6 Simulation Interface

The simulation presented here is in its development stage and does not have any Graphical User Interface. The inputs for the simulation are controlled by four .txt files:

- **Input_Geometry** that defines the geometry of the preform and the different zones of materials,
- **Input_Material-parameter** defines the material parameters (number of layers, permeability relationship, compaction behaviour, fluid viscosity, Prada’s coefficients),
- **Input_Process** defines the process controls (atmospheric and vent pressure, end of filling condition, post-filling time),
- **Input_Processing_Parameter** that defines some processing parameters (convergence criterion, tracking points, time step updating parameters).

The simulation program is compiled into an executable file that reads the four input files and creates a set of output files. Three output files are of interest.

- **Nodal_Output.dat**, This file contains process information at all nodes at all time instances during the complete process. There is a block of data for each time instant. This file is in a format suitable to TECPLOT.
- **3pointTrk.txt** this file records the laminate properties and fluid pressure at a defined set of points at all time during the process. This file can then be opened in Excel for further processing and analysis.
- **Data_OutputTrk.txt** each time the flow front passes a new node during the filling stage, this file records the time, flow front position, flow rate and size of the last time step. This file can then be opened in Excel for further processing and analysis.
5.7 Simulation Results

In this section, the results of one simulation will be presented as a showcase of the output capabilities of the presented code. Discussion about the comparison of experimental and simulated results will be presented in the next chapter. The preform being simulated is a 380x200 mm preform composed of 10 layers of CSM. At the inlet, a 900 mm long tube with an internal diameter of 4 mm connects the resin pot to the beginning of the preform. At the vent side, a 15 mm long, quasi incompressible distribution tape is simulated with a thickness of 4 mm, a porosity of 0.7, and a permeability estimated at 7.5x10^{-6} m². The permeability was estimated through the calculation of the equivalent permeability for a flow between two parallel plates (Poiseuille flow) [114]. The fluid considered is the Mobil DTE Heavy oil with a viscosity of 0.226 Pa.s at 23.0°C.
Numerical Simulation

Figure 5-20: Evolution over time along the length of the preform of: a) the laminate thickness; b) the $V_f$; c) the permeability; and d) the fluid pressure.

For a quick overview of the simulation results, the evolution of the laminate properties and fluid pressure during the process can be plotted in a 3D graph in a similar manner as was presented in Section 4.4.4. Figure 5-20 presents the evolution of the laminate thickness, $V_f$, permeability and fluid pressure as predicted by the simulation. These figures are useful to evaluate at a glance the amplitude of the laminate properties changes as well as the time necessary to reach equilibrium in the post-filling. For a more precise comparison with an experiment, it might be preferable to plot the evolution of the desired variables at points corresponding to the measurement points utilised during the experiments. Figure 5-21 presents the evolution of the fluid pressure and laminate thickness at points corresponding to the location of the pressure transducers used in the experiment presented in Section 4.4. It can also be useful, as a way of comparison, to plot the pressure profile along the laminate at various instants during both filling and post-filling as in Figure 5-22; this permit
to evaluate the pressure gradient present in the preform at various instants during the process. Plotting the thickness profile along the length in the same format as the pressure in Figure 5-22 can help determining the time required for the laminate thickness to equalize along the length in order to minimise the thickness gradient in the final part. The flow rate into the laminate can also be plotted as in Figure 5-23, knowledge of the flow rate is important to properly design the inlet system and minimise the pressure losses in the inlet tube.
Figure 5-21: Evolution of the fluid pressure (a), and laminate thickness (b), at the location of the five pressure transducers.
Figure 5-22: Pressure profile along the length of the preform at various instants of the filling and post-filling.

Figure 5-23: Evolution of the resin flow rate into the laminate.
5.8 Discussion

When comparing the simulation performed in Section 5.6, to the RI experiment presented in Section 4.4; the filling stage appears to be in reasonable accordance between experiment and simulation. However, the simulated post-filling stage does predict a much faster pressure decay in the laminate than what is seen in the experiment. Different solution methods have been tested to make sure that this discrepancy was not a problem due to the solution method. In [112], Robison and Kosmatka used the same governing Equation but the compaction flow caused by the decreasing laminate thickness is calculated separately before being re-introduced to calculate the pressure field. This technique was also tried in the simulation presented here but did not provide any difference.

Another method was tried, solving the flow equations in parallel with the reinforcement stress equations as mentioned in Section VI.4 of [144]. The fluid flow was calculated using the pressure profile and pressure gradient and in parallel, the laminate thickness and compaction was calculated from the balance of fluid pressure and compaction pressure. However, the results were again not satisfactory.

One more solution that might provide better results would be to model the flow through the thickness. In the fourth chapter of his PhD thesis [144], Pham provided a study of the consolidation of a thin composite part under a flexible bladder, and in the appendix IV he presented a study of the Finite Element Method applied to the consolidation equations. Figure 5-24 presents the results of a consolidation case where a 2D square of an imaginary isotropic reinforcement with a linear elastic behaviour and a porosity of 0.5 is submitted to a uniform pressure on the top edge. The sides are left unconstrained and with no pressure, while the bottom is constrained to no displacement.
Figure 5-24: a) Fluid pressure; b) resin speed; and c) reinforcement displacement. In the case of consolidation under a flexible bladder (from [144]).

Towards the bottom the fluid is pushed upwards by the decreasing reinforcement porosity, while near the top there is no vertical fluid flow but a vertical reinforcement displacement, resulting in a through thickness flow of the resin relative to the reinforcement. This was a purely imaginary case but it demonstrated the existence of a through thickness flow when the reinforcement was compacted. In the RI process the boundary conditions are slightly different in that the fluid pressure on the sides of each element is non-zero and there is no transverse displacement of the reinforcement. During filling, the flow is mainly governed by the pressure difference between the elements. During post-filling as the pressure gradient along the laminate decreases, more and more of the flow is derived from the compaction of the reinforcement which possibly includes a through thickness component. As the through thickness permeability of most reinforcements is usually an order of magnitude lower than the in-plane permeability, this could explain why the post-filling is happening slower in the experiment than in the current simulation.

5.9 Conclusion

The simulation presented in this chapter includes some developments previously not seen in the composites manufacturing literature. The simulation developed is able to predict the preform behaviour during the pre-filling, filling and post-filling stages of the RI process. The use of the interpolated re-compaction model allows for a better modelling of the preform behaviour during
all three stages of the RI process. The use of a modified Darcy’s law results in a pressure gradient remaining inside the laminate at the end of the post-filling. This phenomenon had been experimentally observed previously [38, 145], but no suitable explanation was given. The residual resin pressures present in the preform at the end of post-filling appear quite small in the case evaluated here because the preform is relatively short; a longer preform would result in much more significant residual pressure at the inlet.
Chapter 6 Validation of the Simulation and Cases Study

As a validation for the capabilities of the monitoring setup presented in Chapter 4 and the simulation developed in Chapter 5, this chapter will present a case study of a selection of infusion and post-filling strategies. The experiments presented here have been performed using the two different reinforcements studied in Chapter 3, on the mould described in Section 4.1.1.b.

6.1 Plan of Experiments

Four different scenarios will be studied, aimed at evaluating various strategies to control the post-filling stage of the process.

First a “standard” experiment scenario is presented in which the fluid was injected into the preform while maintaining the vacuum pressure at 470 Pa (4.7 millibar), the inlet being clamped as soon at the fluid reached the end of the preform. The preform was connected to the vent via a 15 mm long and 200 mm wide strip of Enkachannel FPF-100 distribution tape. The vent pressure was maintained at the same pressure during the post-filling.

A second scenario, related to the study presented by Daval and Bickerton in [38], consisted in changing the vent pressure during post-filling to a higher
pressure while keeping all the filling parameters unchanged in relation to the “standard” experiment.

The third case was defined to look at the effect of the “brake” zone often used in industrial application cases. To ensure that the preform is fully impregnated and prevent dry spots from forming due to race tracking, it is common to use some sort of brake or sacrificial material between the vent and the edge of the preform. In this particular case, a 5 mm long piece of peel ply is used between the end of the preform and the Enkachannel FPF-100 distribution tape. All other parameters were kept similar to the “standard” experiment.

The fourth and last scenario studied in this chapter, looks at the effect of clamping the inlet early once a desired quantity of fluid has been injected. In this case the flow front does not reach the end of the preform before clamping the inlet; the final step of the filling is performed through the compaction of the preform in the saturated part.

The four different scenarios were applied to the two different reinforcement already characterised in Chapter 3. Due to the relatively long time required to prepare and perform each test, it was deemed too time consuming to perform repeats of each test. As a compromise, only the standard experiment was repeated. The filling stage conditions were similar for the other three scenarios, and therefore this data could also be used to check for the repeatability of the experiments.

6.2 Experimental Procedure

For every experiment, the same procedure was applied. In all cases the preform dimensions were 380 mm long and 200 mm wide. The preform was weighed and placed on the mould, taking care of aligning the edge of the preform with the inlet groove. The distribution tape was placed over the vent at the desired distance from the preform (either in contact or with a 5 mm gap). The preform and distribution tape were maintained in place using small pieces of tacky tape. In the cases where the preform was composed of CSM, a strip of
tacky tape was laid along the sides of the preform to prevent race-tracking. A single layer of peel ply was then laid over the preform and distribution tape. The vacuum bag was first painted with a speckle pattern while leaving two 24 mm wide stripes to allow for flow visualisation, as can be seen in Figure 6-1. The vacuum bag was then sealed over the preform.

Figure 6-1: Preform infused on the "post-filling" mould.

