ISOTHERMAL FLOW SIMULATION OF LIQUID COMPOSITE MOLDING

Xiao-Lin Liu

Cooperative Research Center for Advanced Composite Structures
506 Lorimer Street, Fishermens Bend, Victoria, Australia 3207

ABSTRACT

This paper proposes a finite element/nodal volume procedure for the isothermal flow simulation of liquid composite molding processes. The formulation and the numerical implementation of the procedure are described. A scheme is introduced to prevent the procedure from possible locking in the flow calculation. The capability and the numerical accuracy of the procedure are investigated through a number of numerical examples.

INTRODUCTION

Liquid composite molding (LCM) techniques, such as resin transfer molding (RTM), structural reaction injection molding (SRIM) and resin film infusion process (RFIP), involve flowing thermoset resin into a closed mold cavity with pre-placed fiber mats or preforms. The resin wets out the fiber until the mold is filled. The composite part is formed after the resin has cured, generally under a pre-designed heating cycle. LCM offers a number of advantages over other composite manufacturing operations such as the autoclave pre-preg process. These includes the capability to produce parts with highly complex shapes, better control over part properties and low chemical emission. Therefore, the techniques have attracted much research attention in recent years and have started being used as manufacturing methods for making advanced composite structures in the aerospace industry.

One of the most important scientific needs in LCM is the ability to predict the flow behavior of the resin during the mold filling stage. There are a number of flow variables which have direct impact on the mold and process design, and which can only be reasonably and cost-effectively predicted by modeling. One such variable is the evolution of the resin flow front position as a function of time. Based on the prediction, special care can be taken through proper design of injection and venting ports to prevent dry spots where resin fails to research or the air is trapped. Thus simulation of the resin flow through the fibrous preform has become an essential task for the development of LCM processes. Considerable research efforts have been devoted to this area and a number of numerical simulation procedures have been developed [1-9]. Among them, a class of the so called finite element/control volumes (FE/CV) methods [5-9] have been gaining popularity due to their simplicity in dealing with the moving boundary problem associated with the flow simulation.

This paper proposes a finite element/nodal volume (FE/NV) procedure for the isothermal flow simulation of liquid composite molding processes. The procedure is of advantages over most of the previously proposed FE/CV methods in the following important aspects:

1. The present procedure does not require the construction of the control volumes explicitly nor does it involve the calculation of the flow velocity vectors, both of which can be complex in three dimensions. Therefore, it is generally simpler and more numerically efficient than the FE/CV methods. In addition, no special treatment is required when elements of different dimensions are combined in the same model.

2. Although the pressure is solved by the Galerkin method which is not only the FE technique implemented in most of the general-purpose FE packages but also the optimal method for solving a self-adjoint problem [3,10], conservation of resin mass is achieved by the procedure. Such conservation can not be obtained by the FE/CV methods unless the pressure is solved by the control volume finite element method or the simplex elements are used [8,10].

3. The procedure is implemented on general-purpose finite element packages. The heat conduction solver of the FE packages is used to solve the pressure equation. A user program is developed to advance the flow front. This approach results in significant savings in the software development time and costs, and makes available to the users the modeling features of the FE packages. As a result, flow simulation can be performed using a variety of elements supported by the packages, including 2D plate, 3D shell and solid elements.

THE PROPOSED TECHNIQUE

The Pressure Equation

On the macroscopic scale, it is a common practice to describe the resin flow through the fibrous reinforcement by the following Darcy's law:

$$\boldsymbol{u} = -\frac{1}{\mu}\boldsymbol{K}\nabla\boldsymbol{P} \tag{1}$$

In the above equation, μ is the viscosity of the resin, $\boldsymbol{u}$ the flow velocity vector:

$$\boldsymbol{u} = \begin{pmatrix} u_x & u_y & u_z \end{pmatrix}^T \tag{2}$$

$\nabla\boldsymbol{P}$ the pressure gradient vector:

$$\nabla\boldsymbol{P} = \begin{pmatrix} \frac{\partial P}{\partial x} & \frac{\partial P}{\partial y} & \frac{\partial P}{\partial z} \end{pmatrix}^T \tag{3}$$

and $\boldsymbol{K}$ the permeability tensor (in principal axes):

$$\boldsymbol{K} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \tag{4}$$

Applying the condition of resin incompressibility to Eqn. 1, one obtains the following pressure equation:

$$\frac{\partial}{\partial x}\left(\frac{K_x}{\mu}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{K_y}{\mu}\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{K_z}{\mu}\frac{\partial P}{\partial z}\right)=0 \tag{5}$$

