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RESIN FLOW DURING INJECTION PULTRUSION WITH MULTIPLE INJECTION GATES

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SUMMARY: During an injection pultrusion process, it is often necessary to employ multiple injection gates in order to further improve the wet-out and to reduce the injection pressure. It is therefore important to investigate the resin flow patterns during the injection pultrusion using multiple injection gates. Unfortunately, little has been reported for this issue either experimentally or numerically. In the present paper, the resin flow patterns during injection pultrusion with multiple gates are investigated numerically using a nodal volume procedure. The procedure is first validated by comparing the predicted flow parameters with those obtained experimentally for the injection pultrusion of a slat using three injection gates. It is then used to predict the flow patterns for the injection pultrusion with various injection gate arrangements. Also modeled is the effect of racetracking on the flow patterns during injection pultrusion. It is shown that the numerical procedure developed at the CRC-ACS is a useful tool for design and optimization of the injection pultrusion processes.

KEYWORDS: Injection Pultrusion, Numerical Analysis, Resin Flow

INTRODUCTION

Injection pultrusion is a relatively new and efficient manufacturing process for making polymer composites. During injection pultrusion, resin is injected directly into the fibre reinforcement as it is continuously pulled through an injection/pultrusion die, and comes out of the die as a cured composite part of constant cross section. Injection pultrusion offers a number of advantages over conventional pultrusion. These include reduced resin volatile emissions, improved wet-out of the fiber reinforcement and possibly higher pull speed. However, additional tooling and process variables associated with the injection, such as the positions of the injection gates, the injection flow rates or injection pressure need to be designed and controlled correctly. For example, for a given pull speed, a slow injection may result in the reinforcement being poorly filled before it reaches the gelation front. On the other hand, excessive resin may flow out of the die entrance if the injection pressure is too great or the distance between the die entrance and the injection gate is too short.

A number of recent attempts have been made to investigate the injection pultrusion process numerically. A numerical model for non-isothermal flow simulation of injection pultrusion has been developed at the University of Minnesota [1,2]. The model is based on the conventional finite element/control volume (FE/CV) method [3]. Test examples in two and three dimensions have been simulated without theoretical or experimental validation. A two-dimensional finite element/control volume model for non-isothermal flow simulation of injection pultrusion has been developed by Lee and his co-workers at the Ohio State University [4]. It was applied to model the injection pultrusion of fiberglass-vinyl ester composite slats. Experiments were conducted to obtain the material parameters used in the model and to verify the simulation results. A different approach has been adopted at the CRC-ACS in the development of a numerical procedure for flow simulation of injection pultrusion. The procedure is based on the finite element/nodal volume (FE/NV) method and is implemented on the general purpose FE package MSC/NATRAN [5]. It is validated against a one-dimensional analytical solution.

For the pultrusion of advanced composites, the fiber reinforcements usually have relatively lower permeability due to the high fiber volume fraction used, resulting in a high injection pressure. The cross section of the pultruded composite parts can be large and/or complicated. In these cases, it is often necessary to employ multiple injection gates in order to improve the fill and to reduce the injection pressure. It is therefore important to investigate the resin flow patterns during injection pultrusion using multiple injection gates. Unfortunately, little has been reported for this issue either experimentally or numerically. In the present paper, the resin flow patterns during injection pultrusion with multiple gates are investigated numerically using the numerical procedure developed at the CRC-ACS. Theoretical background and numerical implementation of the procedure are described. The procedure is validated by comparing the predicted flow parameters with those obtained experimentally. It is then used to predict the flow patterns for the injection pultrusion of composite slats with various injection gate arrangements. It is shown that the numerical procedure developed at the CRC-ACS is a useful tool for tooling and process design/optimization of injection pultrusion processes.

THE NUMERICAL PROCEDURE

Governing Equations

The following assumptions are made in deriving the governing equations:

(1) The pultrusion die is of constant cross section;
(2) The resin is a Newtonian fluid;
(3) The flow is isothermal in the injection section of the die.