The cavity was then evacuated and checked for leaks. Full vacuum was maintained for 10 minutes. The vacuum was then released and the preform was left without any applied compaction for 5 minutes. After that period, the vacuum was applied again. After a further five minutes under full vacuum, the laminate thickness was measured in the middle of the laminate using a dial gauge before removing the gauge, starting the picture acquisition for the stereophotogrammetry and opening the inlet to start the filling stage.

During filling, the vent was maintained at full vacuum and the inlet remained open. The filling stage was terminated by closing the inlet valve when the flow front reached the end of the preform or the desired position. At the onset of post-filling, the vent pressure was adjusted to the post-filling pressure if required.

The pre-filling sequence described here was designed to minimise the differences due to different loading history of the samples. Maintaining the preform under vacuum for the first 10 minutes allows for discovery of possible
leaks, and for sealing these in a relatively short amount of time relative to the
time held at full vacuum. The cycling of the vacuum was also designed to
diminish the influence of previous compaction of the reinforcement, as well as
providing a loading similar to the one used for the material characterisation in
Chapter 3.

The tests using CSM reinforcement were infused using the Mobil DTE
Heavy oil characterised in Section 3.4. Tests employing CFM reinforcement
were infused using the Mobil DTE Vacuoline also presented in Section 3.4. As
these experiments were performed on the "post-filling study" mould, the
temperature was not controlled, however the temperature was monitored
throughout the experiment, the ambient temperature was measured with a
standard thermometer, and the oil and mould temperatures were measured at
regular intervals using an infrared thermometer. The temperature did vary a
modest amount from one experiment to another, the viscosity of the fluid being
then calculated from the measured temperature.

During pre-filling, filling and post-filling, the pressure at the vent and inlet
as well as at the points P1, P2, P4, P6, and P7 were recorded. The flow rate
was measured during filling by monitoring the weight of the resin pot. The
laminate properties were monitored throughout the filling and post-filling stages
through the use of the stereophotogrammetry system.
6.3 Repeatability

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Infusion Strategy</th>
<th>Temperature (°C)</th>
<th>Approximate Fluid Viscosity (Pa.s)</th>
<th>Fill Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSM</td>
<td>Standard 1</td>
<td>23</td>
<td>0.226</td>
<td>1175</td>
</tr>
<tr>
<td>CSM</td>
<td>Standard 2</td>
<td>21.7</td>
<td>0.247</td>
<td>1307</td>
</tr>
<tr>
<td>CSM</td>
<td>Post-filling Pressure</td>
<td>25.6</td>
<td>0.192</td>
<td>1059</td>
</tr>
<tr>
<td>CSM</td>
<td>Brake</td>
<td>27.6</td>
<td>0.167</td>
<td>1202</td>
</tr>
<tr>
<td>CSM</td>
<td>Clamp Early</td>
<td>23.8</td>
<td>0.215</td>
<td>964 then 1201</td>
</tr>
<tr>
<td>CFM</td>
<td>Standard 1</td>
<td>18.6</td>
<td>1.098</td>
<td>536</td>
</tr>
<tr>
<td>CFM</td>
<td>Standard 2</td>
<td>22</td>
<td>0.816</td>
<td>371</td>
</tr>
<tr>
<td>CFM</td>
<td>Post-filling Pressure</td>
<td>22</td>
<td>0.816</td>
<td>390</td>
</tr>
<tr>
<td>CFM</td>
<td>Brake</td>
<td>20.5</td>
<td>0.928</td>
<td>401</td>
</tr>
<tr>
<td>CFM</td>
<td>Clamp Early</td>
<td>21.5</td>
<td>0.851</td>
<td>303 then 391</td>
</tr>
</tbody>
</table>

Table 6-1 presents the fill time measured for the different experiments as well as the fluid viscosity estimated from the measured fluid temperature. For the infusion strategy where the inlet was clamped before the flow front reached the end of the preform, two fill times are given. The first represents the time at which the inlet was clamped, and the second indicates the time at which the flow front reached the end of the preform. The measured fill times displayed a relatively small variability that can be attributed mainly to variation in temperature but also to small process or reinforcement variability. To verify the repeatability of the process it can be useful to compare the evolution of pressure as a function of time relative to the fill time as presented in Figure 6-2. This figure presents the comparison between the two repeats of the standard RI scenario for each reinforcement. It can be noted that despite the fill time being quite different, the pressure traces appear very similar on each repeated test when normalising the time.
Figure 6-2: Comparison of the fluid pressure during the two repeats of the standard experiment. a) For CSM and b) for CFM.
As a further analysis of repeatability, the dependence of the fill time on the fluid viscosity can also be evaluated. Figure 6-3 presents the evolution of the measured fill time for experiments using the first three scenarios. A perfect repeatability of the process would result in the evolution of fill time being a perfectly linear function of the fluid viscosity (R value of 1). For the CSM reinforcement, the experiment using a brake fall relatively far from a linear distribution, when taking out that experiment, the linear approximation results in an R value of 0.92. For the CFM experiments, all experiments also fall close to a linear fit with an R value of 0.92. The experimental procedure can therefore be considered as providing sufficient repeatability.

![Figure 6-3: Evolution of the fill time as a function of fluid viscosity.](image)

To be able to compare the results of the simulations of the various scenarios, the simulations were performed by assuming a unique viscosity for each mineral oil. For the CSM simulation, the Mobil DTE Heavy oil was assumed to have a viscosity of 0.230 Pa.s and the Mobil DTE Vacuoline was assumed to have a viscosity of 0.850 Pa.s.
6.4 Chopped Strand Mat

6.4.1 Standard Experiment

6.4.1.a Experimental Results

Figure 6-4 and Figure 6-5 present the evolution of the fluid pressure and laminate thickness respectively, as measured during two repeats of the standard experiment. In Figure 6-4, the fluid pressure during filling and the beginning of post-filling are magnified in the top right corner; the dashed line representing the end of filling by closing the inlet. While the thickness measurement was only carried out for just over 2 h and 45 min, the pressures were recorded over 8 h and 20 min. From these two figures it can be observed that the maximum thickness and fluid pressure at each transducer are very similar for both experiments. The fill times for these two experiments are slightly different as seen in Table 6-1, but most of this difference can be related to the difference in fluid viscosity.

Discussions of the experimental results for the standard experiments were provided in Section 4.4 and Figure 6-4 and Figure 6-5 were presented here only for ease of comparison with the simulation and the other test cases.

Figure 6-6 presents the fluid pressure and laminate thickness profiles along the mould at various instants during the first standard experiment. The pressure appears to follow a quadratic distribution during the filling and most of the post-filling, but tends toward a linear distribution by the end of post filling. At 3700 s, the laminate thickness appears to be uniform across the mould while the pressure difference between the inlet and vent is about 30000 Pa. Further on during post-filling, the thickness at the inlet drops below that at the vent.
Figure 6-4: Fluid pressure traces for the two standard RI experiments using CSM reinforcement.
Figure 6-5: Laminate thickness traces for the two standard RI experiments using CSM reinforcement.
Validation of the Simulation and Cases Study

Figure 6-6: Pressure (a) and thickness (b) profiles at various instances during the standard infusion 1.
6.4.1.b Simulation Results

Figure 6-7 presents the pressure and thickness traces at the location of the transducers P1, P2, P4, P6 and P7 for simulation of the standard infusion with the CSM reinforcement. It can be noticed that the thickness increase at P1 and P2 during filling are underestimated in the simulation when compared to the experiments, however the pressure at those points appears to be consistent with the pressures measured in the experiment.

The simulation appears to be predicting much faster pressure decay for the post-filling than was measured during the experiments. However the predictions of the residual pressure gradient and laminate thickness distribution appears to be qualitatively good.
Validation of the Simulation and Cases Study

Figure 6-7: Pressure (a) and thickness (b) traces of the simulation of the standard infusion with CSM reinforcement.

Figure 6-8 presents the pressure profile along the preform during simulation of the filling and post-filling for the standard experiment. The time steps presented have been selected to be comparable with the pressure
presented in Figure 6-6, rather than at equivalent times. The pressure distribution along the length of the preform is consistent with the experiment.

![Pressure profile along the preform](image)

Figure 6-8: Pressure profile along the preform during the simulation of the standard experiment with CSM reinforcement.

### 6.4.1.c Comments on the Comparison

Figure 6-9 presents the comparison of the pressure traces for both experiment and simulation by normalising the time scale to the fill time. The simulation appears to give very good results during filling and the beginning of post-filling, but predicts much faster changes during post-filling than that measured during the experiments.
At the onset of post-filling there is a rather large pressure gradient along the length of the laminate. That pressure gradient being larger at the vent side than at the inlet side as can be observed in Figure 4-31 and Figure 6-6. As post-filling proceeds, the pressure gradient drops quickly and tends to be more linear along the length of the preform. Following on the argument presented in Section 5.8, it can be estimated that as the pressure gradient along the laminate decreases, an increasing fraction of the flow is generated by the compaction of the preform (the $\frac{\partial h}{\partial t}$ term from Equation (2-20)) and would possibly include a significant through thickness flow component. As the through thickness permeability of most fibrous reinforcement is an order of magnitude smaller than
the in-plane permeability, this may explain why, during post-filling, the pressures evolve much more slowly in the experiments than in the simulation.

6.4.2 Change of Post-filling Pressure

In this second experimental scenario, the filling stage is unchanged compared to the standard experiment. This results in the laminate thickness and fluid pressure variation during the filling phase being comparable to that observed during the standard experiment.

At the onset of post-filling, the vacuum pressure was raised from 470 Pa to 11300 Pa. It is quite common in the industry to raise the vacuum pressure during post-filling to prevent boiling off of components within the resin. This technique was also investigated in [38] as a way to control the final $V_f$ and therefore the laminate quality.

