Three-Dimensional Resin Transfer Molding Process: Developments for Thick Composite Manufacturing Applications

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Three-Dimensional Resin Transfer Molding Process: Developments for Thick Composite Manufacturing Applications

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13. ABSTRACT *(Maximum 200 words)*

The Resin Transfer Molding (RTM) process has been increasingly used in the manufacture of large reinforced composite components, and the current trend is towards manufacturing of thick composites and thick composite sections with impermeable inserts. Current practices involved in the computer simulation of RTM resin impregnation are restricted to two-dimensional formulations based on Darcy's law for flow through thin cavities. The multiple fiber layers in thick composites, and the presence of impermeable inserts inside the fiber bundles, make the resin impregnation a three-dimensional flow, and a better understanding of the resin impregnation can be achieved by considering a fully three-dimensional model. In this paper, a fully three-dimensional simulation of resin impregnation in a porous fiber media based on Darcy's law is considered. The developments are based on a Finite Element-Finite Volume (FE-FV) technique in which the pressure field is solved using the finite element method and the saturated regions of the resin are determined based on conservation of mass. The technique permits an accurate tracking of the resin impregnated fronts involving multiple gates, inserts, and the like. The computational tool will be effective in design of better molds with optimum location of injection ports, vents, and forms a basis for process cycle optimization with a knowledge of mold filling time, fill pattern, and the pressure histories. Simulations involving multiple injection ports, impermeable inserts inside the mold and the flow around them, and airgaps can be effectively handled and are demonstrated.

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1 Introduction

Advanced composites made of fiber-reinforced polymer resins have increasingly been used in the military, automotive, aerospace, and electronic industries due to their excellent properties, such as the high stiffness to weight ratio, long fatigue life, increased corrosion resistance, and the ability to manufacture consolidated parts. To obtain these improved properties, a good control over the fiber layout in the final part and accurate monitoring and modeling of the manufacturing processes is necessary. The Resin Transfer Molding (RTM) process is being increasingly employed and is indeed an emerging manufacturing technology well suited for manufacturing large components of fiber-reinforced composite materials. A schematic description of the RTM process is shown in Figure 1(a). The reinforcements employed usually consist of several layers of fiber mats, woven rowings, or chopped layers of fiber mats laid inside a mold cavity. The resin enters the mold through the injection ports and impregnates progressively the reinforcement. The process involves a mold cavity and since good close tolerances can be obtained by a good mold, the process is suited for manufacturing situations involving close tolerances. Other conventional manufacturing processes, such as hand layup and autoclave molding, allow the manufacturer a good control over the fiber reinforcement in the final part, and therefore over the mechanical properties; However, they are labor intensive for high volume production.

The success of RTM depends on the successful complete wetting of the polymer resin before the formation of the gel and avoidance of the dry spots. An understanding of the impregnation of the resin inside the fiber mold helps the mold designer:

1. Understand the effect of positioning the injection ports and vents and selecting optimum locations to ensure complete filling of the mold without dry spots.

2. Provide a knowledge of the expected pressure distribution inside the mold and design the molds with structural integrity to withstand the pressures.

3. Optimize production cycle using the mold filling time information

All of these can be achieved by a computer simulation of the RTM injection process. Experimental investigation of the analysis of the flow through the

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porous medium in complex and three-dimensional(3-D) parts is highly cost prohibitive and impractical during the initial manufacture. Various numerical simulation techniques to understand the resin flow inside a mold based on Darcy's law have been primarily used in thin RTM components by various researchers. With the increase in the demand for thicker fiber-reinforced composites, the two-dimensional(2-D) simulations do not give an accurate understanding of the representative flow in the thick composite sections. There is also a need for the development of thick composite configurations with embedded reinforced plates that are impermeable to the resin flow. Such structures have numerous practical benefits, such as armor protection in military applications. Analysis of such configurations and the flow fields involved in them are not feasible with 2-D simulations. Furthermore, flow in corners and junctions that are encountered in complex geometries can be better understood only by detailed 3-D models. Hence, there is a critical need for the modeling and simulation of 3-D flows involved in composite components manufactured by the RTM process.

Most of the earlier work in the process modeling of the RTM has been restricted to thin composite components and is governed by 2-D Darcy's law for flow through a permeable porous medium. The main emphasis in these simulations has been on the macroscopic flow through the 2-D porous medium.

In one of the earlier studies, Castro [1] conducted a comparative study of a flow simulation model based on the theory of flow through porous media with a boundary-fitted coordinate system that involved grid generation with experimental results obtained for a 2-D anisotropic impregnation. Lee et al.[2] showed that the equations governing the 2-D RTM flow process are the same as that for injection molding into an empty mold when the Hele-Shaw approximation is made. This approximation thus allowed the use of one of the available injection molding programs to predict the RTM flow process. Fracchia [3] and Fracchia et al.[4] conducted a finite element/control volume simulation to model resin transfer mold filling. This simulation solves the continuity and Darcy's law equations during filling and for predicting the flow front patterns, cavity pressures, and fill times in parts of complex geometry. Um and Lee [5] applied the boundary element method to the modeling of the RTM process. Darcy's law for anisotropic porous media was considered along with the mass conservation to construct

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the governing differential equations. Their formulation did not consider the effect of heat transfer, reaction kinetics, and thermal curing typically involved in a 2-D flow situation. The change in solution domain was tracked by rearranging the boundary nodes at each time step. Bruno et al. [6] modified the commercial injection code "faBest," which is used to model filling of empty cavities with thermoplastic resins, to account for the fiber mats present in the RTM process. The resistance to flow from the fibers was obtained by underestimating the thickness of the part and overestimating the viscosity of the resin. Comparisons were made with experimental predictions.