On the macroscopic scale, the resin flow through the fibrous reinforcement can be described by the following Darcy's law:

$$\mathbf{u}' = \begin{Bmatrix} u_x' \\ u_y' \\ u_z' \end{Bmatrix} = \left\{ -\frac{K_x}{\mu}\frac{\partial p}{\partial x} \quad -\frac{K_y}{\mu}\frac{\partial p}{\partial y} \quad -\frac{K_z}{\mu}\frac{\partial p}{\partial z} \right\}^T \tag{1}$$

In the above equation, μ is the viscosity of the resin, K_x, K_y and K_z are the permeabilities of the reinforcement in principal axes, p is the resin pressure, and $\boldsymbol{u}'$ is the velocity of the resin.

In injection pultrusion, the pultruded part is moving at the pulling speed v. Assuming that the part is pulled in x direction, the total velocity of the resin movement, referenced to the stationary coordinate system, can then be written as:

$$\mathbf{u} = \left\{ -\frac{K_x}{\mu}\frac{\partial p}{\partial x} + v \quad -\frac{K_y}{\mu}\frac{\partial p}{\partial y} \quad -\frac{K_z}{\mu}\frac{\partial p}{\partial z} \right\}^T \qquad (2)$$

The injected resin is considered as incompressible, i.e.,

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \qquad (3)$$

Combining Eqns. 2 and 3 and noting that v is usually a constant, one obtains the following pressure equation:

$$\frac{\partial}{\partial x}\left(\frac{K_x}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{K_y}{\mu}\frac{\partial p}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{K_z}{\mu}\frac{\partial p}{\partial z}\right) = 0 \qquad (4)$$

Let us define a scalar f which is the ratio of the current resin content to the saturated resin content in a small volume considered. f represents the concentration of the resin in the reinforcement and is often referred to as fill factor in a numerical scheme based on fixed mesh. Its value ranges from 1 for saturated reinforcement to 0 for dry reinforcement.

For a small volume Ω with a resin concentration of f in the stationary Cartesian coordinate system, the conservation of resin mass in the volume requires that:

$$\frac{\partial}{\partial t}\int_{\Omega} \rho f \phi d\Omega + \int_{S_x} \rho f \phi v dS_x + \oint_S \rho\left(u'_x dS_x + u'_y dS_y + u'_z dS_z\right) = 0 \qquad (5)$$

where ϕ is the porosity of the reinforcement, ρ is density of the resin and S is the surface of Ω.

Let:

$$q = \oint_S u'_x dS_x + u'_y dS_y + u'_z dS_z = \oint_S \mathbf{u}' d\mathbf{S} \qquad (6)$$

q is the rate of the resin flow entering the small volume caused by the Darcy's flow $\boldsymbol{u}'$.

Eqn. 5 can be rewritten as:

$$\frac{\partial}{\partial t}\int_{\Omega} f \phi d\Omega + \int_{S_x} f \phi v dS_x + q = 0 \qquad (7)$$

Eqn. 7 indicates that for injection pultrusion the change in the resin content in the small volume is caused by both the part movement v and the Darcy's flow $\boldsymbol{u}'$.

Numerical Technique

A finite element/nodal volume method has been developed to solve the above governing equations numerically. The technique is based on Eulerian fixed meshes. The pultruded part is discretised into finite elements/nodal volumes (FE/NV) [6]. In time domain, the transient resin flow process during injection pultrusion is treated as a series of steady problems by time incrementation. Within a time step, the pressure is solved by the finite element method. Similar to the other numerical techniques developed at CRC-ACS for process modeling, this is done by employing the conduction heat transfer solver of a commercial finite element package, MSC/NASTRAN, and hence the development of a finite element program is avoided.

The flow calculation is performed on the nodal volumes. Each of the nodal volumes is assigned a fill factor f. The flow front is considered as located at the nodes whose fill factors are between 0 and 1. The flow calculation usually involves the determination of the flow fluxes to the nodal volumes at the flow front and the advancement of the flow front. A feature of the finite element/nodal volume method is that the nodal fluxes at the flow front, obtainable from the finite element solution, are used directly in the flow calculation. Therefore, the method is much simplified in that it does not involve the calculation of the flow surfaces and flow fluxes as those required by the finite element/control volume method [6]. The flow front is then advanced using the algorithm described below.