6.4.2.a Experimental Results

Figure 6-10 presents the evolution of fluid pressure and laminate thickness during the experiment. As expected, the fill time, fluid pressure and laminate thickness during the filling stage are very similar to the values observed during the two standard experiments.

At the beginning of post-filling, as the vent pressure is increased, a relatively large jump in pressure from 470 to 15800 Pa can be noticed at P7. An increase of pressure is also noticeable at P6 where the pressure rises from 27700 Pa just at the end of filling to 35100 Pa at the onset of post-filling. At P4 the increase is much smaller, from 66580 to 68700 Pa as the vacuum pressure was increased. At P2 and P1, the rise of pressure is barely noticeable; however a rapid increase of thickness is perceptible at P1 and P2, signifying a small increase in fluid pressure. The thickness at P3 also exhibits a small increase related to the pressure increase, but much less prominent. At P6 and P7 no thickness increase is detectable. This relates well to the compaction behaviour observed and characterised in Chapter 3, from the tests performed in the
Instron universal testing machine for the wet unloading. At low compaction levels, the $V_f$ appeared very sensitive to the applied compaction stress, whereas at high compaction levels, a small variation of compaction stress had no apparent effect on the $V_f$.

In this experiment, fluid pressures along the laminate appear to reach an equilibrium level much faster than in the standard experiment; after 15000 s there is no more apparent changes, whereas it took over 25000 s in the standard experiment for the pressures to reach a stable level. Figure 6-11 presents the pressure profile along the laminate at various instants during the filling and post-filling. The pressure gradient inside the laminate appeared to evolve in the same manner as in the standard experiment (shown in Figure 6-6, only the pressure at the vent being higher in this experiment. The pressure decay at the beginning of post-filling does not seem affected by the increased pressure at the vent; the pressure drop at P1, P2 and P4 appear as fast as during the standard experiment during this period. It therefore makes sense that the post-filling time is shorter when the pressure at the vent is increased during post-filling.
Validation of the Simulation and Cases Study

Figure 6-10: Pressure (a), and thickness (b) traces for the CSM infusion experiment with a higher post-filling pressure.
6.4.2.b Simulation Results

Figure 6-12 presents the pressure and thickness traces at the location of the five pressure transducers for the simulation of the case where the vent pressure was changed to 13000 Pa during post-filling. For the filling stage, the same observation as for the previous scenario can be made. For the post-filling, the simulation compares quite well with the experiment until about 1600 s, after that it predicts much faster changes than measured in the experiment, but the magnitude of the changes is in the same range as observed in the experiment. The pressure and thickness gradient at the end of post-filling also appear to be in the same range as those measured in the experiment.
Figure 6-12: Pressure (a) and thickness (b) traces for the simulation of the CSM infusion with change of post-filling pressure.
6.4.3 Use of a “Brake” Material

It is common in industry to use some sacrificial material between a vent and the end of the preform. This prevents the flow front reaching the vent before the whole preform is fully impregnated. A range of materials can be used for this purpose, including peel ply, felt, or unidirectional fabric oriented perpendicular to the flow. Each of these materials acts to slow down the progression of the resin front towards the vent.

In the scenario studied here, a 5 mm band of peel ply was chosen as the brake material. The peel ply permeability is on the same order of magnitude as the CSM reinforcement, but has a lower porosity. In addition, only one layer is used, being much thinner than the CSM preform. This significantly limits the amount of fluid able to flow through the brake region.

6.4.3.a Experimental Results

Figure 6-13 presents the evolution of fluid pressure and laminate thickness during the experiment. Again as the conditions during filling are identical to those during the standard experiment, very little difference can be observed during this stage of the process. However, large increases in pressure can be observed near the vent, as the flow front hits the end of the preform and enters the brake region. At P7 the pressure rises from 470 Pa to a maximum of 54060 Pa, at P6 it goes from 27080 to 61450 Pa. The pressure increase is more limited at P4, going from 71770 to 77240 Pa. No pressure increases were detected at P1 or P2. Laminate thickness at P4, P6, and P7 is affected by these pressure increases, going from 3.84 to 3.92 mm at P4, from 3.69 to 3.80 mm at P6 and from 3.65 to 3.77 mm at P7. Again, no increases were detected at either P1 or P2.

In the previous experiment, the pressure was suddenly raised at the vent, reversing temporarily the direction of the flow, this effect was observed all along the preform, albeit with a decreasing amplitude towards the inlet. However in
this experiment, the flow is never reversed, but as the flow front was reaching the end of the preform, the peel-ply acted as a brake dramatically reducing the flow. The pressures were then tending towards equilibrium, decreasing at the inlet and increasing at the vent. After that sudden increase of pressure in the vent side of the mould, the pressures all over the mould start decreasing as the excess fluid is drawn out through the vent. The pressure decay is however slower than in the standard experiment as the peel ply acts as a brake restricting the flow of fluid towards the vent. Figure 6-14 presents the pressure profile along the preform at various instances during the experiment. It can be observed that less than five minutes after clamping the inlet, the pressure gradient inside the laminate has reached its final profile. After that the pressure slowly decreases uniformly over the whole preform. While the brake acted as a high pressure resistance slowing down the pressure decay in the preform, it also helped the pressure to equilibrate faster along the preform.
Validation of the Simulation and Cases Study

Figure 6-13: Pressure (a), and thickness (b) traces for the CSM infusion experiment with a brake material.
6.4.3.b Simulation Results

Figure 6-15 presents the pressure and thickness traces for the simulation of the infusion case where a brake material was placed between the end of the preform and the vent. As in the previous cases it appears that the filling stage is correctly simulated. The onset of post-filling represents a significant deviation from the standard case, with a large rise of pressure in the vent half of the preform. The simulation accurately predicts the changes in laminate thickness and fluid pressure as the flow hits the brake zone. However after about 2000 s, the simulation predicts a faster drop of pressure than measured in the experiment, but the simulation still provides qualitatively good results for the behaviour and amplitude of changes in both fluid pressure and laminate properties during the post-filling. The pressure distribution as presented in Figure 6-16, closely match the experimental results seen in Figure 6-14.
Figure 6-15: Pressure (a) and thickness (b) traces for the simulation of the CSM infusion with use of a brake material.
6.4.4 Clamping the Inlet Early

In this fourth scenario, the influence of clamping the inlet before the end of filling was investigated. The idea behind this is that by decreasing the amount of excess fluid injected to a minimum, the post-filling period could be shortened. Different methods can be applied to determine when to clamp the inlet. The mass of fluid injected was monitored and this data could have been used to decide when to clamp the inlet. However, a small variation in the width of the preform would have a great influence on the quantity of fluid required, and uncertainty about the mass of fluid in the inlet tube resulted in that method not being chosen. Instead the inlet was clamped once the flow front reached a predetermined position. A few simulations were performed to determine a flow front position at which the inlet could be clamped, and the mould filled with confidence. From this analysis it was decided to clamp the inlet once the flow front had travelled 340 mm, leaving another 40 mm to be filled using only the excess fluid contained in the saturated part of the preform.
6.4.4.a Experimental Results

Figure 6-17 presents the evolution of fluid pressure and laminate thickness during the experiment, the dashed line represents the clamping of the inlet and the continuous vertical line signals the flow front reaching the end of the preform. Up until the clamping of the inlet, the evolution of fluid pressures and laminate thicknesses were very similar to that during the standard experiment. Once the inlet was closed, the pressure and thickness at P1 and P2 started decreasing while the pressure was still increasing at P4, P6 and P7. The peak pressures experienced at each pressure transducer are slightly lower than during the standard experiment. The time required for the pressure to stabilise during post-filling in this experiment is just marginally shorter than in the standard experiment.

By clamping the inlet earlier, 8% less fluid was injected in the mould, further study would be needed to optimise the amount of resin that could be saved by this technique. Also if the inlet was to be clamped earlier, further saving in post-filling time could maybe be achieved.
Figure 6-17: Pressure (a), and thickness (b) traces for the CSM infusion experiment where the inlet was clamped early.
6.4.4.b Simulation Results

Figure 6-18 presents the pressure and thickness traces predicted by the simulation of the case where the inlet was clamped early. As the inlet was closed early, the pressure and thickness traces reached a lower peak than in the standard scenario. The simulation predicted well the end of filling when the inlet was closed and the flow front progressed through the displacement of the excess fluid present on the inlet side of the preform. Again, further on during the post-filling, the simulation did predict faster changes than what could be observed during the experiment.
Figure 6-18: Pressure (a) and thickness (b) traces for the simulation of the CSM infusion with inlet clamped early.
6.4.5 Discussion

Four infusion scenarios have been tested and compared using a Chopped Strand Mat reinforcement. The effect of the different infusion scenarios will be reviewed in Section 6.6, using data from both CSM and CFM reinforcements.

The simulation developed in this thesis has provided very accurate predictions for the fill time, fluid pressure and laminate properties during filling. However, during post-filling the simulation predicts pressures and thicknesses to evolve significantly faster than observed during the experiments. Figure 6-19 presents a comparison of the compaction behaviour as observed during the infusion experiments, to the compaction model used in the simulation. For each experiment, the $V_f$ at P1 as calculated from the stereophotogrammetry was plotted as a function of the compaction pressure calculated from the fluid pressure. It appears that the model used is in reasonably good agreement with the experiments. This may indicate that the disparity between the simulated and experimental laminate evolution during post-filling is not caused completely by the choice of compaction model. The calculated pressure distribution as presented in Figure 6-8 and Figure 6-16 is also in good agreement with the experimental data presented in Figure 6-6 and Figure 6-14 respectively. The hypothesis of the importance of through the thickness flow during post-filling, as proposed in Section 5.8, still appears to be a valid suggestion.
6.5 Continuous Filament Mat

6.5.1 Standard Experiment

6.5.1.a Experimental Results

Figure 6-20 presents the evolution of the fluid pressure during the two repeats of the standard infusion method with six layers of CFM reinforcement. Despite using a much more viscous oil for the infusion with the CFM reinforcement, the fill time is much shorter than in the CSM case. This is due to the fact that the permeability of the CFM is much greater than that of the CSM. It can also be observed that the pressures equilibrate much faster during post-
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filling than what could be observed for the CSM reinforcement. Apart from the fill time, a noticeable difference between the CFM and CSM experiments is in the inlet pressure. The inlet pressure in the CFM experiments never reached a constant level. Due to the high flow rate into the preform, a significant flow rate dependant head loss is generated in the inlet tube. As the flow rate decreases with the progression of the flow front, the pressure at the inlet increases more slowly than for the CSM experiments. At the end of filling, the inlet pressure had only reached 94000 Pa.

