Modeling of resin transfer molding of composite materials with oriented unidirectional plies
by Dell Raymond Humbert

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Chemical Engineering
Montana State University
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Abstract:
The goal of this research was to develop a computer model for the treatment of Resin Transfer Molding
(RTM) of unidirectional layer stranded fabrics oriented in various directions. The individual fabric
layers contain high fiber volume fraction strands, separated by channels, which the model includes as
separate phases. A finite difference approximation has been developed to determine the effective
permeability of the channels. This approximation is based on classical channel flow equations, and is
applied to all three directions of the channels. The axial permeability in the strands has been measured.
The transverse permeabilities in the strands are assumed to be equal, and are fitted to the model results.

The model consists of a finite difference routine which uses cell centered grids to approximate the
geometry of the reinforcement. The moving boundary resin is treated as a constant pressure condition.
The injection and vent ports are also modeled as constant pressure conditions.

The model has been correlated with experimental results. Simulations and experiments have been run
using a single fabric layer at 0°, two layers at ±45°, and three layers at 45°/0°/-45° and 0/±45°. The
model accurately captures the flow front shape for each case, and shows general agreement with the
positions vs. time.
MODELING OF RESIN TRANSFER MOLDING OF COMPOSITE MATERIALS
WITH ORIENTED UNIDIRECTIONAL PLIES

By
Dell Raymond Humbert

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APPROVAL

of a thesis submitted by

Dell R. Humbert

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Approved for the Major Department

Date

Head, Major Department

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ABSTRACT

The goal of this research was to develop a computer model for the treatment of Resin Transfer Molding (RTM) of unidirectional layer stranded fabrics oriented in various directions. The individual fabric layers contain high fiber volume fraction strands, separated by channels, which the model includes as separate phases. A finite difference approximation has been developed to determine the effective permeability of the channels. This approximation is based on classical channel flow equations, and is applied to all three directions of the channels. The axial permeability in the strands has been measured. The transverse permeabilities in the strands are assumed to be equal, and are fitted to the model results.

The model consists of a finite difference routine which uses cell centered grids to approximate the geometry of the reinforcement. The moving boundary resin is treated as a constant pressure condition. The injection and vent ports are also modeled as constant pressure conditions.

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CHAPTER ONE

INTRODUCTION

Polymer matrix composites are very strong and light weight materials. These materials consist of many strong fibers surrounded by a polymer matrix. The fibers provide the strength and stiffness to the material, and the matrix holds the fibers in place and transfers internal loads between them. The matrix also protects the fibers from environmental damage. The fiber properties, content, orientation and arrangement determine the strength of the composite. Composites are now finding application in products ranging from computer main boards and automobile parts, to high performance athletic equipment such as skis and bicycles.

As composite material applications have increased in breadth, a demand for new, low cost, high-quality fabrication techniques has also developed. Current techniques for manufacturing composites include prepreg molding, pultrusion, resin transfer molding, filament winding, compression molding, and hand lay-up. These methods represent a broad spectrum in terms of product expense and quality. Resin Transfer Molding (RTM) has shown promise in its ability to produce high quality products at a relatively low cost. It also has advantages in decreased volatiles
emissions and geometric flexibility. Historically, this method has increased in popularity as lower viscosity resins have been developed, since the resin flow requirements are more demanding than with other processing methods.

Resin Transfer Molding involves placing oriented fiber preforms into a mold. The mold is then closed, and resin is injected into the mold cavity. Air is vented from the mold at strategic points during resin injection. The resin is allowed to cure, and the part is removed. The part may then be post cured in an oven to complete the resin cure.

Fiber preforms in structural parts typically consist of many layers of fibers, each in the form of stitched fabrics containing strands of hundreds or thousands of individual fibers. Each layer can have a different fiber orientation. Since the layers have strong properties in only one direction (parallel to the fibers), these differing orientations produce a finished product which is strong in the required directions only, saving material when compared with randomly oriented fibers. The materials of which these layers are made can consist of anything from woven fabric to unidirectional stitched fabrics, and random fiber mats. This variability of reinforcement types, and their complex interlayer interactions, provide a rich variety of resin flow patterns during fabrication. These interlayer flow patterns can make the difference between a mold design which works well, and one which produces flawed parts.

The increasing use of RTM in the production of high performance composite materials has sparked interest in the modelling of these processes. Of great interest is the ability to predict the flow patterns and pressures required for the production of
complex geometries. The flow patterns allow the accurate placement of injection and vent ports. If these ports are placed inaccurately, the mold may fill incompletely, resulting in part rejection and inefficient use of both time and materials.

Two approaches to modeling RTM prevail in the literature. The first assumes that the fabric is a homogeneous, anisotropic medium; which has limitations when the principal permeabilities of the plies cannot be captured in an overall approach. The second approach assumes a regular fiber packing and models fluid flow around individual fibers. A model based on such fine detail would be prohibitively complex and time consuming to implement in an algorithm. The present approach is an attempt at combining these two methods. The micro flow regime is taken into account by application of Darcy's law to the bundles, and by calculating an equivalent permeability from the geometry of the channels. This approach leads to a view of the process which will maintain most of the microflow characteristics, while remaining general enough to capture the entire flow progress in a reasonable amount of calculation time.
CHAPTER TWO

LITERATURE REVIEW

An accurate representation of the effects of molding parameters on fluid profiles and pressure distributions in the RTM mold would greatly assist mold designers. Knowing the geometry of the fluid profiles with time would allow the mold designer to properly place the inlet ports and vent ports, which can dramatically enhance processing time as well as the quality of the finished part. Information about the pressure profile can be used to design the mold. RTM molds need not be made from traditional steel construction, but can be produced from lower cost composite.

Several processing variables have a major impact on the RTM process. These include the viscosity of the resin, the permeabilities of the reinforcement, the injection pressure or flow rate, and the mold geometry. The shapes which are generally produced with RTM are complex, and they have either constant pressure or constant velocity boundary conditions. These and other complexities make analytical solutions nearly intractable, which accounts for the prevalence of numerical solutions in the literature.
Viscosity

The resins used in RTM are usually viscous polymeric fluids. One approach to modeling this system is to assume a fluid which is Newtonian at the pressures and shear rates present [1,2]. This eliminates any complications which would arise due to non-Newtonian flow. The fluid is also modeled as incompressible. All non-Newtonian effects of the resin on the flow characteristics are generally neglected as these effects are not yet fully understood [1]. The viscosity of the resin can be measured with a cone and plate, or capillary rheometer; typically, uncatalized resin is used, as the addition of a catalyst does not significantly change the viscosity during the experimental time for resin impregnation [3]. The resin viscosity change during flow is either neglected, or modeled as a power law [4].

Permeability

The permeability of the reinforcement is an important parameter to evaluate in order to properly model the flow in the RTM mold. The permeability of the reinforcement varies with direction and can be interpreted as the resistance of the fiber preform to the flow of resin. If the permeability is too low, then the pressure required to fill the mold becomes prohibitively high, or the fill time becomes long.

Many authors begin with Darcy's law, which is applicable to flow through porous media, as a basis for evaluation of the permeability parameters.
\[ q_x = \frac{k_x A}{\mu} \frac{\partial P}{\partial x} \]

$q_x$ is the flow rate in the $x$ direction

$k_x$ is the permeability in the $x$ direction

$A$ is the cross-sectional area for flow

$\mu$ is the viscosity of the resin

$\partial P/\partial x$ is the differential of pressure in the $x$ direction


Another popular approach used by Bruschke and Advani [1], Coulter and Guceri [2,7], Gauvin and Chibani [3], Chang and Kikuchi [8], and Martin and Son [9], is to determine the permeabilities of a reinforcement fabric from experimental data. The procedure involves filling a rectangular mold with reinforcement and then measuring the flow rate of a fluid through the mold under a prescribed pressure drop. Another method for determining the principal permeabilities of a preform has been used by Bruschke and Advani [1], Young and Wu [10], and Adams et al. [11]. In their studies a layer of mat was placed in a mold, the resin was injected in the center of the mold, and the resulting elliptical flow front was measured. Equations have been developed [11] which allow estimation of the principal permeabilities and their ratio, from the principal axes of the ellipse.
Of the two main ways in which permeabilities have been studied, the use of a completely filled mold gives permeabilities in the fabric which is completely filled, and at steady state. The method of elliptical flow front allows measurement of the permeability as the reinforcement is filling. This method has an added advantage in that both the transverse and longitudinal permeabilities can be determined with one experiment. The use of a completely filled mold requires that the reinforcement be realigned in the other direction before the transverse permeability may be measured.