Nodal volumes are constructed based on the finite element mesh to advance the flow front: see Fig. 1. Since it is assumed that the pultrusion die is of constant cross section, the discretisation applied on the cross section is kept constant. The flow front advancement is achieved by updating the fill factors of the nodal volumes at the end of each time step.

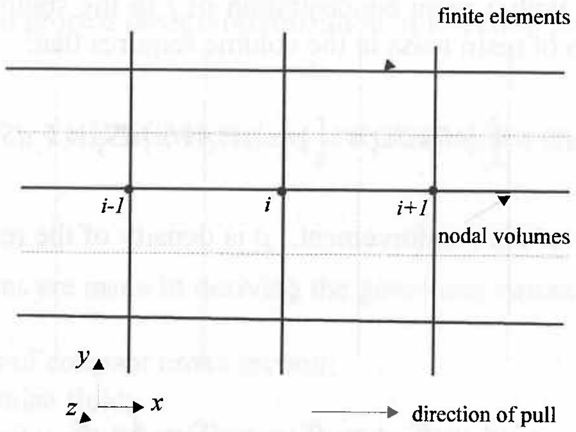


Figure 1 Finite element/nodal volume mesh.

Assuming that the resin is uniformly distributed in a nodal volume, for nodal volume i, the first two terms of Eqn. 7 can be integrated to give:

$$\frac{\partial f_i}{\partial t}\phi\Omega_i + (f_i - f_{i-1})\phi v A + q_i = 0 \tag{8}$$

where A is the cross section of the nodal volume in the pulling direction.

Dividing both sides of the above equation by $\phi\Omega_i$, this can be simplified to:

$$\frac{\partial f_i}{\partial t} = \frac{(f_{i-1} - f_i)v}{L_i} - \frac{q_i}{\Omega_{ri}} \tag{9}$$

where L_i is the length of nodal volume i in the pulling direction and Ω_{ri} is the saturated resin volume.

Applying a mixed time integration scheme in the time domain, at time step n we have:

$$\left[\frac{\Delta f_i}{\Delta t}\right]^n = \left[\frac{(f_{i-1} - f_i)v}{L_i}\right]^{n-1} - \left[\frac{q_i}{\Omega_{ri}}\right]^n \tag{10}$$

INJECTION PULTRUSION OF COMPOSITE SLATS

Model Description

The problem considered in the present work was the injection pultrusion of composite slats with different numbers of injection gates and various injection gate arrangements. The dimension of the slat was 77 mm wide by 1.72 mm thick. The reinforcement was made of unidirectional and triaxial non-crimp fiberglass fabrics: SP Systems UT-250 (234 g/m^2) and Cotech ETLX583 (584 g/m^2), compacted to a fiber volume fraction of 47.4%. The lay-up sequence used was: one triaxial, four unidirectional and one triaxial fabrics. The 0° plies of the fabrics were aligned with the pulling direction. The fluid used for injection was a mixture of a pharmaceutical grade glycerine and water, with the viscosity of the fluid at the injection temperature (21.1°C) being calibrated to 0.034 Pa.s.. The injection pressure was 60kPa.

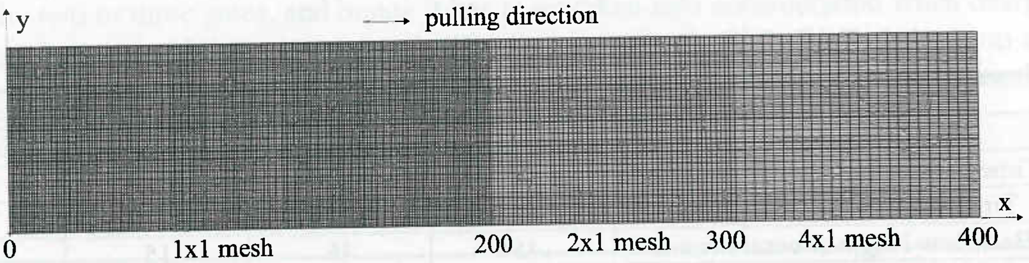


Figure 2 2D FE/NV model for a composite slat.