At the onset of post-filling, the fluid pressure at P1 and P2 first decreased very rapidly down to about 36000 Pa, before the rate of pressure change decreased sharply. These pressures then kept on decreasing until stabilising at about 1400 Pa. The pressure at P4, P6 and P7 kept rising for about 30-50 s after the closing of the inlet. After about 7000 s no more pressure change was noticeable in the laminate, however a small gradient of pressure remained between the inlet and the vent (~1000 Pa difference between the pressures at P1 and P7). In the second experiment, the pressure stabilised at 2210 Pa at P1 and 740 Pa at P7, while the vacuum pressure remained stable at around 350 Pa during the whole experiment.

Figure 6-21 presents the evolution of laminate thickness during the two repeats of the standard experiment. Figure 6-22 presents the pressure and thickness profiles along the preform at various instances during the process. Comparing Figure 6-22 and Figure 6-6, it can be observed that during filling, the pressure profile along the laminate looks more linear with the CFM reinforcement than with the CSM preform. As with the CSM, the vast majority of the thickness changes happened in the inlet half of the preform. The thickness increase is equivalent to 27.3% at P1, 13.6% at P2 and 2.3% at P4. This thickness increase corresponds to 89.9%, 43.4% and 5.7% of permeability increase at P1, P2 and P4 respectively. While these changes are still significant, they are much smaller than the changes observed for the CSM trials. Another important point to notice is that during filling, the thickness in the dry part of the preform was slowly decreasing. The thickness at P6 and P7 decreased from 4.93 to 4.85 mm, corresponding to 1.58% decrease, over the 371 s filling period in the second experiment. Despite the precautions taken in
the development of the experimental procedure, there was still some time
dependent reduction in reinforcement thickness (creeping)
happening at the onset of infusion.

It is also interesting to note that as opposed to the observation made in
[145], there is no evidence of a thickness drop at the flow front. The CFM
reinforcement used in that previous study was a different product, however from
the characterisation performed in Chapter 3 one would have expected to see a
drop in thickness at the flow front for the experiments presented here.

At the onset of post-filling, the laminate thickness decreases quickly at P1,
P2 and P4. The rate of decline of thickness at P6 and P7 also increases slightly
compared to what was observed on the dry portion of the laminate during filling.
Shortly after the beginning of post-filling (at around 750s), the rate of thickness
change at P1, P2 and P4 sharply decreases to a value close to that
experienced at P6 and P7. After a post-filling period equivalent to about 1.8
times the fill time, the thickness at P1 becomes smaller than the thickness at
P7. At the end of post-filling a large thickness gradient is present in the
laminate, the thickness being greater on the vent side (4.3 mm) than on the inlet
side (3.97 mm). This last observation relates relatively well to the observations
made in Section 3.2 about the influence of the compaction history. Near the
inlet, the reinforcement went through a full wet unloading and re-compaction
cycle, while at the vent the preform remained fully compacted throughout the
process. This would explain why the laminate became thinner at the inlet when
the pressure was still higher there than on the vent side.
Figure 6-20: Fluid pressure traces for the two standard RI experiments using CFM reinforcement.
Figure 6-21: Laminate thickness traces for the two standard RI experiments using CFM reinforcement.

Figure 6-22 presents the pressure and thickness profiles at various instants during the experiment. It is interesting to notice that at $t = 783$ s, the fluid pressure is almost 30000 Pa at P1 and 2000 Pa at P7 but the laminate thickness is almost equal at those two points. Later in the post-filling stage, the
fluid pressure at P1 remains greater than at P7 however the laminate thickness is smaller at P1 than at P7.

Figure 6-22: Pressure (a) and thickness (b) profiles at various instances during the standard experiment with CFM reinforcement.
6.5.1.b Simulation Results

Figure 6-23 presents the pressure and thickness traces during the standard infusion as predicted by the simulation. It appears that the predicted thicknesses behave very differently from what was observed in the experiment. The decrease of stiffness in the wet preform that was observed during the material characterisation tests (presented in Section 3.2.3) result here in a large drop of the laminate thickness at the flow front, while this effect was not observed during the experiments. This large drop in thickness results in a higher $V_f$ and a 25% drop in permeability at the flow front and in the impregnated zone just after the flow front. This in turn results in a reduced flow at the flow front and therefore a longer fill time. The peak pressure and thicknesses were also overestimated in the simulation as compared to the experiment. This could be due to the inlet pressure being over estimated, the definition of the inlet tube parameters would need to be reviewed.

The simulation also overestimates the rate of change during the post-filling. However the residual pressure gradient appears to be in the same ballpark as that measured during the experiments. The simulation predicts that the laminate will be thinner at the inlet than at the vent, but the amplitude of the variation is not adequately predicted, it appears that the time dependant compaction behaviour is having more influence.
Figure 6-23: Pressure (a) and thickness (b) traces of the simulation of the standard infusion with CFM reinforcement.
6.5.1.c Comments on the Comparison

Figure 6-24 presents the compaction behaviour of the reinforcement as observed during the second standard experiment. The compaction stress calculated from the fluid pressure at each transducer is related to the $V_f$ at that point as calculated from the stereophotogrammetry. The traces of the dry unloading, wet unloading and wet compaction modelled from the characterisation experiment in the Instron are overlaid as a comparison. It was noticed in the characterisation experiments that the presence of fluid induced a significant decrease in the reinforcement stiffness. However in the RI experiment no lubrication effect was noticeable at the flow front. During the filling stage, the preform appears to follow the dry unloading model even though the preform is saturating.

During post-filling, the compaction traces bend upwards showing a decrease of rigidity as the preform compacts further. In the light of the pressure traces in Figure 6-20, this appears to signify a significant visco-elastic effect; as the rate of pressure change slows down, the preform is allowed to creep and compact further. This effect was not observed in the characterisation experiments as the tests were performed at a constant loading rate.
A previous CFM reinforcement of similar density that had been utilised in RI experiments presented in [145] displayed a significant lubrication effect at the flow front as seen in Figure 6-25. However, the newer reinforcement utilised in this thesis was developed specifically for a faster infusion. It appears that by altering the structure or binder of the reinforcement, the manufacturer was able to delay the collapse of the reinforcement due to the lubrication effect and therefore improve the flow at the resin front.
6.5.2 Change of Post-filling Pressure

6.5.2.a Experimental Results

As expected, with no change in the filling conditions, the filling stage in this experiment was similar to that in the standard experiments. Figure 6-26 presents the traces of fluid pressure and thickness measured over the five pressure transducers during the infusion experiment. At the onset of post-filling, the vent pressure was changed from 470 Pa to 22000 Pa. This change of pressure at the vent resulted in a rise of pressure at P6 and P7, but no pressure increase was noticeable at P1, P2 and P4. At P6 the pressure reached 34000 Pa as compared to 26000 Pa reached during the standard experiment. At P7 the pressure reached 25000 Pa, instead of 9000 Pa for the standard experiment.

During post-filling, after the initial pressure rise close to the vent, the fluid pressure inside the laminate evolves in a similar fashion as for the standard
experiment. The post-filling time necessary for the pressure to stabilise is roughly equal to that of the standard experiment. At the end of post-filling, a very similar pressure gradient exists as for the standard experiment. However, the remaining thickness gradient is smaller for the experiment with increased vent pressure. This difference in the final thickness gradient as compared to the standard experiment can be explained by the difference in loading history along the laminate. While in the standard experiment the preform at the vent remained compacted with about 1 bar of compaction, in this latest experiment, the vent was unloaded to a certain point (here about 0.75 bar of compaction). The final compaction stress in this experiment was around 0.8 bar, the re-compaction was therefore to a less extent than in the standard experiment.
Figure 6-26: Pressure (a), and thickness (b) traces for the CFM infusion experiment with a higher post-filling pressure.
6.5.2.b Simulation Results

Figure 6-28 presents the pressure and thickness traces at the location of the five pressure transducers for the simulation of the case where the vent pressure was changed to 20000 Pa during post-filling. For the filling stage, the same observation as for the previous scenarios can be made. For the post-filling, the simulation still predicts much faster changes than measured in the experiment, but the magnitude of the changes is in the same range as observed in the experiment with a good prediction of the pressure rise at P6 and P7 at the beginning of post-filling. The pressure gradient at the end of post-filling also
appears to be in the same ballpark as that measured in the experiment. As in the experiments, the simulation predicted a smaller thickness gradient present at the end of post-filling than for the standard experiment.
Figure 6-28: Pressure (a) and thickness (b) traces of the simulation of the CFM infusion with a change of post-filling pressure.
6.5.3 Use of a “Brake” Material

6.5.3.a Experimental Results

As with the CSM reinforcement, a 5 mm band of peel ply was placed between the vent and the end of the preform. Figure 6-29 presents the evolution of fluid pressure and laminate thickness during the filling and post-filling stages of the experiment. There was no major difference in the filling period when compared to the standard experiment. However, as the flow front reached the peel ply brake and the inlet was closed, the pressure at all transducers quickly converged towards 60000 Pa. As the peel ply acts as a brake restricting the flow of fluid towards the vent, the pressure in the laminate tends to equilibrate. Due to the very large difference in flow resistance offered by the CFM preform and the peel ply, the majority of pressure drop occurs through the brake. Once all the pressures converged, with only 1000 Pa difference between the pressures at P1 and P7, the pressure all over the laminate decreased at a slow, almost linear rate. This rate of pressure drop is dictated by the amount of fluid able to flow through the peel ply. The effect of the brake is much more noticeable as compared to the CSM experiment, due to the greater permeability difference between the reinforcement and the brake material. After 15000 s of post-filling, the pressure in the laminate ranged from 28400 Pa at P1 to 27600 Pa at P7 and was still decreasing, but the pressure gradient remained stable.