Permeability has been studied as a function of the reinforcement porosity by Gauvin, Chibani, and Lafontaine [12].

Mathematical Models

A unified approach to modeling composite processing was undertaken by Dave [13], who derived the governing equations in terms of Darcy's law. The general approach was to substitute Darcy's law for the equation of motion in the mathematical analysis. This allows for the derivation of simple equations from the continuity equation for the system of interest. For the RTM process, these equations are fundamentally elliptical in nature, and require the specification of all boundary conditions. However, due to the resin flow front, at least one of these boundaries is constantly moving, and its shape is constantly changing. The movement of the boundary is treated with a quasi-equilibrium assumption, that at any time step there is an equilibrium of forces along the flow front. This boundary can also be treated with
a condition of vanishing shear stress; however, a constant pressure condition is more widely accepted. There are also two different ways to handle the injection port. At that point on the boundary a constant velocity or a constant pressure condition can be specified.

The moving boundary condition, and the complexity of shapes typically produced with RTM, make the analytical solution intractable. There are some one-dimensional problems which can be solved analytically, but the two and three dimensional problems become increasingly complex. This system is therefore generally treated with numerical methods.

Numerical Solutions

Much work has gone into developing numerical methods for simulating the RTM process. One such effort was conducted by Crochet, Davies, and Walters [14], who developed a numerical solving code by the name of POLYFLOW. This package is a two dimensional finite element routine which was originally designed for modeling thermoplastic molding; it has been modified by Martin and Son [9] for use with RTM systems. Martin and Son found good agreement between experimental studies and the corresponding simulations for flow front position and pressure profile. They also considered resin distribution channels and the effect of varying permeabilities.

Coulter and Gucerri [2] simulated two dimensional resin impregnation with a
boundary fitted coordinate system method. This effort resulted in a finite difference code by the name of TGIMPG. The boundary fitted coordinate system has the advantage of being able to fit the flow front closely, which helps eliminate the error generated at the flow front due to interpolation between the cells in either a finite difference or finite element solver routine. With this approach, however, the generation of the mesh becomes complex.

Finally, Trochu et al. [15] developed a three dimensional finite element solver for the express purpose of solving RTM problems. Their solving routine, called RTMFLOT, solves the Darcy's law equations to obtain a pressure profile. Reference [16] describes the package which consists of DATAFLOT, MESHFLOT, FLOT, VISIFLOT, and HEATFLOT. These are five separate programs for meshing, solving and visualizing the pressure profiles and flow fronts.

All of the previous models concentrate on the macroflow front; that is, the overall movement of the fluid front. They do not take into account the presence of individual bundles of fibers or the channels present between these bundles. This approach is particularly useful when working with permeabilities which are not associated with one particular phase, such as in random mat. Although random mat can have anisotropic permeability properties, it does not have well defined channels. Another class of material which has been successfully modeled with this approach are the woven materials, as they too do not have well defined channels, but have definite directional properties. These models may show deficiencies in treating the channeling caused by misaligned preforms [2, 17].
There are fewer models which concentrate on the aspects of microflow [6, 17, 18], or the flow between the bundles of fibers. This type of microflow model is very useful in determining a flow regime within the bundles, and it gives a good approximation for the permeabilities within the bundles. These models set a packing arrangement for the fibers, usually defined on a set geometric grid. This grid is always regular, and facilitates the mathematical solution of the flow problem. The microflow models tend to lose sight of the overall resin flow, and add prohibitive complexity to numerical solutions.

Both macroflow and microflow regimes contribute to the overall solution, and as a result both approaches to solving the problem are significant [2]. Chang and Kikuchi [8] used an approach which treated the two phases differently, treating the bundles with Darcy's law, and treating the channels with Stokes flow. They then used a finite element routine to bring this microflow view to bear in solving the macroflow front problem.

Verification

The general approach to verification of these models is to construct a mold of the shape being simulated, and experimentally measure the flow front to determine if it corresponds to the numerically calculated flow front [1, 2, 4, 7, 8, 13, 17, 20-23]. The pressure profile is then correlated against a few discrete points at which a pressure tap can be placed in the experimental mold [2, 4, 5, 8, 17, 20, 21].
CHAPTER THREE

MATHEMATICS

Microscale

The RTM process consists of flowing resin into preforms composed of previously assembled fiber mats. These mats contain strands at high fiber content alternating with large channels which allow passage of resin. The channels provide areas of low permeability for the distribution of the resin, and the large strands provide a high fiber content which increases the structural performance of the composite.

The overall numerical model requires the determination

Figure 1 Composite Cross-section.
of six permeabilities or effective permeabilities. These parameters describe the flow in the three principal directions in the strands, and the three principal directions in the channels. The flow in the strands can be described by application of Darcy's law, and is characterized by permeabilities in three directions. The permeability in the transverse direction within the strands is difficult to measure due to the difficulty of obtaining a constant packing arrangement independent of the pressure difference. The flow in the channels is treated with the application of laminar flow equations. These equations provide a velocity profile within the channels which can be used to directly relate the flow rate through a cell with the pressure difference across the cell. The ratio of these is used in the macroscopic model as an effective permeability in the channels.

A typical cross-section of the finished composite is shown in figure 1. This photograph shows the geometry of the resin channels. They consist mostly of I—shaped channels with elliptical sides. A finite difference solver routine has been used to approximate the laminar flow patterns inside of these channels. Since the flow in the channels is slow, the resin is usually very viscous and the diameters are small, it is expected that there will be little turbulent flow. Using a typical distance, \( D \), of 415 \( \mu m \), a fluid velocity, \( v \), of 2 cm/s, a density, \( \rho \), of 3.3 g/cm\(^3\), and a viscosity, \( \mu \), of 2 poises, the Reynolds number calculated \([24]\) from \( DV\rho/\mu \) is 0.1369, which is well within the laminar region. The flow of resin through the channel cross-section is calculated from classical channel flow equations.
In developing the basis for a mathematical model for the fluid flow in one unidirectional layer of fiber reinforcement, it is important to define the problem accurately. The cross-section of the channel in which the fluid flows is shown in figure 2. Several assumptions are made in the model.

First, it is assumed that the effects of gravity are negligible. This assumption is reasonable since, in most cases, the pressures which are applied to a unit volume of fluid are much greater than the weight of the fluid element. In most cases these channels are short in length. If a very long part were injected vertically, then gravity might have a significant effect, and would have to be taken into account.

Second, the velocity of the resin in the $x$ and $y$ directions is zero. Resin will not flow in the $x$ direction since it cannot flow through the walls of the mold. It will not flow in the $y$ direction because, as the resin enters the bundles, it becomes trapped at the flow front and subsequent flow does not displace the original fluid [25].

Third, the density of the resin is a constant in both time and space, as the resin is an incompressible fluid. If the resin changes density rapidly as it cures, this code will require modification.

**Figure 2** Channel Cross-section.
The equation of continuity for this system in rectangular coordinates is given in equation 3.1. The density of the polyester resin is constant in space and time.

\[ \rho \frac{\partial V_z}{\partial z} = 0 \]

(3.1)

The equations of motion for this system are [26]

\[
\begin{align*}
-\frac{\partial p}{\partial x} &= 0 \\
-\frac{\partial p}{\partial y} &= 0 \\
\rho \left( \frac{\partial V_x}{\partial t} + V_z \frac{\partial V_x}{\partial z} \right) &= -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right)
\end{align*}
\]

(3.2)

This assumes that viscosity is not a function of position, but that it is only a function of time. By using the equation of continuity, the equation of motion can be further simplified to the following

\[
\rho \left( \frac{\partial V_x}{\partial t} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right)
\]

(3.3)

The location of the sides of the ellipse will be found from

\[ x = \sqrt{a^2 - \frac{a^2(y-h)^2}{b^2}} \]

(3.4)
here (a) is the x radius and (b) is the y radius; (h) is half the height of the channel.