Since the slat was relatively thin, an in-plane two-dimensional model was considered to be adequate for the flow simulation. The FE/NV model was applied to a section of the slat die 400mm in length. To reduce the size of the model without losing numerical stability, FE/NV meshes of three different sizes in the pulling direction were used to discretise the slat: see Fig. 2. Permeability of the hybrid reinforcement in the pulling direction, K_x, was measured as $3.74\times10^{-11} m^2$. The ratio of K_x/K_y was taken as 3.6, the same as that experimentally determined for the same reinforcement at 55% fiber volume fraction [7]. The effect of racetracking was considered in the model by specifying a considerably larger permeability for the two columns of elements on both edges of the slat.

During injection pultrusion, the flow pattern of the resin is initially transient and approaches a quasi-steady state when the upper stream flow front becomes stable. In the present work, a steady state was considered to have been reached if the total resin flow rate on the upper stream flow front was less than 1% of the rate of resin injection.

Model Calibration and Validation

Experiments were conducted using the injection pultrusion set-up shown in Fig. 3. The injection die was made of an aluminum base plate and a glass top. Lines at 5mm interval were drawn on the glass to facilitate the measurement of the flow distance. Three injection gates, arranged in line and at 19mm, 38mm and 58mm respectively in the transverse direction, were used. The reinforcement was pulled at 2mm/sec and 4.2mm/sec respectively. In the numerical model, the injection gates were placed 100mm from the entry end.

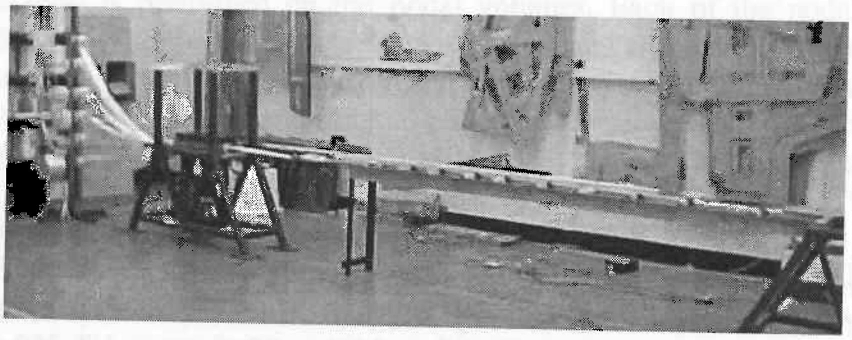


Figure 3 Injection pultrusion set-up

Racetracking was only observed during the experiment with the lower pulling speed (v=2mm/sec). The resulting backflow lengths on the edges were 75mm. This value was used in the numerical trial-and-error conducted to determine the permeability to be used for the elements on the edges. A permeability value of $5.61\times10^{-10}m^2$ was found to match the test result and was used for the rest of the simulation.

Table 1 Comparison of numerical and experimental results

Pull speed	v=2.0mm/sec.		v=4.2mm/sec.	
	experimental	numerical	experimental	numerical
Time for fluid to reach y=0 (sec.)	14	14.4	N.A.	20.0
Time to reach y=77mm (sec.)	19	14.5	N.A.	20.4
Backflow length at centre (mm)	45	46	15	19
Upper stream racetracking or backflow length on edges (mm)	75	75	N.A.	observed

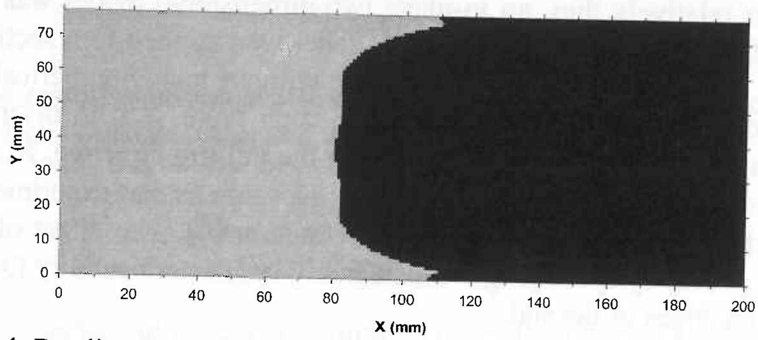


Figure 4 Predicted steady state upper stream flow front for v=4.2mm/sec

The numerical and experimental results are compared in Table 1. For the case of v=2mm/sec, the predicted results, i.e. backflow length at the centre and the time to reach the edges, were in reasonably good agreement with the experimental ones. For v=4.2mm/sec, the predicted backflow length at the center was considerably larger than the experimental one. A slight racetracking effect was also observed at the steady state upper stream flow front shown in Fig. 4. It is possible that the experiment conducted for v=4.2mm/sec did not reach the steady state.