Looking at the evolution of the laminate thickness, it is interesting to note that at the onset of post-filling, not much increase in thickness can be observed at P4. However, at P6 and P7 the thickness increases from 4.32 mm to 4.61 mm, thicker than at P4 (~ 4.56 mm), despite the pressure being marginally lower at P6 and P7 as compared to P4. This thickness difference is quite small and close to the level of confidence of the thickness measurement system. However a possible explanation for that phenomenon could be due to some time dependent reinforcement compaction effect. As the pressure rise at P4 is much slower than at P6 and P7, locally the reinforcement has more time to rearrange during the wet unloading phase. Therefore the material may achieve
less spring back as compared to the reinforcement at P6 and P7, where the unloading is almost instantaneous. At the end of post-filling, there is a small thickness gradient remaining, the thickness at the inlet being smaller than the thickness at the vent. However the amplitude of the thickness gradient is much smaller than in the standard experiment, with only 0.1 mm difference between P1 and P7, compared to 0.34 mm in the standard experiment.
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Figure 6-29: Pressure (a), and thickness (b) traces for the CFM infusion experiment with a brake material.
6.5.3.b Simulation Results

Figure 6-31 presents the pressure and thickness traces at the location of the five pressure transducers for the simulation of the RI case where a brake material is placed between the preform and the vent. In this scenario, the simulation does not over-predict the rate of change happening during the post-filling. In this case the flow during post-filling is limited by the amount of fluid
able to flow through the brake material. In the simulation, the pressures quickly settle to 80000 Pa instead of the 60000 Pa observed in the experiment but this could be due to the difference in the inlet pressure, leading the simulation to over-predict all the pressures in the laminate during filling. But the simulation still produces excellent qualitative results for this scenario. The through thickness permeability of the CFM is greater than the permeability of the peel ply used as a brake and therefore does not significantly affect the flow in this case. As the brake material is composed of only one layer of distribution media, the through thickness flow can be assumed inexistent. This case therefore provides further hint that the disparities between the simulation and experiments in all other cases might be due to the effect of through thickness flow in the laminate.
Figure 6-31: Pressure (a) and thickness (b) traces of the simulation of the CFM infusion with use of a brake material.
6.5.4 Clamping the Inlet Early

6.5.4.a Experimental Results

In this experiment, the inlet was closed as the flow front reached 340 mm, the remaining unsaturated 40 mm of preform being filled with the excess fluid already present in the saturated part of the preform. Figure 6-32 presents the evolution of fluid pressure and laminate thickness. As expected the filling stage was very similar to that observed during the standard experiment. But as the inlet was closed earlier, the pressures reached a lower maximum compared to those observed in the standard experiment. In the first part of post-filling, while the flow front was still progressing along the preform, the pressure at P1, P2 and P4 were decreasing at a rate comparable to that observed in the standard experiment, while the pressure at P6 remained stable, and the pressure at P7 started rising as the flow front hit the end of the preform. The remainder of the post-filling stage is very similar to that observed during the standard experiments, for both the fluid pressure and laminate thickness. The pressure distribution has equilibrated after a time equivalent to that of the standard experiment, to similar levels of fluid pressure and laminate thickness. While there was no significant saving in post-filling time, clamping the resin inlet earlier enabled 13% less fluid to be injected to fill the mould.
Validation of the Simulation and Cases Study

Figure 6-32: Pressure (a), and thickness (b) traces for the CFM infusion experiment where the inlet was clamped early.
6.5.4.b Simulation Results

Figure 6-33 presents the pressure and thickness traces predicted by the simulation of the case where the inlet was clamped early. The pressure and thickness traces reached a lower peak than in the standard scenario, and reached equilibrium faster during the post-filling. The pressure and thickness gradient at the end of post-filling are equivalent to those predicted for the standard case. In this case there is a significant difference in behaviour from the beginning of the post-filling, but this could be due to the inaccurate prediction of the inlet pressure, leading to different pressure along the laminate at the time of closing the inlet.
Figure 6-33: Pressure (a) and thickness (b) traces of the simulation of the CFM infusion with the inlet clamped early.
6.5.5 Discussion

It was observed during the experiments, that the dry preform was still compacting at the beginning of the infusion and throughout the filling stage. The final laminate thickness after post-filling was also much smaller than predicted by the simulation. Figure 6-34 presents the traces of the $V_f$ at P1 as a function of the compaction stress during both filling and post-filling stage for the four different infusion strategies, as well as the models for wet unloading and wet compaction as developed in Section 3.2. From this figure it can be seen that the CFM reinforcement displays very repeatable behaviour for wet unloading (during the filling period), but does not match the proposed compaction model. During post-filling, the experimental traces match each other at the beginning of the compaction, but then diverge at later times due to a difference in compaction rates. To fully understand the behaviour observed, one needs to take into account the locally applied loading rate or the rate of decay of the fluid pressure during post-filling. At the beginning of post-filling, the fluid pressure decreases rapidly. Further into the post-filling stage the rate of decay of the fluid pressure slows down tremendously. This results in the preform being at first compacted at a relatively high rate ($\approx 300 \text{ Pa.s}^{-1}$), while the rate reduces to a much smaller rate later in the process ($< 1 \text{ Pa.s}^{-1}$). The compaction model proposed in this thesis has been derived from unloading and compaction experiments performed at a constant rate of 26.7 Pa.s$^{-1}$. While a characterisation at a much lower compaction rate would enable the final volume fraction to be predicted more accurately, it would still fail to account for the effects observed at the flow front. A more complex model including transient and time dependant effects is needed to fully capture the behaviour of this CFM reinforcement.
6.6 Conclusion

In this chapter four different RI strategies were presented in an effort to better understand the post-filling stage of resin infusion, and to control the final laminate thickness.

Changing the vent pressure during post-filling appeared to decrease the thickness gradient in the final part and can also be used to decrease the compaction on the reinforcement and therefore decrease the final $V_f$. Increasing the vent pressure during post-filling is also beneficial to prevent the resin from boiling off in the laminate. Also if voids are entrapped in the laminate, the size of the voids will increase as the resin pressure decreases, which would reduce the part quality if the resin pressure drops too low.

The use of a brake material allows for a much faster reduction of the pressure gradient along the laminate by restricting the flow of fluid out of the preform. The fluid pressure near the vent greatly increases when the resin front hits the brake material, the difference in compaction history along the laminate
is therefore greatly reduced and this results in a much smaller thickness gradient in the finished part. The ability to choose the permeability, porosity and dimensions of the brake material may allow a better level of control of the final part quality.

The closing of the inlet before completion of the filling did not improve the thickness gradient in the final part. However this technique allowed saving of around 10% in the quantity of fluid used. This could therefore offer significant savings in material cost and should be further evaluated.

The simulation presented here provided very good predictions for the filling stage with the CSM reinforcement, and good qualitative results for the post-filling. However the CFM reinforcement displayed too much time and rate dependency to be accurately represented with the mainly elastic compaction behaviour developed in this thesis.

The influence of the pressure drop in the inlet was observed in the experiments but some improvements are required to accurately model this effect in the simulation.

As a general conclusion on the simulation, the filling phase is very well predicted even in the case where the inlet was clamped early. The post-filling simulation provided excellent qualitative results, picking up the deviations from the standard scenario. While some improvements are still required, the simulation as presented in this thesis can be used to explore ways to better design the post-filling stage.
Chapter 7 CONCLUSION AND FUTURE WORK

The main goals of this research were to develop a comprehensive resin infusion monitoring setup as well as to develop a numerical tool capable of simulating both the filling and post-filling stages of the resin infusion process.

7.1 Conclusion

Following are the main conclusions that can be drawn from the results of the research presented in this thesis.

- A comprehensive RI monitoring setup was designed and built, including the development of a full field stereophotogrammetry system in collaboration with the CITR from the University of Auckland. The implementation of the monitoring system involved the measurement of fluid pressure in the laminate as well as at both inlet and vent, and also the monitoring of the flow rate and flow front progression. Through the stereophotogrammetry system, the local changes in laminate thickness were dynamically recorded with an accuracy of ±0.05 mm. The full field thickness measurement was then used to evaluate the evolution of the local fibre volume fraction and permeability.
A new procedure adapted to the RI process was devised to characterise the complex compaction behaviour of fibrous reinforcements.

A new compaction model was developed taking into account the compaction history of the reinforcements. This model is based on simple elastic behaviour for better computational performance and ease of characterisation. Such a model was required to be able to consider the simulation of the pre-filling, filling and post-filling of the RI process.

A modified Darcy’s law sourced from the petroleum and ground water flow literature was implemented, based on experimental observations of residual pressure fields in the laminate and slower than expected progress during post-filling. This model had not previously been used in the field of LCM processes.