Discretizing the differential equation yields

\[
p \frac{(V_{x(r+1)} - V_{z})}{\Delta T} = -\frac{\Delta P}{\Delta z} + \mu \left( \frac{V_{x(x-1)} - 2V_{x} + V_{x(x+1)}}{(\Delta x)^2} + \frac{V_{z(y-1)} - 2V_{z} + V_{z(y+1)}}{(\Delta y)^2} \right) \quad (3.5)
\]

As the system is considered at equilibrium, the time derivative drops out, and what is left is

\[
\frac{\Delta P}{\Delta z} = \mu \left( \frac{V_{x(x-1)} - 2V_{x} + V_{x(x+1)}}{(\Delta x)^2} + \frac{V_{z(y-1)} - 2V_{z} + V_{z(y+1)}}{(\Delta y)^2} \right) \quad (3.6)
\]

The channel in figure 1 is meshed in the x and y directions and eq.3.6 is used to solve for the velocity distribution given the change in pressure along the z direction

\[
\frac{\Delta P}{\mu\Delta z} = \frac{V_{x(x-1)} - 2V_{x} + V_{x(x+1)}}{(\Delta x)^2} \cdot \frac{V_{z(y-1)} - 2V_{z} + V_{z(y+1)}}{(\Delta y)^2} \quad (3.7)
\]

This final equation, 3.7, provides the coefficients of the variables in the system of linear equations. The solution to this system of linear equations provides a relationship between the pressure drop through the channels and the velocity of the resin within the channels. Given a pressure drop, the velocity profile can be obtained. This system of equations can be solved most easily in matrix form.

\[
[A] = [V_x][Q] \quad (3.8)
\]
\[
\begin{pmatrix}
\frac{2}{(\Delta x)^2} & -\frac{2}{\Delta y^2} & \frac{1}{(\Delta x)^2} & 0 & 0 & \frac{1}{(\Delta y)^2} & 0 & 0 & 0 \\
\frac{1}{(\Delta x)^2} & \frac{2}{(\Delta x)^2} & -\frac{2}{(\Delta y)^2} & 0 & 0 & \frac{1}{(\Delta x)^2} & 0 & 0 & 0 \\
0 & \frac{2}{(\Delta x)^2} & \frac{1}{(\Delta y)^2} & 0 & 0 & \frac{1}{(\Delta x)^2} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{(\Delta x)^2} & -\frac{2}{(\Delta x)^2} & \frac{2}{(\Delta y)^2} & \frac{1}{(\Delta x)^2} & 0 & 0 & 0 \\
\frac{1}{(\Delta y)^2} & 0 & 0 & \frac{1}{(\Delta x)^2} & \frac{2}{(\Delta x)^2} & -\frac{2}{(\Delta y)^2} & \frac{1}{(\Delta x)^2} & 0 & 0 \\
0 & \frac{1}{(\Delta y)^2} & 0 & 0 & \frac{1}{(\Delta x)^2} & \frac{2}{(\Delta x)^2} & -\frac{2}{(\Delta y)^2} & \frac{1}{(\Delta x)^2} & 0 \\
\end{pmatrix}
\]

\text{etc.}
The pressure drop and the length are already known, so the solution only requires arranging the resulting equations into a five-diagonal matrix, inverting the matrix, and multiplying the resulting matrix by the solution vector. A typical grid would produce a \([Q]\) matrix like that shown in equation 3.9.

For a 10x10 grid the resulting matrix would have 100 rows and 100 columns. This matrix can then be inverted and multiplied by the left-hand-side vector \([A]\) to produce the solution vector \([V_z]\). The left hand side vector \([A]\) contains a column of values which are

\[
\frac{\Delta P}{\mu \Delta z}
\]

The solution vector \([V_z]\) will contain the steady state velocity of the fluid in that particular cross-section. The average velocity in the entire channel is then calculated by multiplying each velocity component by the cross section over which it acts, and then dividing that product by the total area of all the cross sections. This average velocity is then used in Darcy's law for one dimensional flow to arrive at a permeability for the channel. Darcy's law for one dimensional flow is

\[
V_z = -\frac{k_z \Delta P}{\mu \Delta z}
\]

(3.10)

Using this equation, a value for \(k_z\) can be back calculated. This value is the equivalent permeability of the channel in the \(z\) direction. The equivalent
permeabilities of the channels in the other two directions can also be calculated in this way, using their respective geometries. These two directions are not expected to be significant in single layers due to the presence of bundles on either side, and the presence of mold faces on the top and bottom. However, in large stacking arrangements, these permeabilities couple the resin in the channels in different layers, and thus are important in the overall model.

The above analysis gives permeabilities in the three principal directions inside the channel areas. This leaves the permeabilities in the bundle areas to be considered. The permeability in the longitudinal direction can easily be measured as described in Chapter 4 (Parameter Measurement); the permeabilities in the transverse directions in the bundles are not so easily measured, and must be obtained separately as described later.

Macroscopic System

The macroscopic system which contains the layers of reinforcement, the mold faces, the injection and vent ports, and the resin is considered next. The reinforcement layers use a different coordinate system than that used by the individual cells. The individual cells use an $x, y, z$ coordinate system, relative to the boundaries of the cells. The reinforcement layers use an $x_2, x_p, x_3$ coordinate system, where, $x_2$ is transverse to the strands, $x_p$ is parallel to the strands, and $x_3$ is through the thickness of the part. For stranded reinforcements $x = x_2$, $y = x_p$, and $z = x_3$. Each layer of reinforcement in
the model uses its own coordinate system, with the \( x_1 \) direction always parallel to the strand direction. All layers share the same \( x_3 \) or through the thickness coordinate, and the same origin. The different coordinate systems allow the permeabilities in the principal directions of the reinforcement to be applied directly to the difference cells, with no modification. The \( x_3 \) coordinate commonality allows for the communication of resin flow between the individual layers.

Darcy’s law is used to model the flow within the fiber mats, but first the pressure profile within the mats must be known. If the system is at equilibrium, then the pressure profile can be calculated from the equation of continuity for this system. Substituting Darcy’s law (eq. 3.10) for the velocity terms, equation 3.11 results

\[
\frac{\rho}{\mu} \left( \frac{\partial^2 K_{x_1} P}{\partial x_1^2} + \frac{\partial^2 K_{x_2} P}{\partial x_2^2} + \frac{\partial^2 K_{x_3} P}{\partial x_3^2} \right) = 0
\]

This is an elliptical equation and can be solved at equilibrium, given the boundary conditions. This equation is then discretized over the domain of the reinforcement.

Equation 3.11 is discretized on the following grids for the \( x_1 \), \( x_2 \), and \( x_3 \) directions. The \( x_1 \) direction is along the length of the strands, the \( x_2 \) direction is along the width of the layers, and the \( x_3 \) direction is through the thickness.

![Figure 3 Macro Flow Grid Definitions for the Spacial Directions.](image)
direction is transverse to the strands, and the $x_3$ direction is in the thickness direction of the part. The $x_2$ direction consists of a series of alternating equal width cells, the $x_1$ direction consists of a series of equal length cells, and the $x_3$ direction consists of a series of unequal height cells. Using Taylor series expansions for the approximations for the three partial derivatives in equation 3.11 on the grids in figure 3 results in an implicit approximation scheme shown below.

\[
\begin{align*}
K_{x_1} & \left( \frac{P_{r-1} - 2P_r + P_{r+1}}{(\Delta x_1)^2} \right) + K_{x_2} \left( \frac{P_{r-1} - 2P_r + P_{r+1}}{(\Delta x_2)^2} \right) + \frac{1}{\mu} \left( \frac{K_{x_3} P_{s-1} - (K_{x_3} + AK_{x_3} P_s + AK_{x_3} P_{s+1})}{(\Delta x_3)^2} \right) = 0
\end{align*}
\]

\[
\Delta x_2 = \frac{\Delta x_{2,1} + \Delta x_{2,2}}{2}, \quad (\Delta x_3)^2 = \frac{\left( \Delta x_{3,s} + \Delta x_{3,s+1} \right)^2}{8} + \frac{A(\Delta x_{3,s} + \Delta x_{3,s+1})^2}{8}
\]

\[
(3.12)
\]

where $K_{x_1}$ and $K_{x_2}$ are the permeabilities in the individual directions divided by the viscosity. This difference scheme is an approximation to the original equation to the order $(\Delta x_1)^2$, $(\Delta x_2)^2$, and $(\Delta x_3)^1$.