Wang et.al. [7] used the finite element code FEMAP-RTM to compare flow patterns in injection molding versus RTM. FEMAP also simulates injection/compression molding. The effects of the location of gates and vents, gravity, anisotropic permeabilities, and viscosity rise due to cross-linking chemical reactions were examined using flow simulations for an aerodynamic fan blade. The authors concluded that due to the complexity of the RTM process, numerical simulations are needed in order to predict the process behavior chemical reaction, gravity, heat transfer in and out of the mold, complex geometry mold filling, processing factors that affect the quality of the resin transfer molded components, effective tools for measuring and predicting critical parameters, such as time to fiber wet-out, viscosity, degree of cure, buildup in modulus, and the like.

Bruschke and Advani [8, 9] present a numerical simulation solution based on the finite element/control volume method to calculate the flow pattern of mold filling in an anisotropic media. Their simulation attempts to model thin shell parts of an arbitrary planar shape, with varying thickness, and multiple gates and inserts. A general 2-D permeability mat preform was considered. A 2-D flow model was coupled with a one-dimensional(1-D) heat transfer model based on an approximate lumped form of the finite difference method in the thickness direction. The validity of such approximations and results is unclear. It is clearly evident that most of the flow simulations involved 2-D flows which are valid for thin composite RTM components. For thick RTM composites, a better understanding of the flow field can be obtained by considering fully 3-D flow models. Preliminary developments of a full 3-D analysis of the RTM process flow model geometries is recently described by Tamma et.al. [10].

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In the manufacture of composites by RTM, the resins employed have a specific residence life before gellation, and it is preferred to complete the process before gellation. Of specific interest from the simulation point of view are the flow pattern, the mold filling time, and the pressure distribution, which will provide a better understanding of the process. With this in mind, the present work focuses attention on 3-D Darcy's law flow model developments, which are governed by pressure-driven potential flows. Since the emphasis in this work is on understanding the 3-D flows governed by Darcy's law as it exists in the RTM of thick composites, the following assumptions are made:

1. The polymer resin is incompressible. The viscosity is taken to be constant during the whole process. The simulation assumes that the resin remains at a constant temperature and there is no significant difference in the resin temperature during the simulation, thereby representing isothermal filling conditions.

2. The flow is governed by Darcy's law, and the Reynolds number is small so that the inertia terms in the equation of motion can be neglected.

These assumptions agree with the earlier works involving 2-D RTM flows.

One problem that exists in the RTM is the phenomenon of "Race Tracking." This exists due to the tendency of the increase in the permeability of the reinforced mats near the mold boundary and the presence of airgaps near the boundary. The mold volume is not completely filled with the fiber mat, and the resin has a tendency to race track along the empty airgap region. To accurately represent the presence of the airgap, an equivalent permeability of the airgap is considered here, which depends on the gap geometry to accurately represent the presence of airgaps and their influence in the flow. An important application for the manufacture of thick RTM components is the presence of impermeable solid inserts, which act as stiffeners and provide armor resistance in military applications. Thick composites involving impermeable inserts are also considered in this work for understanding the flow in these 3-D RTM flow situations.

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2 Relevant Mathematical Model and Governing Equations

Due to the high viscosity of the resin and the low Reynolds number of the flow, the flow through a complex 3-D geometry involving multiple body regions, corners and junctions, presence of inserts, and the like is modeled by considering the average velocity field along the three coordinate directions $x_i (i = 1, 2, 3)$. The flow is pressure driven and the average velocity components are related to the pressure gradients by Darcy's law.

$$\hat{u}_i = -\nu K_{ij} P_{,j} \qquad i = 1, 2, 3 \qquad (1)$$

with summation on j and $P_{,j}$ representing $\frac{\partial P}{\partial x_j}$, the pressure gradient, ν is $\frac{1}{\mu_{eff}}$, representing the inverse of effective viscosity.
The flow satisfies the continuity equation,

$$div\, \boldsymbol{u} = 0. \qquad (2)$$

Using Eq. 1 in the previous continuity equation, an equation governing the pressure distribution in a complex 3-D configuration is governed by:

$$div[K_{ij} P_{,j}] = 0 \qquad (3)$$

or

$$\frac{\partial q_i}{\partial x_i} = 0 \qquad i = 1, 2, 3, \qquad (4)$$

where

$$q_i = K_{ij} P_{,j}. \qquad (5)$$

and the permeability matrix, which depends on the fiber arrangement, is defined as,

For 3-D Flow:

$$\begin{bmatrix} K \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}. \qquad (6)$$

The boundary conditions for the pressure are that the pressure is zero at the free surface and there is no flow through the mold wall. At the mold wall,

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$\boldsymbol{u} \cdot \vec{n} = 0$, which is expressed in terms of the pressure based on Darcy's law. It is assumed that the permeability matrix is known a priori and determined based on the arrangement of the fiber mats and orientations. Resin inflow rates at the gate locations can be either nodal or along the edges (both can be multiple) and are appropriately modeled.

3   Numerical Methodology

The difficulties in the numerical solution of the flow field in RTM simulations comes from the fact that the mold filling simulation is a transient problem. To solve numerically using the finite element method, the pressure field solution and the moving free boundary within the porous fiber mat region have to be kept track. It should be noted that the pressure in the empty mold is zero, and the flow front boundary continually changes. Various techniques have been employed to determine the filled regions, which are determined based on the filled finite element nodes. In principle, all of these techniques involve updating the location of the flow front at each time step using the Darcy's velocity field and the computed mass fluxes into the discretized mold regions.