A 1D finite element simulation was developed, incorporating the new compaction model and modified Darcy’s law. This simulation predicts the fluid flow and change in reinforcement properties during the filling and post-filling stages of the resin infusion moulding process. Good comparisons to experimental results were produced for the filling stage, and qualitatively good comparisons for the post-filling stage of the process.

In a ‘standard’ infusion experiment, there are some significant laminate property changes at the inlet and in the inlet half of the saturated portion of the preform. By the end of filling, a third of the preform has a permeability two or more times greater than values at the flow front. The post-filling stage typically takes more than twice the filling time to achieve an equilibration of the pressure and thicknesses along the laminate. It was also observed that at the end of post-filling, the laminate near the inlet is able to compact more than the material at the vent side, due to differences in loading history.
An experimental investigation of various factors affecting the post-filling was proposed accompanied by the simulation of the different cases investigated. It was found that significant control of the post-filling can be achieved through careful selection of a brake material, and possibly in conjunction with a change of post-filling pressure. While the action of clamping the inlet before the end of filling did not appear to have significant influence on the post-filling, this technique provides an opportunity to decrease the amount of resin needed by around 10%.

The simulation, while allowing good qualitative comparison for the post-filling was not able to fully capture the time scale required for the pressure and thickness to stabilise during post-filling. Some hypotheses were raised to try to explain that discrepancy, but these will need further investigation to validate them.

7.2 Recommendation for Future Work

On the basis of the research presented in this thesis, the following recommendations are made with regards to further developing the numerical simulation of the resin infusion process and improving the control of the process:

- Further investigation should be devoted to understanding the flow of resin and consolidation of the laminate during the post-filling phase, including the possibility of through-thickness flow.

- The simulation will be extended to 2D, implemented in the SimLCM package. It may also be necessary to extend to 3D if the through-thickness flow is proved to be important during the post-filling stage.

- A new experimental procedure should be devised to more accurately determine the parameters of the modified Darcy’s law. The use of a rigid tool with accurate displacement control would allow establishment of a uniform and controlled preform
permeability. An accurate flow meter would also be needed to precisely measure the flow when approaching the critical pressure gradient.

- A time and temperature dependant model of the fluid viscosity can be implemented to model the progressive curing of the resin during the process. A similar extension could address reinforcement presenting double scale flow, incorporating a local mass sink term in the flow equations.
Chapter 8 REFERENCES


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APPENDICES
Appendix A  POST FILLING MOULD
Technical drawing of the post-filling mould

Cross section of the post-filling mould at the inlet, transducers and vent.
Appendix B  Development of the Solution Method

In this thesis, it was chosen to use one dimensional linear elements, meaning that each variable is approximated using linear shape functions over an element. The linear shape functions are expressed in local coordinates as:

\[ N_1(\xi) = \frac{1-\xi}{2} \quad \text{and} \quad N_2(\xi) = \frac{1+\xi}{2}, \quad (1) \]

and the transformation from global to local coordinates follows the following Equations:

\[ x = \frac{1-\xi}{2} x_i + \frac{1+\xi}{2} x_{i+1}, \quad \xi = \frac{2(x-x_i)}{x_{i+1}-x_i} - 1, \quad \frac{dx}{d\xi} = \frac{2}{(x_{i+1}-x_i)} = \frac{2}{L}. \quad (2) \]

1. I/CM Case

For this simulation the assumption of no spatial variation will be conserved:

\[ \frac{\partial h}{\partial x} = 0. \quad (3) \]

Combining Equations (2-12 and 2-13) leads to the I/CM governing Equation:

\[ \frac{K_{xx}}{\mu} \frac{\partial^2 P}{\partial x^2} = \frac{1}{h} \frac{dh}{dt}. \quad (4) \]
Appendices

As the permeability does not vary spatially (5-31), Equation (2-19) leads to the formulation of the volume average velocity at the flow front:

\[ q_z = -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} + (x_c - x) \left( \frac{1}{h} \frac{\partial h}{\partial t} \right). \] (5)

Different compression methods are available for the compaction phase of I/CM, prescribed velocity of the B side mould or a prescribed applied force on the tool. In this preliminary simulation, only the constant B side mould velocity will be evaluated as it is the only method allowing for a simple analytical calculation of the fill time to compare with the simulation.

Using the Galerkin finite elements method, the strong formulation of the I/CM governing Equation (5-32) is:

\[ I = \int_{x_i}^{x_f} \left( \frac{d}{dx} \left( \frac{K_{xx}}{\mu} \frac{dP}{dx} \right) - \left( \frac{1}{h} \frac{dh}{dt} \right) \omega(x) \right) dx = 0, \] (6)

which, by integrating by parts, gives the weak formulation:

\[ \int_{x_i}^{x_f} \left( \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} \omega \right]_{x_f}^{x_i} + \left( \frac{1}{h} \frac{dh}{dt} \omega(x) \right) \right) dx = \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} \omega(x) \right]_{x_f}^{x_i}. \] (7)

Considering the B side mould velocity as a constant:

\[ \frac{\partial h}{\partial t} = \dot{h}, \] (8)

discretising the pressure in Equation (7) results in:

\[ \int_{x_i}^{x_f} \left( \left[ \frac{K_{xx}}{\mu} \left( P_i \frac{N_1}{dx} + P_{i+1} \frac{N_2}{dx} \right) \frac{dN_j}{dx} \right]_{x_f}^{x_i} + \left( \frac{\dot{h}}{h} N_j \right) \right) dx = \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} N_j \right]_{x_f}^{x_i}, \] (9)

then transposing into local coordinates gives:
\[
\int_{-1}^{1} \left( \frac{K_{xx}}{\mu} \left( P_i \frac{N_j}{d\xi} \frac{d\xi}{dx} + P_{i+1} \frac{N_j}{d\xi} \frac{d\xi}{dx} \right) + \frac{h}{h} N_j \right) \frac{L}{2} d\xi = \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} N_j \right]^{x+1}_{x-1}, \tag{10}
\]

which, using the set of Equations (5-2), can be simplified to:

\[
\frac{K_{xx}}{\mu} \frac{2}{L} (P_i - P_{i+1}) \int_{-1}^{1} \frac{dN_j}{d\xi} \frac{d\xi}{dx} + \frac{L}{2h} \int_{-1}^{1} N_j d\xi = \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} N_j \right]^{x+1}_{x-1}. \tag{11}
\]

Therefore for each shape function:

\[
j = 1 : \quad \frac{K_{xx}}{L\mu} (P_i - P_{i+1}) \int_{-1}^{1} d\xi + \frac{L}{4h} \int_{-1}^{1} (1 - \xi) d\xi = -\frac{K_{xx}}{\mu} \frac{dP}{dx} \bigg|_{x_i},
\]

\[
j = 2 : \quad \frac{K_{xx}}{L\mu} (P_{i+1} - P_i) \int_{-1}^{1} d\xi + \frac{L}{4h} \int_{-1}^{1} (1 + \xi) d\xi = \frac{K_{xx}}{\mu} \frac{dP}{dx} \bigg|_{x_i+1}.
\]

The elemental matrices are obtained by integrating (12):

\[
\overline{K}_{el} = \frac{K_{xx}}{L\mu} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \quad \text{and} \quad \overline{F}_e = \left[ \frac{K_{xx}}{\mu} \frac{dP}{dx} \bigg|_{x_i} \right] - \frac{L}{2h} \frac{\dot{h}}{h} 
\]

It should be noted that when building the global right hand side matrix, the \( \frac{dP}{dx} \) terms cancel at overlapping points, but the B side mould velocity term adds up. The linear system of Equations to solve is then expressed as:

\[
\overline{K}\overline{P} = \overline{F}, \tag{14}
\]
2. RI Classic Darcy’s Law

The mathematical formulation of the resin infusion process with an unmodified Darcy’s law is detailed in Section 2.2. The strong formulation of Equation (2-14) is:

\[
I = \int_{x_i}^{x_f} \left( \frac{d}{dx} \left( \frac{K_{xx}}{\mu} \frac{dP}{dx} \right) - \frac{dh}{dt} \right) \omega(x) dx = 0,
\]

which leads to the weak formulation:

\[
\int_{x_i}^{x_f} \left( \frac{K_{xx}}{\mu} \frac{\partial h}{\partial x} \right) \omega dx + \frac{\partial h}{\partial t} \omega(x) \right) dx = \left[ \left( \frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} \right) \omega(x) \right]_{x_i}^{x_f}. \tag{16}
\]

Discretising the variables using trial functions gives:

\[
\int_{x_i}^{x_f} \left( \left( K_{xx} \frac{h}{\mu} - \frac{\partial h}{\partial x} \right) \omega(x) \right) dx = \left[ \left( K_{xx} \frac{h}{\mu} \frac{\partial P}{\partial x} \right) \omega(x) \right]_{x_i}^{x_f}.
\]

Transposing (17) into local coordinates:
\[ j = 1: \]
\[
\frac{(P_i - P_{ri})}{8\mu L} \int_{-1}^{1} \left( (K, h_j \cdot (1-\xi)^2 + (K, h_j + K, h_j) \cdot (1-\xi) \cdot (1+\xi) + K_{ri}, h_{ri} \cdot (1+\xi)^2 \right) d\xi
\]
\[ + \frac{L}{8} \int_{-1}^{1} \left( \frac{\partial h_j}{\partial t} (1-\xi)^2 + \frac{\partial h_{ri}}{\partial t} (1-\xi)(1+\xi) \right) \]
\[ = \left[ \frac{K}{\mu} h \frac{\partial P}{\partial x}(x) \right]_{x_i} \]

\[ (18) \]

\[ j = 2: \]
\[
\frac{(P_{ri} - P)}{8\mu L} \int_{-1}^{1} \left( (K, h_j \cdot (1-\xi)^2 + (K, h_j + K, h_j) \cdot (1-\xi) \cdot (1+\xi) + K_{ri}, h_{ri} \cdot (1+\xi)^2 \right) d\xi
\]
\[ + \frac{L}{8} \int_{-1}^{1} \left( \frac{\partial h_j}{\partial t} (1-\xi)(1+\xi) + \frac{\partial h_{ri}}{\partial t} (1+\xi)^2 \right) \]
\[ = \left[ \frac{K}{\mu} h \frac{\partial P}{\partial x}(x) \right]_{x_i} \]