Equation 3.12 can then be solved in the same way that the previous difference scheme was solved; that is, by writing an equation for each of the cells, and including the permeability terms of the bordering cells, then inverting the coefficient matrix and solving for the solution vector. This method of solving for the pressures at each of the nodes would work and be the most accurate. However, these systems of nodes usually run in the tens of thousands of elements, and large moldings could conceivably run much higher. In sets of linear equations of this magnitude the time of solving by this method becomes unmanageable. Instead, an iterative relaxation method was used.
In this method (called the Gauss-Seidel method [27]), the difference equation is solved for the pressure present at the central cell. Then this equation is applied to all of the cells, and the pressure of the central cell is calculated. Once all of the cells have been calculated once, the procedure repeats. With enough iterations, the system of cells approaches the same solution which one would obtain by inverting the matrix each time. There is a trade off in accuracy and time; matrix inversion introduces machine error, and it is costly in terms of the additional time required for more cells. The relaxation methods can achieve highly accurate solutions, however they converge rather slowly. One must determine if the time required to invert the matrix is more than the time required to relax the solution to within an acceptable tolerance. The pressure profile must be solved at the beginning of each time step, and this is clearly not feasible with a matrix inversion routine. Here is where the iterative method is most effective. As the resin flows through the cells, the pressure profile evolves from the previous pressure profiles. If the start of the iteration for the current profile is set to the profile at the end of the previous time step, then the iteration scheme only has to make up for the addition of current flow. If the time steps are small, then the pressure profiles at subsequent time steps differ little from those at the previous ones, and the relaxation method converges rapidly to the new pressure profile. This routine reduces the time required for the resulting algorithm to $O(n^2)$ instead of $O(n^3)$, in most cases [27].
CHAPTER FOUR

PARAMETER EVALUATION

There are several parameters inherent in the model which must be determined. These parameters are the viscosity of the resin, the geometric parameters, and the permeability parameters.

**Viscosity**

The viscosity of the resin was measured using a capillary rheometer (figure 4). It consists of a small capillary of known diameter connected to a large precision milled piston. The piston chamber is filled with the resin, and a weight is applied to the piston. From the force applied on the piston, the length and diameter of the capillary, and the flow rate

![Figure 4 Capillary Rheometer.](image)
of the resin, a viscosity can be calculated. This rheometer was fabricated by Hedley [25] according to ASTM standard D 3835-90 [28], and the viscosity of the resin is calculated using equations supplied with the standard.

Geometric

The geometric parameters relate to the geometry of the mold and the architecture of the reinforcement. The geometry of the mold is in this case a flat rectangular plate. This geometry is hard coded into the mesh generator, and is a sum of the numbers and arrangements of the cells included in the solution set. These parameters are the length and width of the mold. The third dimension, the height, is not given explicitly, but it is a result of the sum of the heights of the individual layers.

The geometric parameters which relate to the architecture of the fabric in the individual layers can most easily be evaluated by producing a molding prototype, and measuring the distances under a microscope. The architecture of the reinforcement is dependent largely on fiber volume fraction. If the geometric parameters of the reinforcement are measured at several fiber contents, then that data can be applied to all future simulations without having to evaluate each case individually.

The fiber architecture parameters are the length, width and height of the channels and strands in the reinforcement. The length is largely an arbitrary parameter as it has little actual physical significance. The fiber strands and channels generally run the entire length of the mold, and thus have no convenient breaking points. It is
Figure 5 Measurements of Channel Geometries
important, however, to keep this length comparable to the other two dimensions to maintain a consistent cell aspect ratio. If the length is too long, the error associated with calculating the pressure profile at the flow front will become significant.

Other parameters can be easily measured under a microscope. Figure 5 shows photographs which were used to measure these parameters. In layers where there is no channel architecture, random mat for instance, this approach makes little sense. In these layers a better approach would be to assign a grid spacing similar to those in adjacent layers. This allows for adequate vertical connections between the layers, and does not compromise the random mat layer.

Permeability

The permeabilities of the layers must also be either measured or approximated. First, the permeabilities of the channels are approximated from classical channel flow theory, which is described in Chapter 3.

The permeabilities of the bundles must then be either measured or approximated. The first approach was used to obtain a measurement of the bundle permeability in the axial, $x_1$ direction. Figure 6 shows a device that can be used to measure permeabilities. It consists of a large reservoir which can be pressurized by application of high pressure air at the inlet. This reservoir is attached to a tube which is packed with the reinforcement. Because the attempt was to pack these fibers as closely as possible to the arrangement seen in the bundles in actual reinforcement, all
of the binder thread which is used to hold the fabric together was removed. The reinforcement fibers were then aligned, and packed into the tube in anywhere from 50% to 66% fiber volume fraction arrangements. At the lower end of the tube, is a metal grid to prevent the fibers from being washed out of the tube.

In operation, resin is placed in the reservoir and air pressure is applied. It is

---

**Figure 6** Permeate Meter.

---

**Figure 7** Permeability as a Function of Pressure.
necessary to wait for a period of time for the reinforcement to become fully saturated, and the resin stream to run free of porosity. Then, varying pressures are applied to the reservoir, and the flow rate of the resulting stream of resin is measured. This is done by measuring the time required for a specific amount of resin to flow through the reinforcement. Applying Darcy's law (eq. 3.10), a permeability can be calculated. Figure 7 shows the resulting data. The permeability is shown to increase slightly with increasing pressure. This behavior is not consistent with theory, but it was observed by Martin and Son [9], Leek et al. [29] and Hedley [25] in fabrics. It is thought to be the result of pressure effects on packing efficiency. Similar data for other fiber contents are given in Appendix A.
The data was also correlated with time, and figure 8 shows that there is a negative correlation between the total length of time that the resin has been flowing through the fibers and the permeability of the fiber plug. Two possibilities for this behavior present themselves. First, the styrene could be evaporating from the resin (Chapter 5), producing a resin which is more viscous as the process proceeds. Second, the resin could be contaminated, and the contaminants could be plugging up the pores between the fibers in the reinforcement. In an attempt to determine if there was a change in viscosity over time, the viscosity of the resin was tested after each permeability test. The results showed that the viscosity of the resin did not change significantly over the course of the experiment (Appendix A).

In order to determine if there was some foreign material in the resin that could be causing problems, a sample was taken to Parker Filtration for analysis. They did find some debris in the resin which could interfere with flow through the bundles, as described in Appendix A.

The final parameter to determine is the radial ($x_2$ direction) permeability in the bundles. As this parameter is difficult to measure due to the shape of the bundles, an attempt was made to calculate this from the Kozeny-Carman equation [24].

$$\frac{\Delta p G_c \Phi s D_L^2 \eta^3}{L V_0 \mu (1-\eta)^2} = 150$$

(4.1)

where $\Delta p$ is the pressure drop, $G_c$ is the Newton's law proportionality factor, $\Phi$ is the sphericity, $s$ is the porosity, $L$ is the total bed depth, $V_0$ is the velocity of the resin,
and $\mu$ is the viscosity of the resin. Rearranging this equation into the form of Darcy's
law, and supplying all of the relevant information should result in a theoretical
permeability. Rearranging and evaluating the equation with a sphericity of 0.192, an
equivalent diameter of 3.124e-4 m, and a porosity of 35%, yields eq. (4.2)

$$\frac{\Phi^2 D^2}{150(1-e)^2} = \frac{Q\mu L}{\Delta P A} = 5.68 \times 10^{-11} \text{m}^2$$

(4.2)

Since this equation was generated for the case of roughly spherical packing, it is
expected that the value obtained will not be particularly accurate. However, it will
provide a starting point with which to begin testing the model. A unidirectional single
layer simulation is evaluated, in which this is the only adjustable parameter. Matching
this simulation to the experimental results provides an improved value for this
parameter.
CHAPTER FIVE

EXPERIMENTAL

Materials

The reinforcements used in this study were manufactured by Knytex, and generally consisted of stranded structures. The fabrics under study were the D155, (figure 9), and the DB240 (figure 10).

The D155 material is a unidirectionally oriented continuous strand mat with a weight of 480g/m (15.5 oz/yd). This mat can be easily cut and arranged in a mold in the directions needed for strength. The DB240 material consists of two layers of unidirectional material stitched together with polyester thread. The two layers in this fabric are oriented at plus and minus forty-five degrees to the normal fabric direction. The combination of D155 and DB240 simulates a triax fabric which has fibers at zero, +45 and -45 degrees to the normal fabric direction.

Figure 9 D155 Fabric.
An orthophthalic polyester resin (COR63-AX-051, BATCH# 1195267), manufactured by Interplastic Corporation, was used for all experiments. The resin consists of polyester with styrene added as a solvent and cross linking agent. Methyl Ethyl Ketone Peroxide (MEKP) was used as a catalyst. This resin has a cure time of 25 minutes at 25 °C (77 °F) when catalyzed with 3% MEKP. No degassing was performed on the resin before injection in any of the experiments.

Mold Release (A1000) sold by CAMIE was used to coat the surface of both the aluminum plate and the glass mold face.

**Equipment**

The resin delivery system for high pressure trials consisted of a pressure vessel which could be filled with compressed air (figure 11). For low pressure runs (less than 13800 pa (20 psi)), a smaller reservoir was used. This reservoir allowed for more accurate...
control of the pressure, and was more manageable where small amounts of resin were required. In both cases the catalyst was added to the resin before it was placed in the reservoir for delivery.