The solution of the pressure field with the associated boundary conditions involves the solution over the entire flow domain, which is changing continuously throughout the mold filling process. Traditional finite element techniques as used in Computational Fluid Dynamics simulations involve modifications of the finite element meshes at each time of simulation. This modification of meshes in a changing flow domain is not only time-consuming in a 3-D simulation but also involves usage of automatic mesh generators and difficulties in the location of the new flow front at the next time step. That is, employing a moving grid finite element technique in which the mesh depends on the location of the flow front may be time consuming and expensive. Further, these moving grid techniques cannot handle easily the case of multiple fronts, dividing and merging fronts inside molds with inserts. To avoid these difficulties, the Finite Element - Finite Volume (FE-FV) method, in which the computational grid is fixed and is based on the mold geometry, is employed in this work. This technique employs one single grid throughout the simulation. The FE-FV technique that is employed for the computation of pressures, flow fields, and tracking of flow

fronts is briefly described next. Though the discussions here are based on 3-D four-noded tetrahedral elements, extension of the concepts to higher order element geometries is easy and feasible.

In the present 3-D RTM computational developments, the mold cavity is divided into four-noded tetrahedral elements. The normal finite element shape functions are used in the computation of the finite element matrices of each element in the mold geometry. In addition, each node is also associated with a specific finite volume region. The finite volume associated with each node in a element involves six faces. The finite volume region is obtained by joining the centroid of each face, the mid points of each of the line segments of the triangular faces and the body centroid of the tetrahedran. Each finite volume region associated with a node has one-fourth of the volume of the element. The continually changing flow domain is determined based on the conservation of mass principle applied to each of the finite volume regions. The mass conservation principle is based on the fact that the net mass flow into a finite volume region is equal to the amount of mass absorbed and accumulated in the fiber bundles within the finite volume region. In this formulation, each node in a element is associated with a sub-finite volume region that is local to the element. The total finite volume region associated with a node involves contributions from the elements sharing a given node and can be determined based on the elemental connectivities. The net mass flux entering a finite volume region associated with a node is computed based on the flux at each face of the finite volume region; the computations are based on the pressure gradients and the associated Darcy's velocity field. The net mass flow rate entering the finite volume associated with a node within a ith element is determined from the surface integrals defining the finite volume and can be represented as,

$$q_i = \int_S \boldsymbol{u} \cdot \vec{n} dS, \tag{7}$$

where the velocity field $\boldsymbol{u}$ is determined from the pressure gradients and nodal pressures within the element. The 3-D velocity field is given by:

$$u_i = -\nu K_{ij} P_{,j} \qquad\qquad i = 1, 2, 3 \tag{8}$$

Note that the Darcy's velocity field and the pressure gradients are computed within the element and are continuous within a given element. This implies

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that the flow rate computed based on the velocity fields satisfies the continuity condition or the local mass conservation condition. This is in contrast to some of the earlier Finite Element/Control Volume techniques in 2-D RTM simulations where the pressure gradients and hence the flow rates were determined across the elements [8, 9], even when the elements employed were C_0 continuous. This also permits use of traditional finite elements as apposed to the nonconformal elements proposed by Trouchu et al. [11] for this purpose.

The continually changing flow front and the filled flow domain is determined from a parameter fill factor F_f that is associated with each node. The parameter F_f represents the status of the finite volume and indicates if a given finite volume region is full or empty. If a finite volume region is empty (has not yet been filled with resin), the associated fill factor F_f is zero, and a finite volume that is filled completely with the resin is given a fill factor F_f of 1. The resin front exists in finite volume regions where the fill factor F_f is between 0 and 1, and the factor F_f is set to the volume fraction of the finite volume that is filled with resin. For these nodes with the associated finite volumes, the pressure is zero at the flow fronts and the corresponding nodes. Hence, the solution process in the RTM simulation involves solving for both the pressure field derived from the continuity equation and the factor F_f. Numerous techniques can be employed for the update of the fill factor F_f. The so-called explicit filling techniques determine the fill regions and time based on the actual flow rates and the finite volumes associated with each node. On the other hand, the so-called implicit filling techniques employ a mass balance equation based on the volume-averaged fill factor and are updated in an iterative manner till convergence for a given time step. In this work, the advancement of the fill factor, hence, the flow front, is based on an explicit algorithm. In this approach, the mold filling process is regarded as a quasi-steady process, which assumes a steady-state condition at each time step. At each time step, the pressure distribution is computed both based on the boundary conditions and the fill factor conditions. The velocity field, hence, the flow rate computed from the pressure field, is used to update the new front location, fill stage, and time of simulation. The selection of the time step for each of the quasi-steady states is based on the following consideration. At any time, the time increment used allows only one finite volume region to be completely filled. This restriction of the time increment ensures the stability of the quasi-steady state approximation.

4 Finite Element Discretization

The assumptions of Darcy's law with average velocities in the coordinate directions lead to a 3-D diffusion equation for pressure. In this study, the finite element discretizations are developed based on the conservation form of the original pressure equation, which is a modified form of the continuity equation. Tamma et al. [11-18] describe finite element developments for analogous forms of related equations in the areas of thermal and structural dynamics applications. The developments emanate from the conservation form of representations and have shown to possess attractive computational attributes and numerical enhancements and feasibilities for applications to parallel computing environments.

In this approach, we start with the continuity equation, which is also the flux-based conservation form for the RTM process. The flux-based conservation form describing the continuity related to the RTM process is given by

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = 0, \tag{9}$$

where $u_i, (i = 1, 2, 3)$ are the velocity components in the three coordinate directions. The velocity field satisfies the generalized Darcy's law, and each of the components in a 3-D velocity field can be expressed in terms of pressure gradients and the components of the permeability tensor. The three components of the velocity field are given by:

$$u_1 = -\frac{1}{\mu}\Big[K_{11}\frac{\partial P}{\partial x_1} + K_{12}\frac{\partial P}{\partial x_2} + K_{13}\frac{\partial P}{\partial x_3}\Big] \tag{10}$$

$$u_2 = -\frac{1}{\mu}\Big[K_{21}\frac{\partial P}{\partial x_1} + K_{22}\frac{\partial P}{\partial x_2} + K_{23}\frac{\partial P}{\partial x_3}\Big] \tag{11}$$

$$u_3 = -\frac{1}{\mu}\Big[K_{31}\frac{\partial P}{\partial x_1} + K_{32}\frac{\partial P}{\partial x_2} + K_{33}\frac{\partial P}{\partial x_3}\Big]. \tag{12}$$