Which after integrating the left hand side gives:

\[ j = 1: \]
\[
\frac{(P_i - P_{ri})}{6\mu L} \left( 2 \cdot K, h_j + (K, h_{ri} + K, h_j) + 2 \cdot K_{ri}, h_{ri} \right)
\]
\[ + \frac{L}{6} \left( 2 \cdot \frac{\partial h_j}{\partial t} + \frac{\partial h_{ri}}{\partial t} \right) = \left[ \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} \right) \right]_{x_i}
\]

\[ (19) \]

\[ j = 2: \]
\[
\frac{(P_{ri} - P)}{6\mu L} \left( 2 \cdot K, h_j + (K, h_j + K, h_j) + 2 \cdot K_{ri}, h_{ri} \right)
\]
\[ + \frac{L}{6} \left( \frac{\partial h_j}{\partial t} + 2 \cdot \frac{\partial h_{ri}}{\partial t} \right) = \left[ \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} \right) \right]_{x_{ri}}
\]

This is then expressed in matrix form as:

\[
\overline{K(\overline{h})}_{el} + \overline{C(\overline{h})} \frac{\partial \overline{h}}{\partial t} = \overline{F(\overline{h})}_{el},
\]

\[ (20) \]

The elemental stiffness vector \( \overline{K(\overline{h})}_{el} \) is expressed as:
The capacitance matrix $\overline{C}_{el}$ is:

$$\overline{C}_{el} = \begin{bmatrix} \frac{L}{3} & L \\ \frac{L}{6} & \frac{L}{3} \end{bmatrix},$$

(22)

The right hand side vector can be ignored as the values cancels at every nodes but the inlet and flow front nodes. However the values at those nodes are replaced by the boundary conditions. Therefore, when assembling the global matrices from Equation (5-5) give:

$$\overline{R}(\overline{h(t)}) = \overline{C}(\overline{h(t) - h(t - \Delta t)}) + \Delta(\overline{K}(\overline{h(t)})^T),$$

(23)

with

$$\begin{bmatrix} \overline{K}_{el}(\overline{h}^{-1}) \\ \Delta\overline{h} = -\overline{R}(\overline{h}^{-1}) \end{bmatrix},$$

$$\overline{K}_{el}(\overline{h}^{-1}) = \frac{\partial \overline{R}}{\partial \overline{h}}(\overline{h}^{-1}),$$

(24)

To solve Equation (5-9), the elemental tangent matrix $\overline{K}_{el}$ can be expressed as:
\[
\begin{align*}
\mathbf{K}_{i,i} &= \frac{(P_i - P_{i+1})}{6\mu L} \left[ 2 \cdot K_i + 2 \cdot h_i \frac{dK_i}{dh_i} + h_i \frac{dK_i}{dh_i} + K_i \right] \\
& + \frac{(2 \cdot K_i h_i + (K_i h_i) + 2 \cdot K_i h_i h_i)}{6\mu L} \frac{dP_i}{dh_i}, \\
\mathbf{K}_{i,i+1} &= \frac{(P_i - P_{i+1})}{6\mu L} \left[ 2 \cdot K_{i+1} + 2 \cdot h_{i+1} \frac{dK_{i+1}}{dh_{i+1}} + h_{i+1} \frac{dK_{i+1}}{dh_{i+1}} + K_{i+1} \right] \\
& + \frac{(2 \cdot K_i h_i + (K_i h_i) + 2 \cdot K_i h_i h_i)}{6\mu L} \frac{dP_{i+1}}{dh_{i+1}}, \\
\mathbf{K}_{i+1,i} &= \frac{(P_{i+1} - P_i)}{6\mu L} \left[ 2 \cdot K_i + 2 \cdot h_i \frac{dK_i}{dh_i} + h_i \frac{dK_i}{dh_i} + K_i \right] \\
& + \frac{(2 \cdot K_i h_i + (K_i h_i) + 2 \cdot K_i h_i h_i)}{6\mu L} \frac{dP_i}{dh_i}, \\
\mathbf{K}_{i+1,i+1} &= \frac{(P_{i+1} - P_i)}{6\mu L} \left[ 2 \cdot K_{i+1} + 2 \cdot h_{i+1} \frac{dK_{i+1}}{dh_{i+1}} + h_{i+1} \frac{dK_{i+1}}{dh_{i+1}} + K_{i+1} \right] \\
& + \frac{(2 \cdot K_i h_i + (K_i h_i) + 2 \cdot K_i h_i h_i)}{6\mu L} \frac{dP_{i+1}}{dh_{i+1}}.
\end{align*}
\]

and the implicit Newton-Raphson algorithm can be used to solve the Equation iteratively.
3. RI Modified Darcy’s Law

When using the modified Darcy’s law as proposed by Prada:

\[ q_x = -\frac{K_{xx}}{\mu} \frac{dP}{dx} - \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda}, \]  

(26)

the modifications of Darcy’s law requires redefining the mathematics of the process; the governing Equation for the RI is now:

\[ \frac{\partial}{\partial x} \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} + h\gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \right) = \frac{\partial h}{\partial t}. \]  

(27)

The volume averaged velocity is then changed to:

\[ q_x = -\frac{K_{xx}}{\mu} \frac{\partial P}{\partial x} - \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} + \left( \frac{x-x_c}{h} \right) \left( \frac{K_{xx}}{\mu} \frac{\partial h}{\partial x} \frac{\partial P}{\partial x} + \gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \frac{\partial h}{\partial x} - \frac{\partial h}{\partial t} \right). \]  

(28)

the strong formulation of (5-53) is expressed as:

\[ I = \int_{x_i}^{x_f} \left( \frac{\partial}{\partial x} \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} + h\gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \right) - \frac{\partial h}{\partial t} \right) \omega(x) dx = 0. \]  

(29)

leading to the weak formulation:

\[ \int_{x_i}^{x_f} \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} + h\gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \right) \frac{d\omega}{dx} + \frac{\partial h}{\partial x} \omega(x) \right) dx = \left[ \left( \frac{K_{xx}}{\mu} h \frac{\partial P}{\partial x} + h\gamma \left( \frac{K_{xx}}{\mu} \right)^{-\lambda} \right) \omega(x) \right]_{x_i}^{x_f}. \]  

(30)

Following the same steps as described in Appendix B-2, leads to the expression of the elemental stiffness vector \( \overline{K(\bar{h})}_e \):
The capacitance matrix remains unchanged and the elemental tangent matrix $\mathbf{K}_{\mathbf{r}'}$ can be expressed as:

$$
\mathbf{K}_{\mathbf{r}'} = \left\{ \frac{(P_i - P_{i+1})}{6 \mu L} \left(2 \cdot \mathbf{K}_i \mathbf{h}_j + (\mathbf{K}_i \mathbf{h}_{i+1} + \mathbf{K}_{i+1} \mathbf{h}_j) + 2 \cdot \mathbf{K}_{i+1} \mathbf{h}_{i+1} \right) \right\}
$$

$$
- \frac{1}{6} \left[ 2 \mathbf{h}_j \left( \mathbf{K}_i \frac{1}{\mu} \right) + \mathbf{h}_j \left( \mathbf{K}_{i+1} \frac{1}{\mu} \right) + \mathbf{h}_{i+1} \left( \mathbf{K}_i \frac{1}{\mu} \right) + 2 \mathbf{h}_{i+1} \left( \mathbf{K}_{i+1} \frac{1}{\mu} \right) \right] 
$$

The capacitance matrix remains unchanged and the elemental tangent matrix $\mathbf{K}_{\mathbf{r}'}$ can be expressed as:
Appendices

\[ \overline{K_{i,i}} = \frac{(P_i - P_{i+1})}{6\mu L} \left( 2 \cdot K_i + 2 \cdot h_i \frac{dK_i}{dh_i} + h_{i+1} \frac{dK_{i+1}}{dh_i} + K_i \right) \]

\[ + \frac{(2 \cdot K_i h_i + (K_i h_{i+1} + K_{i+1} h_i) + 2 \cdot K_{i+1} h_{i+1})}{6\mu L} \frac{dP_{i+1}}{dh_{i+1}} \]

\[-\frac{1}{6} \left( 2\gamma \left( \frac{K_i}{\mu} \right)^{\gamma - 1} - 2h_i \gamma^2 \left( \frac{K_i}{\mu} \right)^{\gamma - 1} \frac{dK_i}{dh_i} + \gamma \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} - h_{i+1} \gamma^2 \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} \frac{dK_{i+1}}{dh_{i+1}} \right) \]