An RTV silicone gasket was used to seal the mold cavity. This material is chemically inert to the resin and the curing agent, and it provides a flexible seal. Since the gasket can be compressed, it allows for greater variability in the thickness of parts which could be produced from this one mold, as compared with a rigid gasket.

A micrometer was used to ensure that the thickness of the plate was uniform throughout the length and width of the mold within a tolerance of 0.1 mm. A flat piece of aluminum was placed on top of the tempered glass to protect it from the C-clamps which were used to hold the glass in place. The injection port was located in the center of the width of the aluminum plate, about one half inch in from the left most edge. The vent ports were located on the right hand edge, approximately one half inch in from the corners.

The resin delivery system was connected to the mold (figure 12), which consisted of a 13.2mm thick polished aluminum base plate, and a 12.3 mm thick tempered glass top plate, separated by the silicone gasket. A series of clamps were used to control the thickness of the

Figure 12 Experimental Mold.
mold cavity. The interior of the mold measured 146 mm by 432 mm. A channel was milled in the aluminum base plate to hold the gasket.

The pressure at the injection port was recorded with a transducer (OMEGA PX26-030GV) which was connected through a T-junction in the injection line. The junction was placed approximately one inch from the injection port, and the transducer was buffered from the resin with four inches of tubing filled with corn oil. This was necessary to protect the transducer from contact with the resin as resin would damage the transducer. Additionally, if the resin were to cure while inside of the transducer, subsequent readings would not be accurate. This transducer mechanism could not be used at pressures of greater than thirty psi, so for the high pressure experiments, the pressure was read from a gage on the high pressure resin delivery system, measuring the air pressure applied to the resin.

A video camera was positioned above the mold to record the position of the flow front with time. A digital camera was also positioned over the mold. The flow positions recorded with this camera could then be used to correlate with the model.

**Single layers**

As mentioned in chapter 4, the first trial was a single layer of unidirectional material, which was used to measure the transverse permeability of the bundles. In this case the effect of the longitudinal permeabilities can be isolated from that of the transverse permeabilities. The best place to measure the transverse permeabilities is
adjacent to the injection port. Special care had to be taken to prevent any channeling along the sides of the mold. The reinforcement was cut exactly to fit. The gasket used in this case was one layer of double sided mounting tape (Scotch™ Cat. #110). It was necessary to switch to this type of seal to allow the mold to reach a thickness of one layer. The presence of the tape also reduced the interior cavity of the mold to 121 mm x 406 mm. The tape expands slightly as the mold is closed. This expansion ensured that no resin could escape around the cut ends of the bundles.

The transverse permeability of the channels is expected to be much greater than that of the strands, and is not expected to interfere with the measurement. An inlet pressure of 137,000 Pa (20 psi) was used for these experiments.

**Multi-Layers**

Three multi-layer experiments were conducted; in all cases, the resin was injected at 34500 Pa (50 psi). The first consisted of two layers of D155 fabric. These were placed in the mold at ±45 degree angles. The mold was sealed with tape.

The second multi-layer experiment consisted of three layers of D155 fabric oriented at +45, 0 and -45 degree angles. The RTV gasket was used in this and the next experiment.

In the third multi-layer experiment, two layers of fabric were used. One layer of D155 fabric was used for the unidirectional layer, and one layer of DB240 fabric was used for the ±45 plies. The final fiber orientation was 0, ±45 degrees.
<table>
<thead>
<tr>
<th>Test Description</th>
<th>Number of Replicates</th>
<th>Motivation</th>
<th>Results to be Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Layer (0)</td>
<td>1</td>
<td>Transverse Strand Permeabilities</td>
<td>Flow Front Positions Especially in $x_2$ Direction</td>
</tr>
<tr>
<td>Tripple Layer (+45/0/-45)</td>
<td>2</td>
<td>Inter Layer $x_3$ direction interactions</td>
<td>Flow Front Positions in Topmost $+45$, Layer</td>
</tr>
<tr>
<td>Forty-Five Layer (±45)</td>
<td>1</td>
<td>Square flow Front Geometry</td>
<td>Shape of Flow Front, and Location in Time</td>
</tr>
<tr>
<td>Fourth Laminate (0/±45)</td>
<td>1</td>
<td>Interactions Between Two Different Types of Fabric</td>
<td>Shape and Position of Flow front with Time</td>
</tr>
</tbody>
</table>

**Table 1 Test Matrix**
CHAPTER SIX

RESULTS

Single Layers

Figure 13 shows experimental data for the position of the flow front within the mold with time for the single 0° layer trials. Figure 14 shows the calculated position of the flow front for the same conditions. The parameters used in the numerical approximation are shown in Table 2. Note that the subscripts 1, 2, 3 refer to the fabric directions for a particular layer parallel to the fibers, perpendicular to the fibers, and in the thickness direction, respectively.

Channel permeabilities were calculated from the channel geometries as described earlier. The strand axial permeability was measured, while the strand radial permeability was varied in several simulations in order to arrive at a value which would closely approximate the width direction position of the flow front (Appendix A). The injection pressure was ramped up to 138,000 Pa (20 psi) in one second, and then held steady at that level for the duration of the simulation.
When determining the experimental position of the flow front with time, a line is hand drawn around the flow front contour on a photograph taken through the glass face of the mold. For purposes of direct comparison, a predicted flow front position is superimposed on the photograph of the flow front at 10 minutes in figure 15. The predicted flow front gives good agreement with the actual flow front. At around 10 minutes injection time, the resin began to flow further ahead inside the strands than in the channels between the strands. This behavior was explained as capillary flow in the strands and is due to surface tension along the resin-fiber interface. This type of flow is not yet included in the model.
Figure 13 Single Layer Experimental Flow Front Position with Time.

Figure 14 Single Layer Calculated Flow Front Position with Time.
Figure 15 Single Layer Experimental (Photograph) and Simulated (Line) Flow Front at 10 min.

Figure 16 Calculated Pressure Profile, Single 0° Layer at 20 min.

The model also calculates the pressure profile on a per-layer basis. For the final time step, where the pressure is the highest, the profile is shown as a series of
isolines in figure 16. The pressure profile is seen to taper off exponentially (figure 17) with distance, which is the expected behavior from the solution to a second order partial differential equation. The pressure profile, however, seems to have a steep gradient just at the flow front boundary. The 1 Pa, and the 10 Pa iso-lines fall nearly on top of each other. The 1000 Pa line is only slightly further back. There is good differentiation between the next three lines though, indicating that once the flow has filled the mold, the filled bundles communicate the pressure profile efficiently in both the $x_1$ and $x_2$ directions. It is only at the flow front that a threshold pressure difference is required to effect appreciable resin flow.

There were 9,640 cells in this simulation, and it required approximately three hours to calculate to twenty minutes running on a 486 computer system.

The two parameters which have the most influence on this simulation are the $x_2$ direction permeability in the strands, and the $x_1$ direction permeability in the channels. The $x_3$ direction permeabilities have no effect in single

![Figure 17 Single Layer Exponential Pressure Profile.](image-url)
layer flow, and the $x_2$ direction permeability in the channels is overwhelmed by the $x_2$ direction permeability in the strands. Likewise, the $x_1$ direction strand permeability is overwhelmed by the $x_1$ direction channel permeability.

The $x_1$ direction permeability in the channels was calculated by the finite difference program from the channel geometry listed in table 2. In addition to the geometric parameters, the grid spacing of the method affects the resulting permeability. As the grid spacing is decreased, and more and more cells are used in the approximation to the channel geometry, the permeabilities decrease slightly. Table 3 shows a numerical representation of this behavior. The permeabilities in table 3 were calculated with a grid of the indicated number of cells and the geometric parameters in table 2. The table shows that the permeability initially starts at a high level, and decreases toward a given number as the grid is refined.

<table>
<thead>
<tr>
<th>Grid Spacing</th>
<th>$kx_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.94e-10</td>
</tr>
<tr>
<td>6</td>
<td>6.03e-10</td>
</tr>
<tr>
<td>8</td>
<td>5.28e-10</td>
</tr>
<tr>
<td>10</td>
<td>3.97e-10</td>
</tr>
<tr>
<td>12</td>
<td>3.51e-10</td>
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<tr>
<td>14</td>
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</tr>
<tr>
<td>16</td>
<td>3.24e-10</td>
</tr>
<tr>
<td>18</td>
<td>2.95e-10</td>
</tr>
<tr>
<td>20</td>
<td>2.83e-10</td>
</tr>
<tr>
<td>22</td>
<td>3.02e-10</td>
</tr>
</tbody>
</table>

Table 3 Variability in the Channel $x_1$ Direction Permeability with Numerical Grid Spacing.