Injection with Different Number of Gates

Using a single injection gate in liquid composite molding significantly reduces the chances of convergent flow fronts which may cause the air to be trapped in the part to form voids [8]. However, this is often not desirable in practice since it requires longer filling time which reduces productivity. Furthermore for injection pultrusion, it may often be necessary to use multiple injection gates to ensure that the part is fully filled before it gels. In the present study, injection strategies with only the central gate and with two and three injection gates arranged in line were investigated.

Plotted in Fig. 5 are the predicted transient flow front locations up to 45 seconds. For the process conditions used, the slat could not be fully filled using only one injection gate (Fig. 5a). A fully filled part was obtained by injecting with multiple injection gates as shown in Fig. 5b and c.

Convergent flow fronts were observed by using either two or three injection gates. However, it should be noted that these only occurred at the early stage of the transient flow period. For injecting at two and three gates, the individual flow fronts merged in about 18 and 3 seconds respectively.

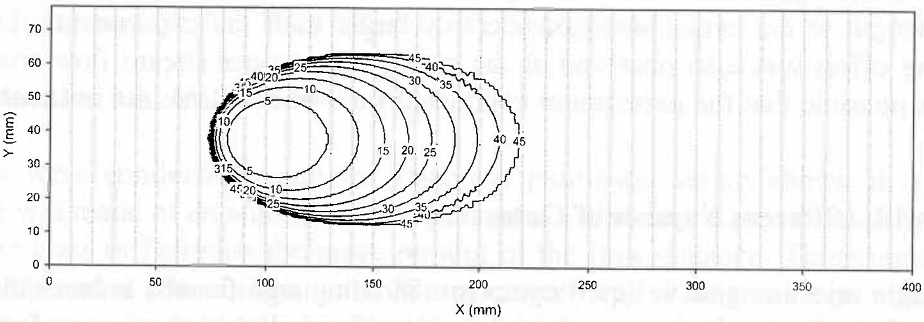
It took about one minute in each case for the flow to reach the steady state. Fig. 6 shows the predicted steady state upper stream flow fronts. The effect of racetracking was obvious for injecting by two or three gates, and hence it has to be taken into consideration when designing the distance between the injection gate and the die entry. As listed in Table 2, both on edges and at the back of an injection gate, the predicted steady state backflow lengths increased with the number of injection gates used.

Table 2 Predicted backflow length at steady state

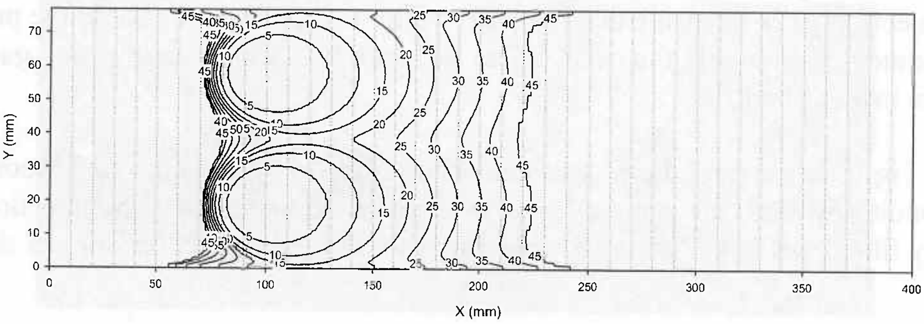
	1 gate	2 gates	3 gates
At the edges (mm)	none	64	75
Ahead of the injection gates (mm)	27	38	46