Unlike the traditional Galerkin finite element formulations, with the proposed notion of flux-based element representations to not only enhance the physical interpretation of the mathematical formulations but also to provide computationally attractive numerical attributes, we introduce typical element approximations as,

$$P = N_\alpha P_\alpha \tag{13}$$

$$u_i = N_\alpha u_{i\alpha} \quad .$$

The shape functions (N) used depend on the type of element employed. Introducing the finite element approximations (Eq.13) into the continuity equation, which is also the conservation form of the diffusion equation involving pressure (Eq. 9), and making use of the Darcy's approximation of the flow field (Eqs. 10 - 12), the discretized system based on the Galerkin weighted residual approximations for the pressure field can be obtained as

$$\{F_1\} + \{F_2\} = 0, \tag{14}$$

where

$$\{F_1\} = \int_{\Omega_e} N_{\alpha,i} N_\beta d\Omega_e \{P_i\} \tag{15}$$

$$\{F_2\} = - \int_{\Gamma_e} N_\alpha N_\beta d\Gamma_e \{P_i n_i\} \quad . \tag{16}$$

Note that the discretized system involves only the solution of the nodal pressures unlike other developments employing mixed formulations, even though both the pressure and velocity fields are approximated. In this formulation, the term $\{P_i\}$ in $\{F_1\}$ mathematically represents the diffusion of pressure or the velocity field-based Darcy's approximations, and the element integrals are independent of the material thermo-physical characteristics, such as those associated with the material permeability and viscosity. For a nonlinear permeability tensor, this term need to be evaluated only once in the entire analysis without disturbing the evaluation of element integrals in a finite element formulation. The element integrals are only dependent on the element geometry and are not dependent on the nonlinear permeability tensor. The term $\{F_2\}$ is associated with the boundary conditions, and general natural boundary conditions can be introduced directly via $\{P_i n_i\}$, again, without disturbing the evaluation of element integrals which are again only geometry dependent. For linear element models, the present formulations are known to reduce to traditional formulations. The characteristic features of the proposed flux-based formulations include:

1. Natural introduction of general linear/nonlinear boundary conditions in an effective and direct manner without disturbing the element integrals.

2. Obviates the need to perform cumbersome numerical integrations for evaluating the element matrices (especially, the commonly adopted 2-D

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and 3-D elements, such as triangles, quadrilaterals, tetrahedrans, hex-ahedrans, etc., with linear variation along a typical edge), which are customarily required in conventional finite element formulations. As such, closed-form formulations of typical element matrices are permissible.

5 Race Tracking and Modeling of Flow in Regions with no Preform

One of the common problems in the RTM process is the phenomenon of "Race Tracking." In a typical manufacturing situation, the fiber preform is not uniformly distributed inside the mold and there is a tendency for the presence of airgaps between the mold walls and the porous fiber mat packing. The presence of airgaps in the absence of the porous fiber mat leads to the racing of the resin through the nonfiber regions. During manufacture, the presence of airgaps and the subsequent race tracking leads to the presence of "dry spots" in the part where the resin has not fully impregnated the fiber. During simulation, the permeability in the airgap regions is approximated to be a value higher than the normal, based on a correction factor. This correction factor is based on experience and is taken to account for the race-tracking effects. In this paper, an empirical relation to determine the effective permeability in thin airgap regions is obtained based on the analysis of slow plug flow, in which the velocities are taken to be constant across the thickness and correlating it to the velocities based on Darcy's flow.

A pressure-driven flow through a narrow cavity is considered. The cavity is of a small thickness and the velocity perpendicular to the cavity is taken to be small. Further, the pressure gradient in the perpendicular direction is small compared to the pressure gradients in the lateral directions. The velocity gradients in the lateral directions are also assumed small compared to the velocity gradients in the perpendicular direction. If the xy plane forms the lateral surface of the cavity and if the z is the perpendicular direction as shown in Figure 1(b), then

$$\frac{\partial P}{\partial z} << \frac{\partial P}{\partial x}, \frac{\partial P}{\partial y} \quad . \tag{17}$$

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Likewise,

$$\frac{\partial u}{\partial x} << \frac{\partial u}{\partial z}$$

$$\frac{\partial u}{\partial y} << \frac{\partial u}{\partial z} \tag{18}$$

$$\frac{\partial v}{\partial x} << \frac{\partial v}{\partial z}$$

$$\frac{\partial v}{\partial y} << \frac{\partial v}{\partial z} \quad . \tag{19}$$

Based on these approximations, the Navier-Strokes equations for incompressible, isothermal, Newtonian fluid can be written as:

$$\frac{\partial P}{\partial x} = \mu \frac{\partial^2 u}{\partial z^2}$$

$$\frac{\partial P}{\partial y} = \mu \frac{\partial^2 v}{\partial z^2} \quad . \tag{20}$$

Assuming no slip conditions at the top and bottom surfaces of the thin cavity of thickness t, the velocity distribution is given by

$$u = \frac{1}{2\mu}\frac{\partial P}{\partial x}[z^2 - tz] \tag{21}$$

$$v = \frac{1}{2\mu}\frac{\partial P}{\partial y}[z^2 - tz] \quad . \tag{22}$$

For plug-type Hele-Shaw flow as it exists in thin cavities, and which corresponds to the Darcy's flow that exists in a pressure-driven flow in a porous medium, the average velocity of flow across the thickness of the cavity is given by:

$$\hat{u} = \frac{1}{t}\int_0^t u\,dz \tag{23}$$

$$\hat{v} = \frac{1}{t}\int_0^t v\,dz \quad . $$

On integration:

$$\hat{u} = -\frac{1}{12\mu}\frac{\partial P}{\partial x}t^2 \tag{24}$$

$$\hat{v} = -\frac{1}{12\mu}\frac{\partial P}{\partial y}t^2 \quad . $$

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The continuity equation based on the average velocity is given by

$$\frac{\partial \hat{u}}{\partial x} + \frac{\partial \hat{v}}{\partial y} = 0 \quad . \tag{25}$$