A 15 x 15 grid was used to determine this value. The calculated flow front lags slightly behind the actual flow front as the time increases. This indicates that the permeabilities in the $x_1$ direction may be too low. There are two possible explanations for this phenomenon: the numerical approximation of the channels may
be inaccurate, or more likely, the channel geometry could be changing in the $x_i$ direction. The center channel width has a large effect on the calculated effective permeability. If this parameter is changing down the length of a channel, then it could explain the difference in flow front profiles. Two numerical models were run to acquire a reasonable range of values for this parameter. In both cases steady state velocity profiles were analyzed to determine the permeabilities of the channels. The same outside geometry of the channels was used, and only the center channel distance was changed. For the maximum case, the unconstricted width of the channels was set to 0.266 mm. For the minimum case, the side bundles touched in the center so the unconstricted width of the channel was set to zero. The velocity profiles are given in figures 18 and 19 respectively. This variation in channel geometry led to a corresponding change in permeability from a high of $5.92\times10^{-10}$ m$^2$ to a low of $8.81\times10^{-11}$ m$^2$. This range is expected to represent the maximum to minimum values of the $x_i$ direction channel permeabilities, and may explain why the calculated flow front lags behind the measured front, if the center channel width is increasing.
Figure 18 Fluid Velocity Profile in an Unconstricted Channel.

Velocity m/s

- 0.33
- 0.60
- 0.98
- 1.31
- 1.64

0.566 mm

0.436 mm
Figure 19 Fluid Velocity in a Constricted Channel.

Velocity m/s

0.057
0.046
0.034
0.023
0.011
The first of the Multi Layer experiments consisted of two layers oriented at +45 and -45 degrees. The plate was 54% fiber by volume, and the mold did not fill completely in the time allotted. There was also a small amount of channeling next to the injection port (bottom) which caused the flow profile to be less than flat. The experimental position of the flow front in the +45 degree layer is shown in figure 20, with the simulation shown in figure 21. The same parameters which were used for the single 0° layer were reused here, with the exception of the channel $x_i$ direction permeability. This parameter was recalculated again based on the new height of the channels. The percent fiber by volume of this part was significantly higher, 54%, than the previous one. The new $x_i$ direction channel permeability was 2.181e-10 m$^2$.

The calculated flow front positions for the top +45 layer are shown in figure 21. This is the layer which is seen through the glass plate of the mold. The resin traveled significantly farther in the simulation for a given amount of time than it did in the experimental case. Since the fiber volume fraction of this part is so much higher
Figure 20 Experimental Flow Front Positions in the +45 Layer with Time.

Figure 21 Calculated Flow Front Positions in the +45 Layer with Time.

than for the previous one, there is a relatively lower permeability in the strands. The assumption that $k_x^2$ and $k_x^3$ are the same as at lower fiber content clearly results in
an over prediction of the flow. The flow front shapes are in good agreement with the experiments. It is not clear why the permeability in the strands should decrease significantly with increasing fiber volume.

A second reason for the higher predicted flow is that, in the forty-five lay-up, the strands in one layer are perpendicular to the strands of another. Under transverse pressure from the mold faces, the strands could deform slightly, causing thickness direction modifications in the geometry of the channel. This would decrease the effective permeability of the channels in the axial direction.

![Pressure in Pa](image)

**Figure 22** Pressure Profiles in the 45 Layers at 15 Minutes.
The calculated pressure profile for the last flow position (10 min) is shown in figure 22. The fibers are always oriented parallel to the $x_1$ direction. These two pressure profiles are stacked in the numerical approximation. The choppy bands at the flow fronts illustrate the areas where adjacent cells have differing pressures. This is particularly the case for stranded reinforcement as the resin can flow more readily down the channels, and cause differing pressure profiles on a microscale level. Unfortunately, these contours are not plotted correctly. The pressure profiles are represented by individual numbers on a grid in the data set. The pressure profiles in the channels are decreasing at a slower rate than the pressure profiles transverse to the channel direction. This phenomenon causes the contour plotting routine used in figure 22 to draw the microscale isopressure lines in the wrong 45 degree direction. While the isopressure lines are generally in the correct positions with respect to the mold, and the microscale isopressure lines also accurately represent the depth of the unsaturated areas, these lines do not represent the fiber orientation.

The two pressure profiles in figure 22 show the differing pressures in individual layers. This separation of pressure profiles for the different layers creates a pressure gradient across layers, and forces resin to flow in the $x_1$ (or through thickness) direction. Thus, the actual

![Diagram](image3.png)

**Figure 23** Computational Strand Packing
flow pattern is strongly three-dimensional in nature, with resin flowing rapidly in the $x_1$ direction of a particular layer, then filling the adjacent layer by flow in the $x_3$ direction through unblocked channels in the $x_3$ direction (figure 23)

Three Layers

The third experiment was a combination of the two previous experiments. Three layers of D155 fabric were included in the mold. They were oriented at $+45$, $0$ and $-45$ degrees. This simulated a common fabric lay-up which incorporates fabrics in all three of these directions. The composite was 43% fiber by volume, as in the single layer runs. The experimental flow front position as a function of time is shown in figure 24. The calculated flow front position as a function of time is shown in figure 25. The parameters used in the simulation were the same as those in table 2.

The flow shown in these figures is in the $+45$ layer which is against the glass mold face in the experimental setup. The number of cells in this model was 63,634 and it required 14 hours to calculate to three minutes on a 486 computer system.

The calculated flow fronts are further ahead than the experimental ones, and they also have a slightly more curved shape. These two characteristics suggest that the axial permeabilities of the zero layer are higher than they should be to accurately predict the flow front. One
posible reason for this behavior is again that the forty five layers are constricting the channels in the transverse direction.
The flow front profiles are slightly asymmetrical. This is probably due to several factors: the asymmetric nature of the lay up, small irregularities in the thickness direction mesh, and the asymmetric injection point. The first is expected. Since the top layer in the simulation is not symmetric about the axis of the mold, the flow is expected to be asymmetric in this layer. If only one layer of +45 fabric were simulated the effect would be very pronounced. The coupling of resin flow from the lower two layers helps to transfer the resin in a symmetric manner. It is expected that the flow profiles on both the top and bottom layers would be mirror images of each other, and the central layer would show symmetrical behavior. The three flow fronts in the three layers are shown in figure 26, and all show the same irregularities in the flow front. It is likely that this is due to slight variations in the interactions of the three grid spacings.

When the three layers are meshed in the thickness direction, they may not match up exactly if the widths of the cells for the different layers are not the same. If this is the case, then there will be one row of cells which do not have connections to the layers below. This variation could be reduced with further refinements of the

**Figure 26** Calculated Flow Fronts in all Three Reinforcement Layers.
Grids. The use of additional layers will further reduce this problem as the resin has many more avenues for flow and will be less affected by the loss of one avenue.

![Pressure in Pa]

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

**Figure 27** Calculated Pressure Profiles for the +45, 0, -45, layers at Three Minutes.

The calculated pressure profiles for these three layers are shown in figure 27. The pressure profile in the single 0° layer is slightly ahead of those in the other two layers. This is expected due to its higher permeability. The flow fronts and the pressure profiles show little difference between the ±45 layers. This may or may not be the proper behavior. It is difficult to determine which layer is further ahead in which areas while only viewing the top most layer. The coupling of the layers can be
controlled with the $k_{x_3}$ permeability. If it is determined that the layers should behave more independently, then this parameter can be recalculated. This parameter is difficult to calculate because it is based on the through-thickness geometry of the single cells. This geometry changes with the elliptical nature of the bundles, and it has a different effect if there are bundles above and below or if there are open channels between the respective layers.

**Fourth Laminate**

The final laminate consisted of two layers of fabric, one layer of the D155 usual in the foregoing, and one layer of DB240 fabric which is ±45°. This laminate had plies in 0 and ±45 directions, the same as triax material, was 34% fiber by volume, and was injected at 345000 Pa (50 psi). The percent fiber by volume of this plate is much lower than was the single layer ply in the first run, and the $k_{x_2}$ permeability was again recalculated for this fiber volume. This run again used all of the previous parameters from table 2, but substituted a height for the channels of 0.386 mm. The effective permeability used for the channels was 5.02e-10 m². The experimental flow front profiles are shown in figure 29, and the numerical ones are shown in figure 29.
Figure 28 Experimental Flow Front Position with Time, Fourth Laminate.

Figure 29 Calculated Flow Front Position with Time, Fourth Laminate.