It is worth noticing that the above quasi-harmonic equation also governs a number of steady state field problems, including steady state conduction heat transfer.

Numerical Implementation

Except for few cases where very simple geometries are dealt with, the above governing equations have to be solved by a numerical technique which usually involves two tasks, namely to solve the pressure equation and to advance the flow front.

In the present procedure, the transient resin flow process is treated as a number of steady problems by time incrementation. The entire mold cavity is discretised into a finite element mesh. Nodal volumes are computed based on the FE mesh. A nodal volume is the volume associated with a nodal point, and it is evaluated as the sum of the fractional volumes of the elements connected to the point. The fractional volume of an element is defined as the volume of the element divided by the number of nodal points associated with the element.

Using the finite element method, the above pressure equation is approximated by the following discretised form:

$$\boldsymbol{SP}=\boldsymbol{Q} \tag{6}$$

where $\boldsymbol{S}$ is the stiffness matrix, $\boldsymbol{P}$ is the nodal pressure vector, and $\boldsymbol{Q}$ is the equivalent nodal applied flux (flow rate) vector.

In a time step, the discretised pressure equation is solved using a general purpose FE package. The nodal fluxes at the flow front, where a pressure boundary condition is prescribed, are conjugate to the pressure. They are in balance with the applied fluxes and can be recovered after the pressure is solved. Indeed, this is automatically performed by most of the FE packages.

The flow front is then advanced by the user program. Each nodal volume is assigned a fill factor, which is varied from 0 for an empty volume to 1 for a fully filled one. The nodal fluxes at the flow front, obtained from the FE solution, are used to compute the resin volumes entering the relevant nodal volumes during the time step. The size of the time step is determined in such a way that only one nodal volume becomes fully filled during the step. This approach for the flow calculation is not only simpler than that used in the FE/CV methods, but more importantly, results in conservation of resin mass on both the global and the nodal volume levels.

Modification in Case of Locking

In solving the pressure equation, a pressure boundary condition is applied at the flow front which is represented by the empty or partially filled nodal volumes (points). This may cause the FE equation to be overconstrained, resulting in a flux flowing out of a nodal volume (represented by a negative flux in the present research) which is empty or partially filled. Such phenomena would not happen to an empty volume physically and should also not be allowed for a partially filled volume. In such a case, the flow calculation can not be performed and the process is referred to as locked.

A scheme is proposed by the present author to eliminate the effect of the locking on the flow calculation. In the scheme, the flux at the locked nodal point is set to zero. The fluxes at the filling nodal points surrounding the locked one are modified using the following equation:

$$q_i^n = q_i^o + \frac{q_i^o}{\sum_{k=1}^{m} q_k^o} q_j^o \tag{7}$$

In the equation, q represents nodal flux, j stands for the locked node, i and k are the filling nodal points connected to j, m is the total number of nodal points in i and k, and the superscripts o and n stand for the FE flux (old) and the modified flux (new) respectively.

It is easy to have:

$$\sum_{k=1}^{m} q_k^n = \sum_{k=1}^{m} q_k^o + q_j^o \tag{8}$$

Therefore, the condition of resin mass conservation is maintained by the modification.

NUMERICAL EXAMPLES

The proposed technique was implemented on two general-purpose finite element packages, LUSAS and NASTRAN. A number of isothermal flow simulations were performed.