In the RTM process involving flow through a porous media, the continuity equation based on the average velocity is the same as Eq. 25, and for pure isotropic fiber mat medium, the average valocities are given by

$$\hat{u} = -\frac{K_{xx}}{\mu}\frac{\partial P}{\partial x} \tag{26}$$

$$\hat{v} = -\frac{K_{yy}}{\mu}\frac{\partial P}{\partial y} \quad .$$

Comparing equations 24 and 26, the effective permeability for the airgap region can be determined to be

$$K_{eff/airgap} = \frac{1}{12}t^2 \quad . \tag{27}$$

Hence, the effective permeability for the airgap regions in RTM simulations can be taken to be a function of the thickness of the airgap and is a better representation of the permeability than those based on correction factors. In this study, these computed permeability values have been used in regions with airgaps during the simulations.

6 Numerical Examples and Illustrative Applications

The proposed developments are implemented into a computer code (Composites Under Resin Transfer [CURT-3D]) involving tetrahedral elements to simulate the RTM flows in complex 3-D geometries. The prescribed boundary conditions for the simulation can be either prescribed pressures or prescribed flow rates.

6.1 Molding of a Flat Plate

A flat plate mold of 2 x 5 x 0.125 in injected with resin at one point on the side is considered. Being a thin plate, the same mold was first simulated

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with triangular elements as a 2-D simulation. With the injection flow rate of 1 in^3/s, the theoretical fill time is 1.25 s, based on a total fill volume of 1.25 in^3. The computed fill time based on a detailed 2-D triangular mesh with 697 nodes and 1,280 elements is 1.248 s. The same mold geometry was modeled with 3-D tetrahedral elements involving 2,091 nodes and 6,400 elements. The computed fill time in this case is 1.247 s and the results are in excellent agreement. The purpose of this example is to validate the 3-D analysis results with 2-D results for a thin plate. The 3-D mesh and the flow contours in the thin flat plate are shown in Figure 2. The flow contours on the top surface when the plate is full are shown for a 2-D model and 3-D model in Figure 3.

6.2   Molding of a Thick Solid Composite Section

In this a thick composite section of 2 x 4 x 1 in is considered. The thickness is large compared to the earlier example, and a detailed understanding of the flow can be obtained from the present 3-D simulation. The resin is injected on the top surface at the center. The thick composite section is modeled with tetrahedral elements, and six layers of elements exist across the thickness of the plate. The mesh geometry and the flow contours indicating the different times of fill are shown in Figure 4. For such thick composite sections, the flow is fully 3-D and the 3-D RTM flow simulation provides a better understanding of the fill pattern and helps identify potential dry spots.

6.3   Molding of a Thick Composite L-section: Effect of Race Tracking/Flow in Corner

This example illustrates the flow in a thick 3-D L-section as well as the effect of race-tracking due to the presence of an airgap when the entire mold is not filled with the fiber preform. The inner and outer surfaces of the mold geometry shown in Figure 5(a) are taken to be free of the fiber preform. For simulation considerations, a layer of 3-D elements was modeled for these regions and was assigned equivalent permeabilities as described in an earlier section. The finite element mesh employed is as shown in Figure 5(b). Two cases involving the line injection and surface injection at the top surface are considered. The flow progression contours on filling for the case of line injection is shown in Figure 6(a). It is clear from this figure that the presence of an airgap leads to racing of the flowing resin and the resin travels faster

along the airgap than along the porous fiber region. The flow progression contours for the case of surface injection are shown in Figure 6(b). This example clearly demonstrates the effect of presence of bends and airgaps in the mold and the flow patterns due to them. The presence of airgaps and changes in permeability are the main causes for the void and dry spot formations in resin transfer molded components.

6.4 Molding of Thick Composite Parts with Impermeable Inserts

One of the objectives of understanding 3-D RTM flow involving thick composites and developing simulation tools is to provide a tool in the design of resin transfer molds. In this study, one of the objectives is to understand the 3-D RTM flows involving mold geometries with regions of impermeable inserts. The impermeable inserts are kept inside the fiber mats inside a mold. These inserts are impermeable to the resin, and Figure 7 shows a 3-D thick composite section with fiber mat and inserts inside them. Such analysis is not feasible with 2-D simulation models, and the present study provides the necessary tools for such analysis. The finite element mesh and the fill progression pattern in such a configuration is shown in Figure 8 for a given line gate location. By varying the locations of the gates, the currently developed tools serve as a good design tool to understand the flow pattern and select the mold design for these types of composite sections.