The experimental laminate experienced a small amount of channeling along the bottom side of the mold. This caused some of the asymmetry in these flow fronts. The numerical prediction in this case lags significantly behind the actual flow front.
This is most likely due to the breakdown of the channel structure between the zero ply and the adjacent 45° ply. If the fiber volume is too low, the channel structure breaks down. When this happens, then the current approach of modelling the channels may require modification.
CHAPTER SEVEN
CONCLUSIONS

The goal of this project was to develop discrete layer model to assist in the design of RTM systems. Of interest to the designers of these systems is the position of the flow front with time, and the pressure profiles seen by the mold.

Each cell in the model contains three geometric parameters which can be measured in a microscope, and three permeability parameters. These permeability parameters can be acquired in many different ways. In this model, the permeabilities in the channels were acquired from an independent finite difference scheme which calculated and integrated the velocity profile, and then back calculated an effective permeability. This permeability served as the proportionality factor between the pressure drop in the channel and the subsequent average velocity of the resin in the channel. This routine can be used to calculate the permeabilities in the three principal directions if the relevant geometric information is supplied.

The permeabilities in the channels was determined in two ways. A series of experiments were run to determine the effect of fiber volume fraction on the axial permeability of the strands. With this information the axial permeability is determined by knowing the fiber volume fraction in the strands. This permeability curve is expected to vary with fiber diameter and packing arrangement. The transverse strand permeability can not be easily measured in the same way, but was fit from a series of single layer experiments. The transverse strand permeability is assumed to be the same in both the $x_2$ and $x_3$ directions.
Of the four systems experimentally tested, two were well modeled. These were the two at 43% fibers by volume including one $0^\circ$ layer and three layers oriented at $45/0/-45$. This is largely due to the fitting of the $kx_2$ parameter in the single layer, and then reusing this parameter. The correlation of these two results indicate that once the proper effective permeabilities in the strands and channels are known, in a single layer, they need not be re-evaluated for subsequent multiple layer models. The two experimental systems which the model did not predict well were the $\pm45$ system at 54% fibers by volume, and the fourth system at 34% fibers by volume. In all of these experiments, the $kx_2$ parameter was taken to be the same as with the single layer experiment. It is likely that this parameter will need to be re-evaluated for each fiber volume fraction of interest before it can be incorporated into the multi layer model.

The first experimental (single layer) system yielded a great deal of information. It verified that the procedure for acquiring the $x_1$ parameters was sufficient. It also demonstrated that the grid spacing and arrangement of the cells designed to simulate the structure of the fabric can effectively capture the shape of the elliptical flow front.

The second experiment ($\pm45$) demonstrated that the method of rotating the cells and coupling them in the $x_3$ direction could effectively capture the complex flow front geometries associated with high fiber volume $\pm45$ layers.

The third experiment ($+45/0/-45$) demonstrated that the parameters determined from calculation, and measured with a single layer experiment, could be directly applied to a multi layer model with no modification.
The fourth Experiment (0/±45) demonstrated that the model cannot predict the flow in low fiber volume fraction laminates well, and that the parameters developed for one type of fabric cannot be applied to another. The experimental flow front profiles show a linear relationship between distance and time. This is most likely due to major channeling, probably between layers or against the mold face, and a deviation from behavior which is well described by Darcy's law. This behavior suggests that the channel structure which is modelled with an effective permeability is no longer present.

This model has many advantages over previous models. It begins with a basic understanding of the microflow nature of the reinforcement, basing the use of Darcy's law not on the mold cavity, but on the fiber architecture. This small scale view of the mold is then incorporated into the larger model. The placement of the cells in the mold simulate the actual geometry of the reinforcement. For instance, high permeability cells using the effective permeabilities for the channels are placed in line, and bracketed by the low permeability cells representing the strands. When these layers are rotated around a common axis, and stacked in the fiber orientation present in the experimental mold, they simulate the network of channels which is seen in reinforcement preforms. The three dimensional nature of the model allows the resin to flow vertically from layers of high permeability to layers of low permeability, and it is this three dimensional nature which allows the model to capture the square flow front geometry witnessed in the forty-five layer experiment. It is essential for this model to
capture such complex flow fronts if it is to be applied to larger three-dimensional geometries.

**Recommendations & Future Directions**

For the model to be more useful, an operating range needs to be defined. Specifically, the model needs to be tested on a spectrum of fiber volumes to determine which ones it can efficiently model, and which ones are outside the scope of this approach. Also, more types of fabrics need to be evaluated, especially at high fiber contents. Once these fabrics have been characterized, and the effective permeabilities calculated for their specific geometries, they should not have to be reevaluated.

The next expansion of the model would be to make the mesh generator truly three dimensional. The current mesh generator is restricted to rectangular structures only. The solver routine is already fully three-dimensional.

The time required to run this simulation is great, even for small laminates like these. There are some approaches which may increase the speed of the solver routine, such as the implementation of a method of successive over relaxation instead of using the Gauss-Seidel system; this should be explored.

This approach to solving the flow front and pressure profile has several powerful features. One of the most useful of these is the development of a pressure difference across each cell. This information could eventually be incorporated into a routine which could determine at what pressure difference fiber wash will occur. As seen in the results section, the pressure profiles near the inlet can become steep.
REFERENCES


APPENDICES
APPENDIX A

PARAMETERS

Viscosity Measurements

The equation used to calculate the viscosity is [24]

\[
Viscosity \ Pa-s = \frac{Fr^4 t}{8 R^2 L V} = \mu
\]

(A.1)

F is the force on the ram, r is the radius of the capillary, t is the extrusion time, R is the radius of the barrel, L is the length of the capillary, and V is the volume of resin extruded all in standard units.

R = 0.0127 m, r = 0.001 m, L = 0.0807 m,

<table>
<thead>
<tr>
<th>Time Since Beginning</th>
<th>Weight Applied</th>
<th>Elapsed Time</th>
<th>Volume Extruded</th>
<th>Flow-rate</th>
<th>Calculated Viscosity</th>
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<td>152</td>
<td>102</td>
<td>1.000e-05</td>
<td>9.80e-08</td>
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Table 4 Viscosity Measurements

Permeability Calculations

Permeabilities were calculated by directly applying Darcy's law (equation 3.10) to the measured parameters below.

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<th>Area</th>
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<td>6.4 cm</td>
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<td>Pressure (Pa)</td>
<td>Elapsed time (Sec)</td>
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<td>---------------</td>
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<td>$M_f = 15g$</td>
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<td>342</td>
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</table>

Vf = 50%

|   |   |   |   |   |
|---|---|---|---|
| 0  | 4.14e+05 | 43 | 1.500e-05 | 3.49e-07 |
| 6  | 1.38e+05 | 91 | 1.500e-05 | 1.65e-07 |
| 9  | 4.14e+05 | 32 | 1.000e-05 | 3.13e-07 |
| 17 | 2.07e+05 | 97 | 1.500e-05 | 1.55e-07 |
| 21 | 4.14e+05 | 42 | 1.500e-05 | 3.57e-07 |
| 27 | 2.76e+05 | 69 | 1.500e-05 | 2.17e-07 |
| 40 | 4.14e+05 | 45 | 1.500e-05 | 3.33e-07 |
| 46 | 3.45e+05 | 57 | 1.500e-05 | 2.63e-07 |
| 50 | 4.14e+05 | 42 | 1.500e-05 | 3.57e-07 |

Vf = 40%

|   |   |   |   |   |
|---|---|---|---|
| 0  | 4.14e+05 | 13 | 2.500e-05 | 1.98e-06 |
| 5  | 1.38e+05 | 18 | 1.100e-05 | 6.26e-07 |
| 7  | 4.14e+05 | 21 | 2.500e-05 | 1.19e-06 |
| 10 | 2.07e+05 | 24 | 1.500e-05 | 6.27e-07 |
| 14 | 4.14e+05 | 13 | 2.000e-05 | 1.53e-06 |
| 16 | 2.76e+05 | 18 | 1.500e-05 | 8.13e-07 |
| 22 | 4.14e+05 | 13 | 2.000e-05 | 1.50e-06 |
| 24 | 3.45e+05 | 15 | 1.500e-05 | 9.96e-07 |

Table 5 Permeability Calculations
Figure 30 Permeability Calculations, for $k_x$
FLUID ANALYSIS REPORT

SAMPLE CODE: 22016    DATE: 01/23/96

Montana State University/Chemical Engr. Dept.
306 Cobleigh Hall
Bozeman, MT 59771
Attn: Daniel Samborsky

Filtration
PARTEST Fluid Analysis Service
Parker Hannifin Corporation
16810 Fulton Road #2
Metamora, OH 43540
Tel: (419) 644-4311
Fax: (419) 644-4691