One Dimensional Flow

The first example considered was a rectangular bar of $10 \times 10 \times 500mm$ with the resin being injected at one end. The resin flow in the reinforcement was predominantly one dimensional in the axial direction. In this simple case, Darcy's law can be solved analytically. For the injection at a constant pressure P_{inj}, the flow front position x_f at time t can be expressed as:

$$x_f = \sqrt{\frac{2KP_{inj}t}{\varepsilon\mu}} \tag{9}$$

For the injection at a constant rate Q_{inj}, the injection pressure is linearly proportional to the flow front position:

$$P_{inj} = \frac{Q_{inj}\mu x_f}{AK} \tag{10}$$

where A is the cross sectional area of the bar.

Flow simulations were conducted for the constant pressure injection (P_{inj}=150kPa) and the constant flow rate injection (Q_{inj}=100$mm^3/sec.$) respectively. The rectangular bar was modeled using 50 one dimensional bar elements. The material properties used were ε=0.4 and K/μ=300 $mm^2/mPa.sec.$) respectively.

Figs. 1 and 2 plot the flow front position and the injection pressure predicted by the simulations for the constant pressure and the constant rate injections respectively. They are identical to those calculated from the analytical solution.

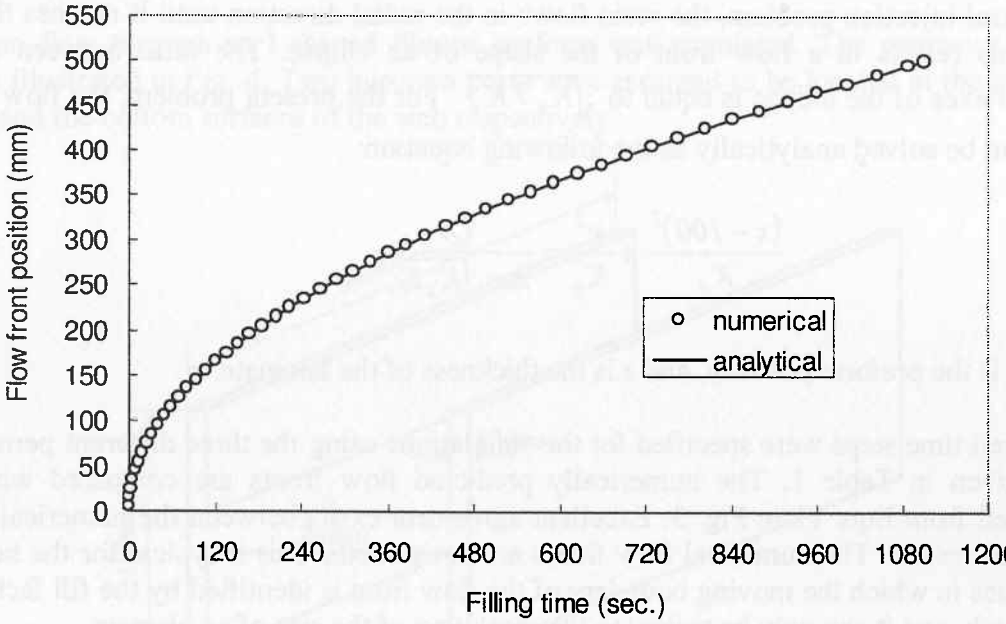

Figure 1. Flow front position for constant pressure injection.