7 Conclusion

The analysis of 3-D flows that exists during the resin impregnation of thick composites becomes critical in the successful manufacturing of thick composite structural configurations by the RTM process. In the present paper, a simulation program has been developed for the RTM process involving 3-D fiber preforms and based on 3-D Darcy's law. Though the developments are based on a fixed grid FE-FV approach for the progression of the resin front, the pressure gradients and hence the flow rates are computed within a finite element and satisfy the mass conservation or the continuity condition locally within an element. From the implementation point of view, only one set of mesh is employed and each node has its own associated finite volume region associated to the element to which it belongs, which is then used in the com-

putations in conjunction with inter element connectivity. This is in contrast to earlier formulations that involved flow rate computations across element boundaries and usage of additional data structures for the finite volume domain identifications. The presence of airgaps and the phenomenon of "race tracking" due to the presence of such airgaps are being effectively modeled using equivalent permeabilities that depend on the thickness of the airgap. Numerical examples indicate the effectiveness of the present developments in situations involving multiple injection ports, demonstrate the effect of "race tracking" in the presence of airgaps and resin impregnation in the presence of impermeable inserts inside the fiber preform and the mold. The present developments are based on a resin which is isothermal and with constant viscosity. This provides a good engineering process modeling tool for understanding the fill pattern, optimize the location of injection ports, flow rates and injection pressures, and to obtain filling times within the residence life of the resin during manufacture. Future work should include the effect of heat transfer, curing and subsequent changes in viscosity of the resin, which affects the fill and subsequent structural integrity of the components.
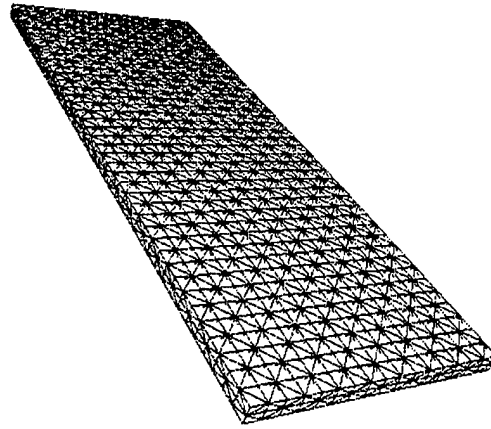
Dry Fiber Preform

Resin Pump

Matched Mold Set
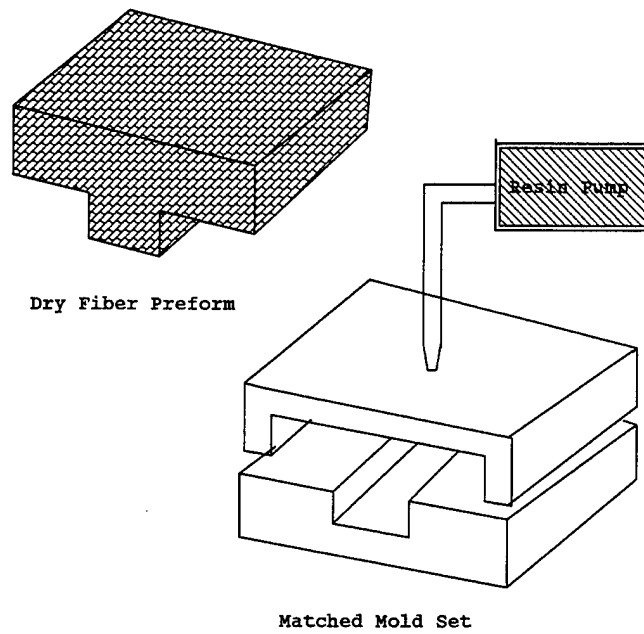
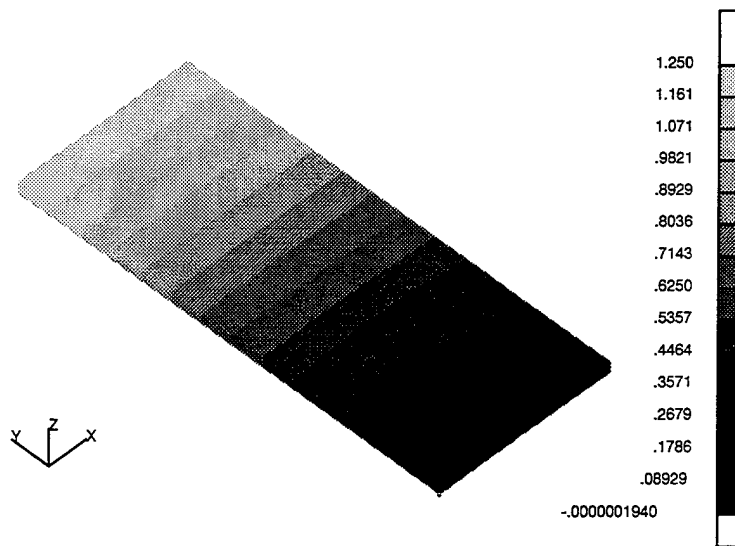(a) RTM process description
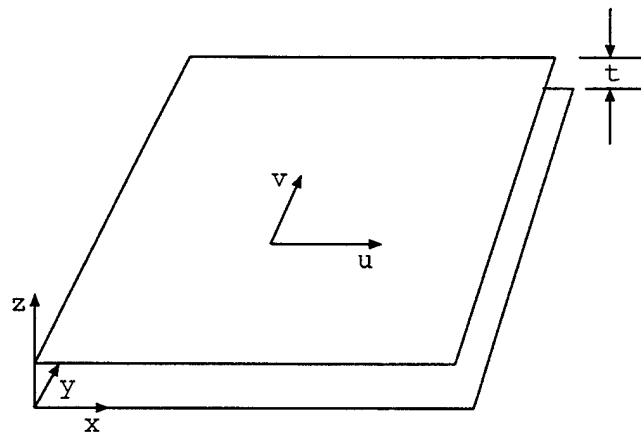
(b) Geometry of thin cavity