Injection with "V" Arrangement of Three Gates

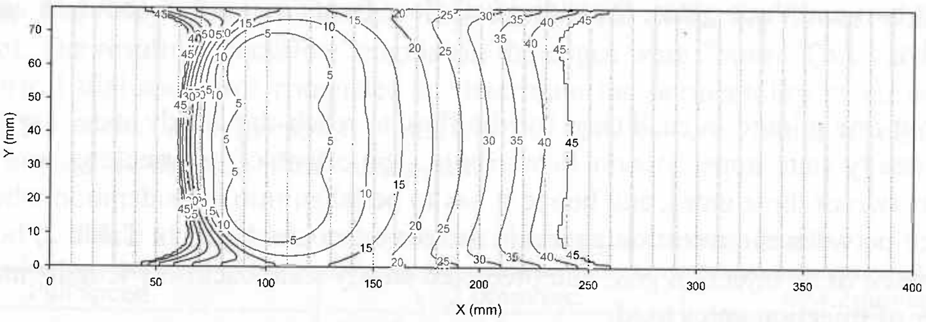
It has been shown that by injecting resin simultaneously at more than one gate, there are initially the same number of individual flow fronts which merge later. Although there may be air entrapment caused by the convergent flow, it should not result in a serious problem for injection pultrusion since the transient period is relatively short. Nevertheless, it is possible to avoid the convergent flow by using a "V" arrangement of three injection gates. In such an arrangement, the two side gates are shifted towards the pulling direction to form a "V" with the central gate. The resin is injected initially through the central gate only. The side gates are also opened after the flow front caused by the central injection has passed these gates.



a. one gate at y=38mm



b. two gates at y=19 and 58mm respectively



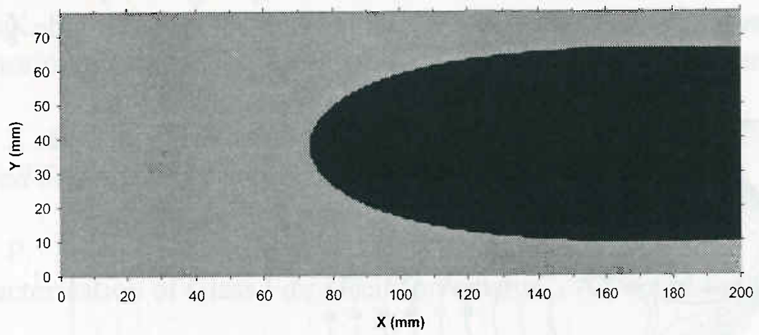
c. three gates at y=19, 38 and 58mm respectively

Figure 5 Transient flow fronts for different number of injection gates

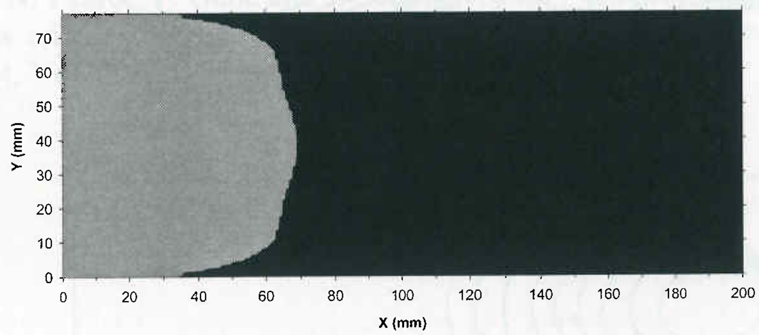
The locations for the side gates and the time for them to be opened can be determined by examining the transient flow front of the single central gate injection. It can be seen from Fig. 5a that if the two side gates were shifted downstream by 50mm (i.e. located at x=150mm, y=19mm and 58mm respectively), they would be passed by the global flow front corresponding to the central injection in about 30 seconds. From the same figure, it is also obvious that shifting the side gates down stream was a necessary measure to be taken since the global flow front produced by the single central gate injection would not fully cover the two side gates if they were arranged in line with the central one.

Simulation was conducted for the "V" shaped gate arrangements with the central gate located at x=100mm and y=38mm, and the side gates at x=150mm, y=19mm and 58mm respectively.