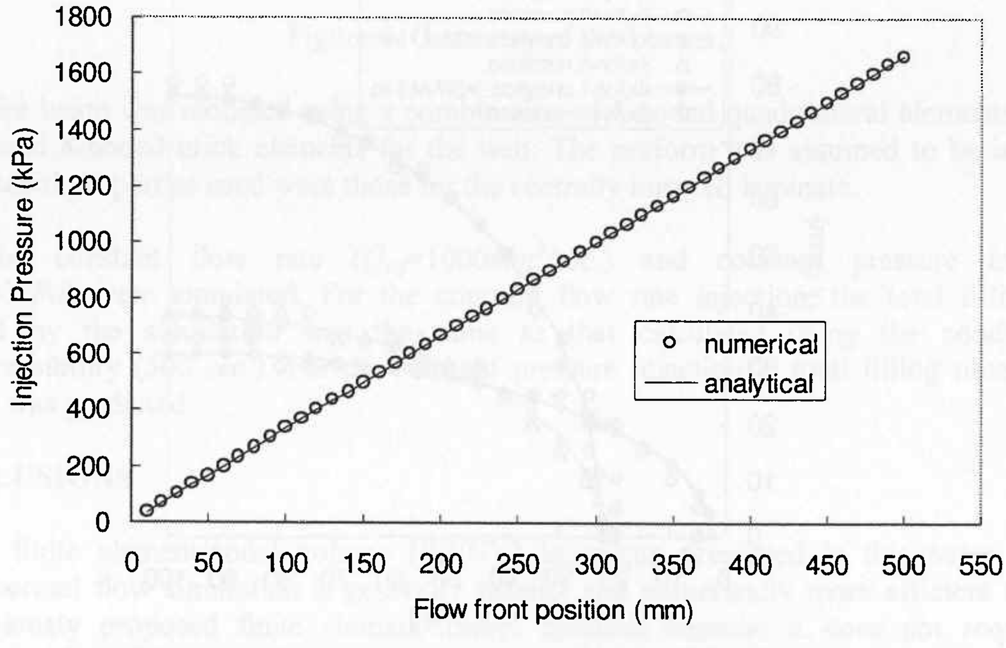

Figure 2. Injection pressure for constant flow rate injection.

Radial Flow

The second example was a flat laminate injected by a constant flow rate at the center of the laminate. The size of the laminate was 200×200×5 mm. Using symmetry, a quarter of the laminate was modeled by 400 uniformly distributed 2D 4-noded finite elements. The rate of injection adopted was 120 $mm^3/sec.$ (30 $mm^3/sec.$ for a quarter of the laminate). The preform was assumed to be orthotropic. The material properties used in the simulation are listed in Table 1.

In a central injection problem, the resin flows in the radial direction until it reaches the mold wall. This results in a flow front of the shape of an ellipse. The ratio between the two principal axes of the ellipse is equal to $\sqrt{K_x / K_y}$. For the present problem, the flow front at time t can be solved analytically as the following equation:

$$\frac{(x-100)^2}{K_x} + \frac{y^2}{K_y} = \frac{Qt}{\pi z \varepsilon \sqrt{K_x K_y}} \tag{11}$$

where ε is the preform porosity, and z is the thickness of the laminate.

A hundred time steps were specified for the simulations using the three different permeability ratios given in Table 1. The numerically predicted flow fronts are compared with those calculated from Eqn. 11 in Fig. 3. Excellent agreement exists between the numerical and the analytical results. The numerical flow fronts are not smooth. This is typical for the numerical techniques in which the moving boundary of the flow front is identified by the fill factors on a fixed mesh, and it can only be tacked to the resolution of the size of an element.

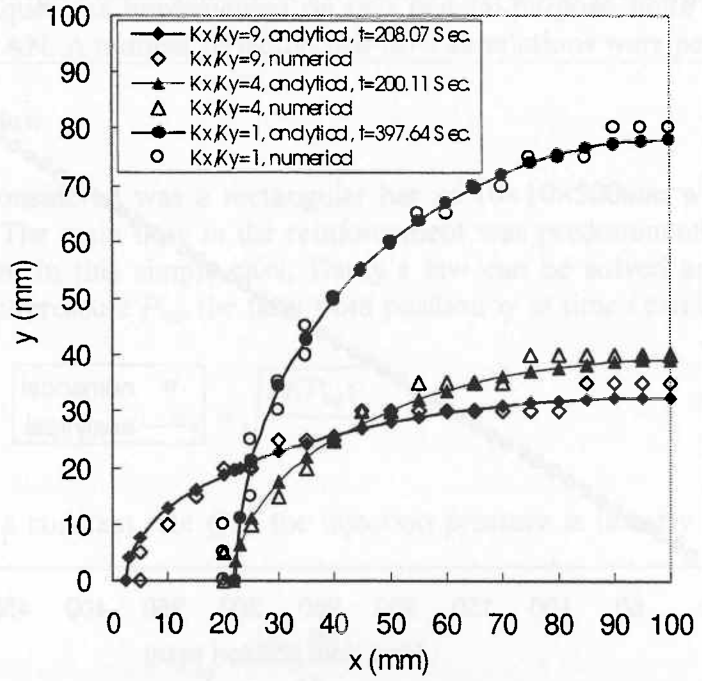

Figure 3. Comparison of numerical and analytical flow fronts for the laminate.