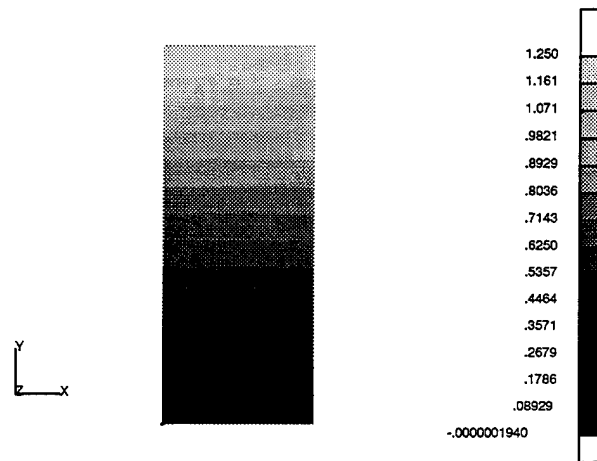Figure 1: Resin transfer molding.
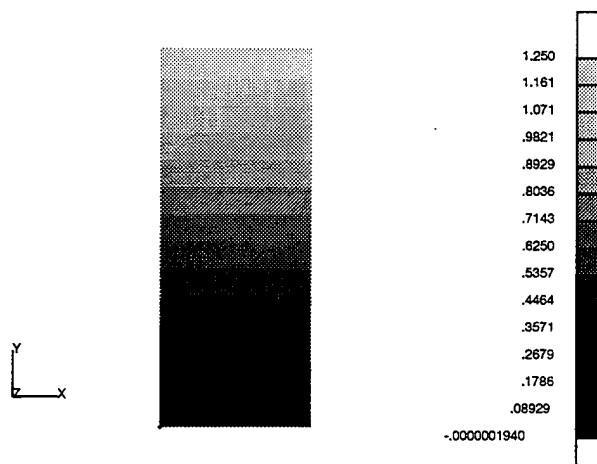
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(a) Mesh geometry

(b) Fill contours in the mold

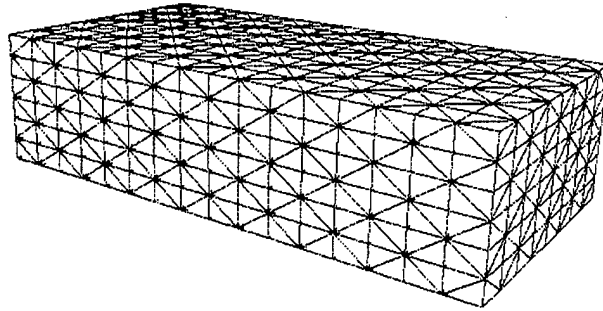Figure 2: 3D thin plate section.
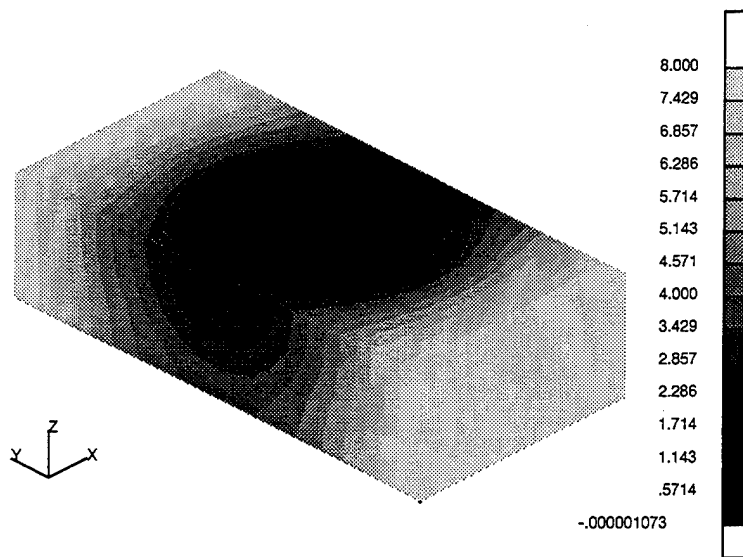
(a) 2D model

(b) 3D model
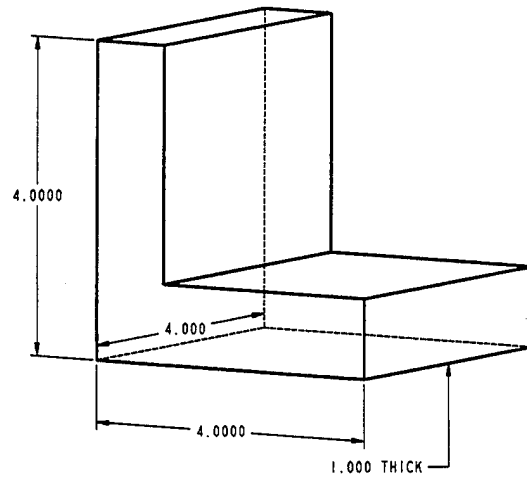
Figure 3: Surface fill contour comparison.
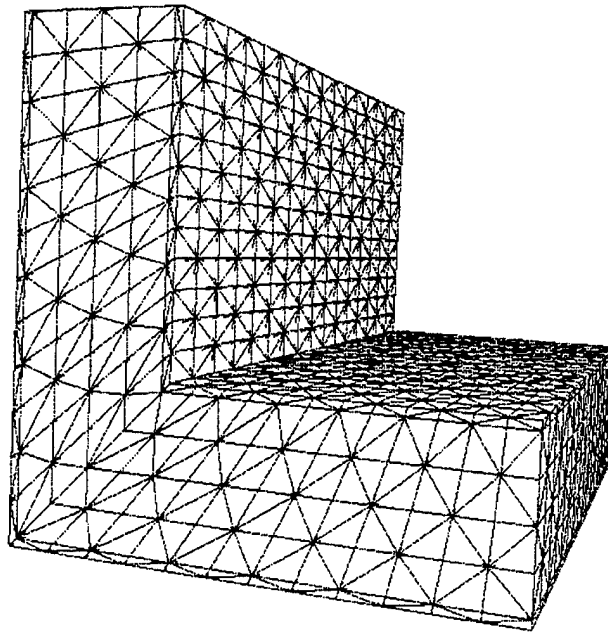
(a) Mesh geometry