SAMPLE DATA

COMPANY NAME: Montana State Univ.
SYSTEM TYPE:
EQUIPMENT TYPE:
MACHINE ID:
FILTER ID:

AUTOMATIC PARTICLE COUNT SUMMARY

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<th>Counts per mL</th>
<th>Cleanliness Code</th>
<th>FREE WATER PRESENT</th>
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<td></td>
</tr>
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<td>&gt; 10 μm</td>
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<tr>
<td>&gt; 50 μm</td>
<td>71.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PHOTO ANALYSIS

Mag.: 100X    Vol.: 20ml    Scale: 1 div = 20μm

REMARKS

ISO Chart reporting is not currently activated due to the installation of new reporting software. Please notify us if you desire a manually prepared ISO chart; otherwise, a complete report will be provided when the installation is complete.
Radial Permeability Evaluations
Determined by Matching Flow Front Width

Experimental

Width Determinations at Four Different Values

Figure 31 Radial Permeability Determinations.
APPENDIX B

COMPUTER PROGRAM OPERATION

Introduction

The computer program consists of two major parts. The mesh generator and the solver routine. The mesh generator produces an ASCII file which contains the maximum time step to be taken, the viscosity of the resin, the number and kinds of cells, and the connections between the individual cells. At the bottom of this file is located the injection and vent port information. This information consists of the cell numbers which are located at the injection port, and a pressure value. The pressure value specified in the mesh file is always used for the vent ports, and it is treated as a constant. The pressure value which is specified for the injection ports must be there, but it is ignored by the solver routine. Instead, another ASCII file is read which contains two columns of data and a header. The header is an integer number indicating how many of the pressure points to use. The first column of data contains time points and the second column of data contains the pressure to be applied at the
injection ports at those times. The solver routine will linearly interpolate between the points if the time steps do not land perfectly on the points.

**Mesh Generator**

The mesh program begins with a main window which looks like figure 31. This first window is basically a dialog box which is asking for the parameters which govern the part as a whole. The "Length" is the length of the part. The "Width" is the width of the part. The "Viscosity" refers to the viscosity of the resin. This parameter is treated as a constant by the solver program. The "Time Step" field is the maximum time step allowed by the solver. The last field is the number of layers in the composite. These fields can be edited in any order. Do not leave any of them blank. When the "OK" button is selected by a single mouse click, then the next dialog is displayed figure 32. This dialog is a complex looking dialog with places to input information about the current layer of reinforcement. Notice that the first box contains the number of the current
layer. This entry field cannot be changed. Any of these pieces of information can be edited in any order. The first group of inputs is the channels or no channels radio buttons. If this is a stranded structure, and you wish to generate alternating cells of differing permeabilities then choose the channels button. The next piece of information is the orientation of the layers. This group consists of radio buttons for 0, +45, -45 and 90 orientations. These are currently the only orientations that the mesh generator can handle.

Figure 33 Mesh Program Second Dialog Box.
The next group of entry fields are the bundle information entry fields. These fields are looking for the width, length, and height of the strand cells. These parameters correspond to the x1, x2, and x3 directions of the composite. It is important to keep in mind that the x2 direction is transverse to the strands. The x1 direction is along the length of the strands, and the x3 direction is through the thickness of the composite. If the "No Channels" radio button is selected, then the rest of the boxes are not used. However, if the channels radio button is selected, then the lower half of the dialog box must be filled out. The only parameters that the mesh generator needs to know are the width of the channel total, and the width of the channel in the center. The rest of the geometric parameters for these cells are assumed to be the same as those for the bundle cells. There are two buttons on the bottom of the dialog box. The "OK" button saves the information for this layer, and moves on the next layer. The "CANCEL" button removes any information or the previous layers, and places control back at the first dialog box. When the OK button is pressed for the last layer, then the mesh program begins processing the information.
The mesh program searches through any of the layers that had the "Channels" radio button selected. If there were any, then the program steps through them one at a time in the order that they occur in the laminate. When one such ply is encountered, then the program needs to know the permeability parameters of the channels. The program then displays the final dialog box, figure 33. The first entry field under the word "Grid" contains the number of grid points to use in the x and y directions of the channel. This number can be anywhere from three to twenty-five. If any other numbers are provided, then the program automatically resets it to the nearest valid number. When the "Calculate" button is selected, the computer will automatically fill in the entry fields with what it has calculated for these permeability parameters. If, after reviewing these parameters, they are considered inappropriate, then they can be changed by simply editing the desired parameters. If it is not desired to calculate these parameters, then the correct parameters can simply be entered. When the correct channel permeability parameters have been entered the "OK" push button should be selected.
After all of the channel permeability parameters have been entered, the computer will generate the mesh file. Enough time should be allotted for the program to complete its disk writing operation before it is closed. After this operation is completed it is OK to close the mesh generator.

The mesh generator will write two files to the disk. The first is the mesh file that the solver program uses. The second is a "mesh.log" file which contains all of the parameters that were entered in the meshing process. The format of the mesh file is self explanatory. Each line of the cell information contains all the information for that cell. The first item on the line is the word cell and an '=' sign. These two items are important markers. Then there is a series of numbers. The first number is the number of the cell. These cells are generated in order, but this is unnecessary. However, they must all be there, and there can be no duplicates. The next six numbers are integers which are the numbers of the six adjacent cells. If the cell is on an edge, then the sides which have no cells next to them will have zeros for their numbers. This is a flag to the solver routine to treat this cell with the boundary conditions on that side.

The next three numbers on the line are three floating point numbers which represent the width, length, and height of the cell, respectively. The final three floating point numbers represent the permeabilities of the cell, $Kx_1$, $Kx_2$, $Kx_3$. Just as they were typed in during the mesh step. The solver does not care how the cells are arranged, or even if they make sense. The only thing which it requires is that all the
links to adjacent cells point to valid cells, and that all the cells are present. The injection and vent ports were explained in the introduction.

**Solver Program**

The solver routine takes as input the mesh file, and requires a bit of additional information. The solver routine treats the cells which are on the edge of the composite with a Neumann boundary condition. This is only consistent with Cell Centered Grids [30] which are what the solver uses to calculate the pressure profile.

The first dialog which is shown when the solver routine is started is shown in figure 34. This is the solver's main window. It contains spaces for the pressure file, and the mesh file names. Also present is the iteration sensitivity box. This is used to input the threshold pressure calculation. If successive pressure calculations update the

![Solver Program Main Window](Figure 35 Solver Program Main Window.)
pressure profile less than this much then the solver will continue and not calculate any more accurate pressure profiles for this time step. The last entry field is the ending time. The solver will quit when it has reached a time larger than, but as close to this number as the time steps allow. The solver automatically saves the pressure profile, and flow front profile when it finishes. In addition, if intermediate times are desired, then a file called "saves" can be created. This file should have an integer on the first line, which is the number of desired intermediate times. This number should be followed by a list of all of the intermediate times, in ascending order. When the solver reaches a time above but as close to these times as the time step will allow, then it will save the intermediate information. When all of the main window parameters have been entered, the 'solver' push button should be selected. This will start the solver engine.
The next dialog box which is displayed is used to interact with the solver engine. It is shown in figure 35. This dialog box generally gives the current status of the solver program. What the target time is, what the current time is, how far the solver program has progressed in time, what the current time step is. It also has the number of pressure calculations required for the current time step, and the amount of memory which the solver routine is using for this particular mesh. There are three push buttons on this dialog box. They are labelled 'Start', 'STOP', and 'Save Intermediate'. These push buttons are used to start the solver engine, stop the solver engine, and restart the solver engine. The 'Save Intermediate' button saves the current

**Figure 36** Solver Engine Control Window.
time step pressure, and flow front profiles. This button can be selected at any time, but the solver places a time stamp in the file name of each saved file, so if the "Save Intermediate" button is selected twice while the solver engine is stopped, only the last file will be saved.

The solver writes two types of files for each time that it saves. The files all have the same form, and consist of the word solver, then the number of the layer, an underscore, then the time stamp in seconds, and finally, there is a three letter extension. this is "num" for the pressure profile, and "max" for the flow front position information. These files are ASCII files which contain the pressure of each cell in the layer, as well as how full the cell is. these files can then be easily imported into either a spreadsheet or plotting program for easy viewing. Gnuplot is the most easily used plotting program for this data, but the save routines are easily modified for other programs as well.
APPENDIX C

Computer Code Available from

Department of Chemical Engineering
301 Cobleigh Hall
Montana State University
Bozeman MT 59717.