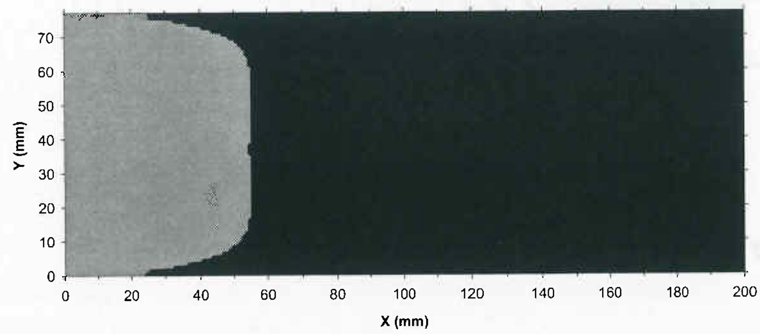
Two injection strategies were simulated: three gates opened simultaneously and the side gates opened 30 seconds later than the central one, referred to as simultaneous injection and sequential injection respectively. Given in Fig. 7 are the transient flow fronts up to 45 seconds for the two injection strategies investigated. It is shown that the convergent flow fronts which existed for the simultaneous injection are avoided by opening the side gates 30 seconds later than the central one. Consequently, the air entrapment caused by the convergent flow should be eliminated. It should be noted that although the wetted area shown in Fig 7b for the sequential injection was relatively small at 45 seconds, it should approach the same steady state area as the simultaneous injection.



a. one gate



b. two gates



c. three gates

Figure 6 Predicted steady state upper stream flow fronts.

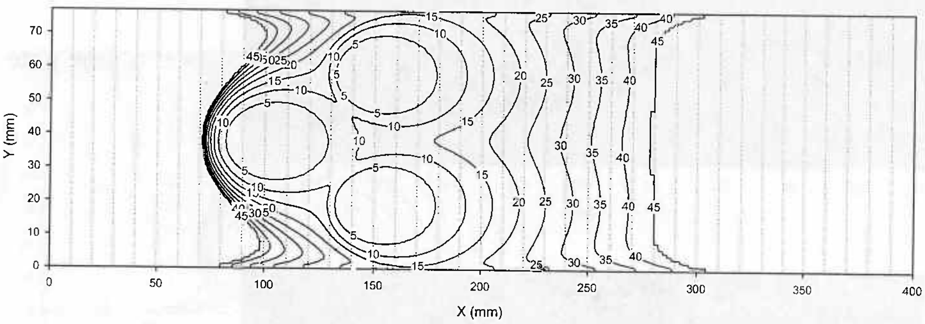
CONCLUSIONS

The following conclusions can be drawn from the work presented in this paper:

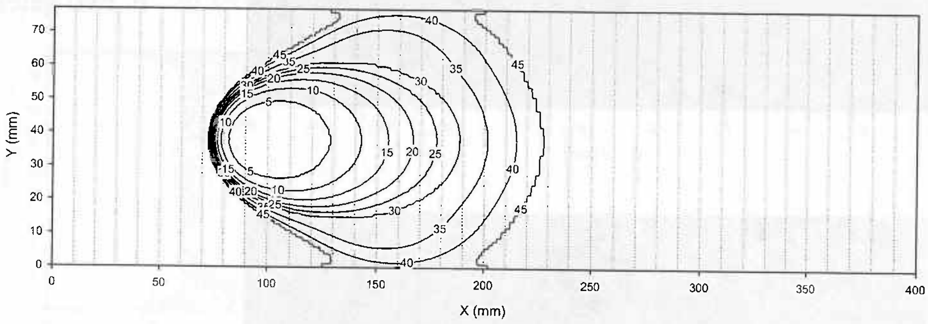
1. The numerical procedure developed for the flow simulation of injection pultrusion appears to be valid. The predicted and experimental flow parameters are in reasonably good agreement. Simulation can therefore be used to guide die design for injection pultrusion.

2. For the problem considered which was an analogue to a practical problem with P_{inj}=600kPa and μ=0.34 Pa.s., more than one injection gate is required to fully fill the composite slat.
3. The backflow lengths both on the edges and at the back of an injection gate increases with the number of gates. Placing a gate 100mm from the die entry appears to be enough to prevent the resin backflow out of the die entrance if the number of gates does not exceed three.

4. The transient convergent flow fronts associated with multiple gate injection can be avoided by arranging three injection gates in "V" shape and opening the side gates 30 seconds later than the central one.



a. gates opened simultaneously



b. gates opened sequentially

Figure 7 Transient flow fronts for "V" injection

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