(b) Fill contours in the mold
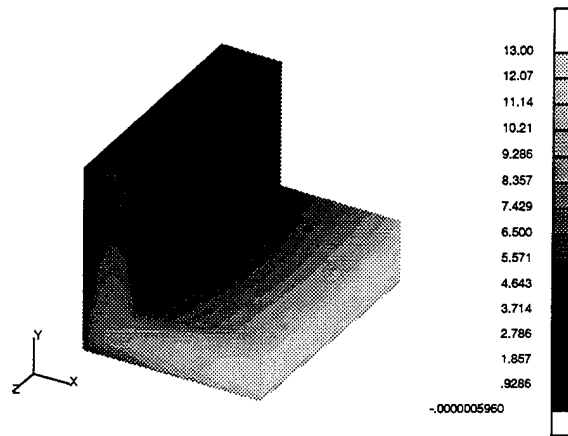
Figure 4: Thick 3D section.
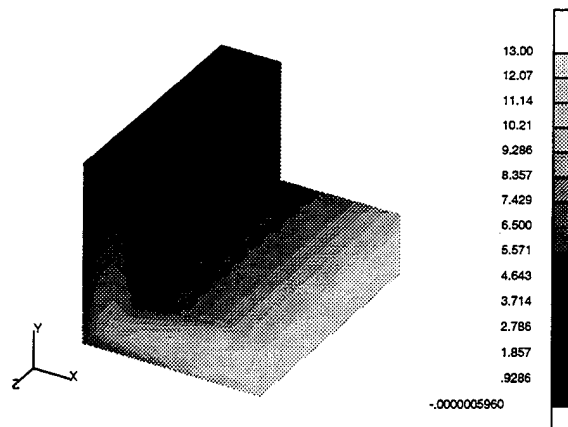
(a) Geometry

(b) Mesh

Figure 5: L-shaped mold with airgaps on the surface.

(a) Line injection

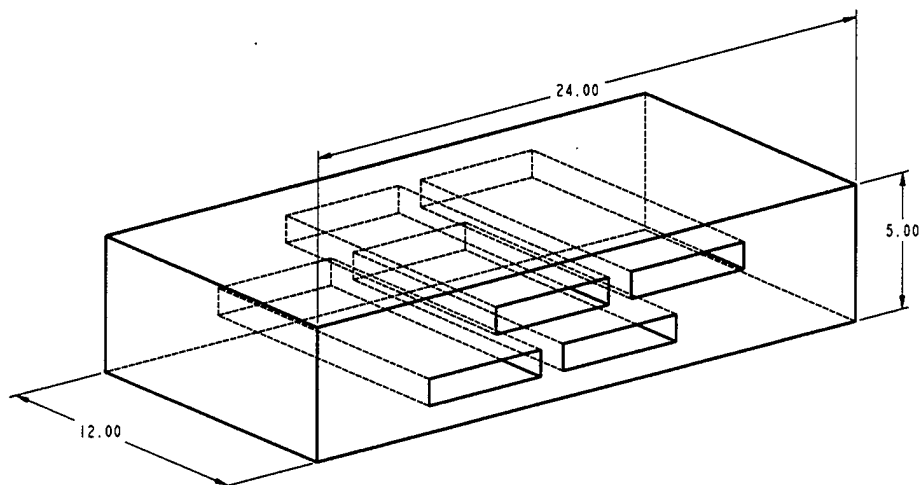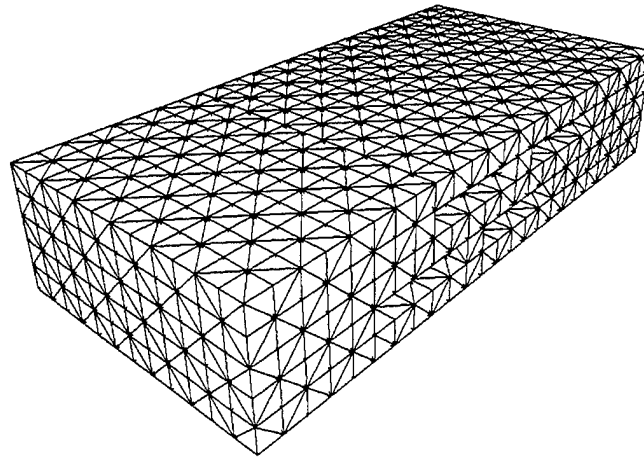(b) Surface injection

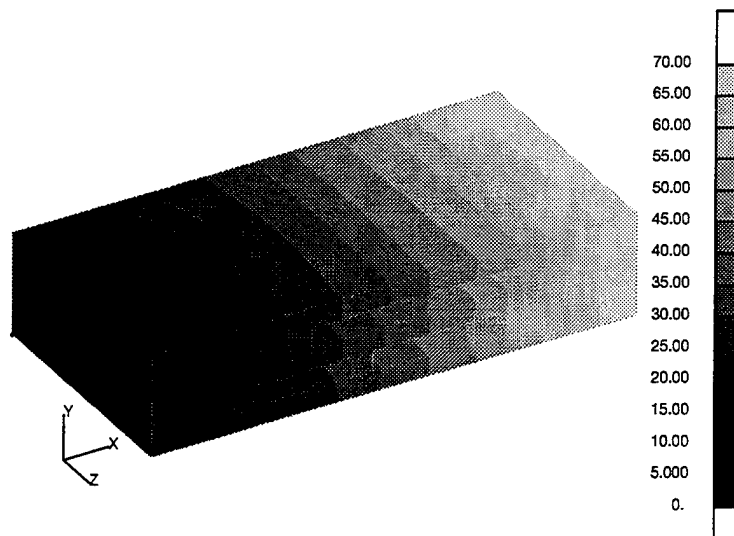Figure 6: Fill contours in the mold.

Figure 7: Thick composite section with impermeable inserts.

(a) Mesh geometry

(b) Fill contours

Figure 8: Thick armor section.

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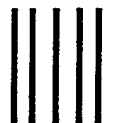**DEPARTMENT OF THE ARMY**

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