(32)

\[ \overline{K_{i,i+1}} = \frac{(P_{i+1} - P_i)}{6\mu L} \left( 2 \cdot K_i + 2 \cdot h_i \frac{dK_i}{dh_i} + h_{i+1} \frac{dK_{i+1}}{h_i} + K_i \right) \]

\[-\frac{(2 \cdot K_i h_i + (K_i h_{i+1} + K_{i+1} h_i) + 2 \cdot K_{i+1} h_{i+1})}{6\mu L} \frac{dP_i}{dh_i} \]

\[+\frac{1}{6} \left( 2\gamma \left( \frac{K_i}{\mu} \right)^{\gamma - 1} - 2h_i \gamma^2 \left( \frac{K_i}{\mu} \right)^{\gamma - 1} \frac{dK_i}{dh_i} + \gamma \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} - h_{i+1} \gamma^2 \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} \frac{dK_{i+1}}{dh_i} \right) \]

\[ \overline{K_{i+1,i}} = \frac{(P_{i+1} - P_i)}{6\mu L} \left( 2 \cdot K_{i+1} + 2 \cdot h_{i+1} \frac{dK_{i+1}}{h_{i+1}} + h_i \frac{dK_i}{h_{i+1}} + K_i \right) \]

\[+\frac{(2 \cdot K_i h_i + (K_i h_{i+1} + K_{i+1} h_i) + 2 \cdot K_{i+1} h_{i+1})}{6\mu L} \frac{dP_i}{dh_i} \]

\[+\frac{1}{6} \left( -h_i \gamma^2 \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} \frac{dK_{i+1}}{dh_i} + \gamma \left( \frac{K_i}{\mu} \right)^{\gamma - 1} - 2h_{i+1} \gamma^2 \left( \frac{K_i}{\mu} \right)^{\gamma - 1} \frac{dK_i}{dh_{i+1}} + 2\gamma \left( \frac{K_{i+1}}{\mu} \right)^{\gamma - 1} \right) \]
Appendix C  FLOW FRONT TRACKING CODE

- main program:

```matlab
clc, close all, clear all
tic
disp('** FLOW FRONT TRACKING CODE **');
disp(' ');
PREFORMLENGTH=380;

disp('Please select a photo set you would like to use (any photo in the set, does not have to be the first one)');
[PhotoSel, pathname]=uigetfile({'*.bmp';'*.*'}); % prompt the user to select their image file
firstPhoto=input('Please enter the number of the FIRST photo to consider : ');
lastPhoto=input('Please enter the number of the LAST photo to consider : ');
index=1;
for pic=firstPhoto:lastPhoto
    picString=int2str(pic);
    undScr='_
    prefix=[PhotoSel(1), undScr];
    suffix='.bmp';
    filename=[pathname, prefix, picString, suffix];
    i=imread(filename);
    %for the first image define the processing parameters by clicking and entering values
    if index==1
        close all;
        imshow(i);
        disp('Pick an upper and lower point that correspond to a vertical line');
        p=ginput2(2);
        [x1,y1]=meshgrid(p(1,1),p(1,2));
        [x2,y2]=meshgrid(p(2,1),p(2,2));
        sign=1;
        if x1<x2
            sign=-1;
        end
        %Measure the rotation angle
        angle=sign*180/pi*atan((abs(x1-x2))/(abs(y1-y2)));
        close all
        rotImage=imrotate(i, angle, 'bilinear');
        imshow(rotImage);
    end
    %calibrate the spatial measurement
    close all, clc, disp('define the preform length');
    imshow(rotImage);
    points=ginput2(2);
    [x1,y1]=meshgrid(points(1,1),points(1,2));
    [x2,y2]=meshgrid(points(2,1),points(2,2));
    pixelDistance=abs(x2-x1);
```

```
Appendices

\[
\text{mmPerPixel} = \text{PREFORMLENGTH} / \text{pixelDistance};
\]
\[
\text{clc;}
\]
\[
\text{disp('Please select the furtherest right point of the preform');}
\]
\[
\text{close all, imshow(rotImage);}
\]
\[
\text{pRight=ginput2(1);}
\]
\[
\text{rightLim=pRight(1);}
\]
\[
\% define cropping area for the top and bottom viewing strips
\]
\[
\text{doneCroppingTop=0}
\]
\[
\text{while doneCroppingTop==0}
\]
\[
\% get top section
\]
\[
\text{close all;}
\]
\[
\text{clc, disp('select the top region - UL then BR');}
\]
\[
\text{imshow(rotImage);}
\]
\[
\text{pTop=ginput2(2);}
\]
\[
\text{rectTop=[pTop(1,1),pTop(1,2),rightLim-pTop(1,1),pTop(2,2)-pTop(1,2)];}
\]
\[
\text{topIm=imcrop(rotImage,rectTop);}
\]
\[
\text{figure, imshow(topIm);}
\]
\[
\text{userInput=input('Are you happy with this cropping? (y/n) :','s');}
\]
\[
\text{if userInput=='y'}
\]
\[
\text{doneCroppingTop=1;}
\]
\[
\text{end}
\]
\[
\text{end}
\]
\[
\text{doneCroppingBot=0}
\]
\[
\text{while doneCroppingBot==0}
\]
\[
\% get lower section
\]
\[
\text{close all;}
\]
\[
\text{clc, disp('select the bottom region - UL then BR');}
\]
\[
\text{imshow(rotImage);}
\]
\[
\text{pBot=ginput2(2);}
\]
\[
\text{rectBot=[pBot(1,1),pBot(1,2),rightLim-pBot(1,1),pBot(2,2)-pBot(1,2)];}
\]
\[
\text{botIm=imcrop(rotImage,rectBot);}
\]
\[
\text{figure, imshow(botIm);}
\]
\[
\text{userInput=input('Are you happy with this cropping? (y/n) :','s');}
\]
\[
\text{if userInput=='y'}
\]
\[
\text{doneCroppingBot=1;}
\]
\[
\text{end}
\]
\[
\text{end}
\]
\[
\text{threshed=0;}
\]
\[
\text{T=0.69; %threshold -- can change to make it automatic later}
\]
\[
\text{close all, clc;}
\]
\[
\text{i1=topIm;}
\]
\[
\% take the first, middle and last pictures and crop to test threshold level
\]
\[
\text{midPicString=int2str(round((lastPhoto+firstPhoto)/2));}
\]
\[
\text{midPicFilename=[pathname,prefix,midPicString,suffix];}
\]
\[
\text{i2=imread(midPicFilename);}
\]
\[
\text{i2=imrotate(i2,angle,'bilinear');}
\]
\[
\text{i2=imcrop(i2,rectTop);}
\]
lastPicString=int2str(lastPhoto);
lastPicFilename=[pathname,prefix,lastPicString,suffix];
i3=imread(lastPicFilename);
i3=imrotate(i3,angle,'bilinear');
i3=imcrop(i3,rectTop);

while threshed==0
    %checking threshold

    i1t=threshImage(i1,T,i);
    i2t=threshImage(i2,T,i);
    i3t=threshImage(i3,T,i);

    figure,subplot(6,1,1),imshow(i1t),subplot(6,1,2),imshow(i1),subplot(6,1,3),imshow(i2t),subplot(6,1,4),imshow(i2),subplot(6,1,5),imshow(i3t),subplot(6,1,6),imshow(i3);
    userInput=input('Are the photos correctly thresholded? (y/n)','','s');
    if userInput=='y'
        threshed=1;
    else
        disp(sprintf('the current threshold is %g',T));
        T=input('Please enter a new threshold between 0-1 : ');
    end
end

else % for all remaining images use the predefined parameters
    disp(index);
    % rotate the image
    rotImage=imrotate(i,angle,'bilinear');
    % crop
    topIm=imcrop(rotImage,rectTop);
    botIm=imcrop(rotImage,rectBot);
end

% Threshold the top and bottom section
top=threshImage(topIm,T,i);
bot=threshImage(botIm,T,i);

% find the length of the saturated preform
avDistTop(index)=findFlowFrontLength(top)*mmPerPixel;
avDistBot(index)=findFlowFrontLength(bot)*mmPerPixel;

index=index+1;
end

close all;

% plot flow front progression as a function of time step
figure,hold on
plot(avDistTop,'--r'),plot(avDistBot,'--b');
legend('Top Section','Bottom Section');
ylabel('Flow front distance (mm)');
xlabel('Picture Number');
ylim([0 PREFORMLENGTH])
% export the result into a .txt file
indexRange=firstPhoto:lastPhoto;
toOutPut(:,1)=indexRange;
toOutPut(:,2)=avDistTop;
toOutPut(:,3)=avDistBot;
filename = 'flowfront.txt';
flowfrontname = [pathname prefix filename];
 fid = fopen(flowfrontname, 'wt');
 fprintf(fid, '%4.0f	%-12.6f	%-12.6f
', toOutPut');
fclose(fid)
toc

- Function threshold:

function bwImage=threshImage(image,T,i)

  % This function binarize the image using the threshold T
  % and then clean the image of smaller objects
  bwImage=im2bw(image,T);
  se=strel('square',round(size(i,1)/467.2)+1);
  bwImage=imopen(bwImage,se);
  se=strel('square',round(size(i,1)/155.733)+1);
  bwImage=imclose(bwImage,se);
  se=strel('disk',round(size(i,1)/233.6)+1);
  bwImage=imopen(bwImage,se);

  return;

- Function flow front length:

function avDist=findFlowFrontLength(bwImage);

  % this function evaluates the size of the flow front object
  % and scale it to get the position in mm
  bwImage=~bwImage;
  maxCol=size(bwImage,2);
  [L,n]=bwlabel(bwImage);
  % finding the flow object
  objectNum=0;
  for j=1:n
    [r,c]=find(L==j);
    if max(c)==maxCol
      objectNum=j;
    end
  end

  if objectNum>0
    [r,c]=find(L==objectNum);
    tempMax(1:max(r))=0;
    tempMin(1:max(r))=999999999999999999999;
    for z=1:length(c)
      if c(z)>tempMax(r(z))
        tempMax(r(z))=c(z);
      end
      if c(z)<tempMin(r(z))
        tempMin(r(z))=c(z);
      end
  end

C 4
if c(z)<tempMin(r(z))
    tempMin(r(z))=c(z);
end

end

dist=abs(tempMax-tempMin);
avDist=mean(dist);

else
    avDist=0;
end

return;