Table 1. Material properties for the flat laminate

Resin viscosity μ (*mPa.sec.*)	1.0×10^{-6}
Preform porosity ε	0.5
Perform permeability in y direction K_y (mm^2)	3.5×10^{-4}
K_x/K_y	1, 4, 9

I BEAM

The resin flow through an I shaped fibrous preform was simulated. The geometry of the I beam is illustrated in Fig. 4. Two injection ports were assumed to be located in the middle of the top and the bottom surfaces of the web respectively.

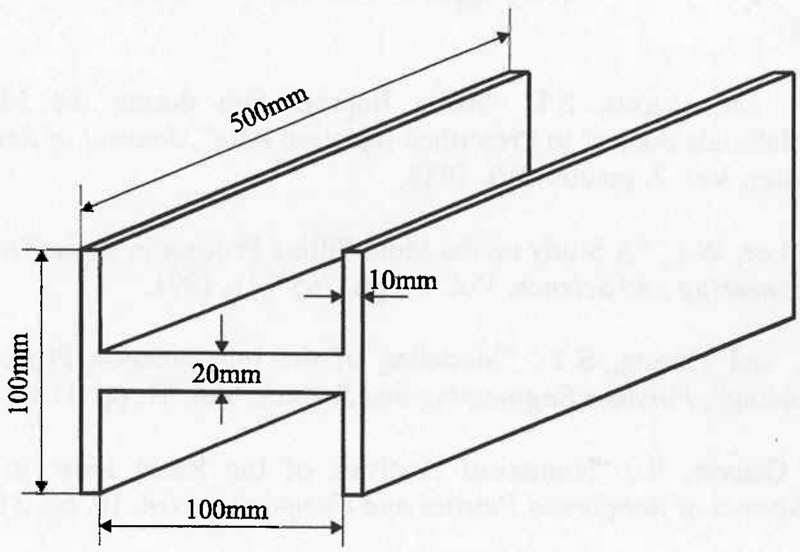

Figure 4. Geometry of the I beam.

The entire beam was modeled using a combination of 4-noded quadrilateral elements for the flanges and 8-noded brick elements for the web. The preform was assumed to be isotropic. The material properties used were those for the centrally injected laminate.

Both the constant flow rate (Q_{inj}=1000mm^3/*sec.*) and constant pressure injections (P_{inj}=200*kPa*) were simulated. For the constant flow rate injection, the total filling time obtained by the simulation was the same as that calculated using the condition of incompressibility (500 *sec.*). For the constant pressure injection, a total filling time of 848 seconds was predicted.

CONCLUSIONS

1. The finite element/nodal volume (FE/NV) technique presented in this paper for the isothermal flow simulation is generally simpler and numerically more efficient than the previously proposed finite element/control methods because it does not require the construction of the control volumes and the calculation of the flow vectors. Satisfaction of the resin mass conservation is guaranteed by the technique.

2. A scheme is proposed to prevent the FE/NV technique from possible "locking" where by the flow calculation can not be continued because the unrealistic flux solution from the finite element method. While it is not clear whether such a numerical locking exists in the various finite element/control volume methods, it was not mentioned in [5] where the fluxes were also obtained from the finite element solutions. The condition of resin mass conservation is maintained by the scheme proposed.

3. The FE/NV technique is implemented in general-purpose finite element packages. This approach resulted in considerable savings in the software development time and cost.

4. The numerical examples presented in this paper demonstrate that the proposed procedure is versatile and robust and produces numerical results which are in excellent agreement with the analytical solutions.

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