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# NUMERICAL ANALYSIS OF FILLING PROCESS IN RESIN TRANSFER MOLDING WITH CONTROLLED INJECTION STRATEGIES

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**SUMMARY**: Minimization of mold filling time without losing the part quality is an important issue in resin transfer molding process. Among the various methods to achieve this, controlling of injection strategies has become a practical way. In this paper, different injection strategies are numerically simulated using the control volume finite element method. First, the switching injection strategy is introduced. In this strategy, the injection is started with a constant flow rate at a gate but it is switched to a constant pressure when the pressure reaches a maximum permissible value. As a result of using constant flow rate, the mold filling can be started with a low inlet pressure reducing the risk of fiber mat deformation or washout near the gate. By applying switching injection, two injection strategies including sequential switching injection and simultaneous adjusted switching injection strategies are investigated and their results are compared. The results show that the maximum reduction in filling time can be achieved by using the simultaneous adjusted switching injection strategy with a reduced number of vents.

**KEYWORDS**: Constant Pressure Injection, Constant Flow Rate Injection, Multiple Injection Gates, Single Injection Gate, Switching Injection Strategy.

## INTRODUCTION

Minimization of mold filling time along with low filling pressure, good fiber wetting, low void content and uniform flow front progression are the most important issues in the mold filling process of RTM. The mold filling process strongly depends on the mold geometry, material and processing parameters. Mold geometry and materials such as fiber preform and resin are dictated by part design while the processing parameters can be viewed as design variables. Gates locations, number of the gates, type and size of the gates, temperatures of the mold wall and preheated resin, injection pressure or flow rate are the common design variables.

Among the various methods to deal with these issues, the injection strategy is a very practical design approach in the RTM in which the resin can be injected through the gates into the mold under constant pressure or flow rate. Although simultaneous resin injection through the multiple gates fills the mold in the fastest way, but it increases the potential for the entrapment of air pockets due to the merging flow fronts coming from the injection gates and hence, increases the need for preparing several vents in the mold. In recent years, some improved injection strategies have been proposed by researchers to enhance the flow and overcome the problems occurred during mold filling in which the resin is injected through the gates under a controlled manner [1-4].

The filling process in RTM can be investigated by both numerical simulation and experimental analysis. Since the experimental analysis are often expensive and time-consuming, the numerical simulation has become an efficient tool to study the mold filling process. In the past decade, different numerical methods such as finite element method, boundary element method, boundary fitted coordinate finite difference method and control volume finite element method have been employed to simulate the mold filling process in the RTM. Of these, the methods based on finite element and control volume are the most popular to solve the filling stage because of their simplicity in handling the moving boundary problems[5-6]. In these techniques, a fixed grid approach is used in which there is no need to regenerate the mesh during flow progression, make the simulation to be rapid and effective for complicated geometries.

In the present paper, an attempt is made for analysis of controlled injection strategy in single and multiple gates using numerical simulation. The filling process of multiple gated mold is simulated by control volume finite element method (CV/FEM). The switching injection strategy is first introduced in which the resin is injected at a constant flow rate and then it is switched to a constant pressure when the inlet pressure reaches a maximum limited value. Finally, different injection strategies including sequential and simultaneous resin injection in multiple gates with switching injection at each gate are studied, the results of which are compared in terms of mold filling time, required number of vents and inlet pressure during mold filling.

## NUMERICAL SIMULATION

Numerical simulation of mold filling process is performed with the computer code RTMS developed in University of Amirkabir based on the CV/FEM [7]. Only a brief outline of the theoretical modeling and computational scheme is given here.

In the RTM, the flow of resin through fibrous media can be regarded as a fluid flow through porous media. Therefore, Darcy's law can be well used to describe the flow through fibrous reinforcements:

$$\vec{v} = -\frac{[K]}{\mu} \cdot \nabla p \qquad (1)$$

in which $\vec{v}$ is the superficial velocity vector, $\mu$ represents the viscosity, $[K]$ is the permeability tensor and $\nabla p$ is the pressure gradient. If Darcy's law is included into the mass conservation equation of incompressible flow, the following equation is obtained:

$$\nabla\left(\frac{[K]}{\mu} . \nabla p\right) = 0 \qquad (2)$$

This equation is solved to give the pressure field in the filled region of the cavity during mold filling. The boundary conditions for Eqn. 2 are as follows.

$$\begin{aligned} p = p_0 \quad &\text{or} \quad v = v_0 && \text{at inlet gate} \\ \frac{\partial p}{\partial n} &= 0 && \text{at mold wall} \\ p &= 0 && \text{at flow front} \end{aligned} \qquad (3)$$

Darcy's law is a steady state equation, while the filling process is a transient problem. This difficulty in solution algorithm can be removed by considering a quasi-steady state process in which one assumes series of sequential steady conditions during filling process. For this purpose, the time increment must be chosen in such a way that one control volume is completely filled. In practice, more than one control volume may be filled in a single time step. This restriction on time increment ensures the stability of the quasi-steady approximation.

In the CV/FEM, the mold cavity is first divided into a number of elements and then control volumes are created around the nodal points. The numerical procedure assumes that the control volume enclosing the inlet nodes are fully filled with the resin at the beginning of mold filling. Eqn. 2 is used to solve the pressure field for the resin filled region. After the pressure field is calculated, the velocity field can be determined by Darcy's law. Then the resin volume entering into control volumes at the flow fronts can be determined by the calculated velocity and choosing the time step. The ratio of occupied volume by the resin for each control volume to its total pore volume is defined as fill fraction f representing the status of each control volume within the entire mold. For an empty control volume f = 0, and f is 1 when the control volume is completely filled with resin. According to this approach, the flow front lies over the control volumes where they are adjacent to filled control volumes and are not completely filled.

Table 1 Processing variable and material properties

| Quantity | Value |
|---|---|
| Viscosity (Pa.s) | 0.4 |
| Permeability | $10^{-9}$ |
| Porosity | 0.65 |
| Maximum permissible inlet pressure during mold filling (kPa) | 80 |

## STANDARD MOLDING CONDITIONS

In order to provide a basis for comparing the results obtained from the various injection strategies, the standard conditions of mold geometry, processing variable and material properties are defined here. The thickness of the mold is 6 mm and the other dimensions are illustrated in Fig. 1. Four elemental nodes with equal sizes (1.5625 $cm^2$) are chosen as the gates in different locations of the top surface of the mold. Of course, the optimized location of each gate can be obtained by an optimization method combined with the numerical simulation. The process variable and material properties used in this study are given in Table 1. Due to some undesirable events such as fiber mat deformation or washout and mold deflection, the inlet pressure cannot be exceeded from a maximum value during mold filling.

For this reason, a maximum permissible pressure is considered here for each injection gate with a value described in the table. Therefore, all injection strategies are analyzed within this constraint.

## RESULTS AND DISCUSSION

### Injection Strategies in Single Gate

In such case, it is assumed that only the gate three is opened and the mold filling is investigated under both constant pressure injection and constant flow rate injection strategies. The maximum permissible pressure 80 kPa is used at inlet gate for constant pressure strategy, however mold filling process is simulated with different values of volumetric flow rate for constant flow rate strategy. First, volumetric flow-rate is chosen so that the mold filling time becomes the same as the value obtained by the constant inlet pressure strategy, 243 sec.

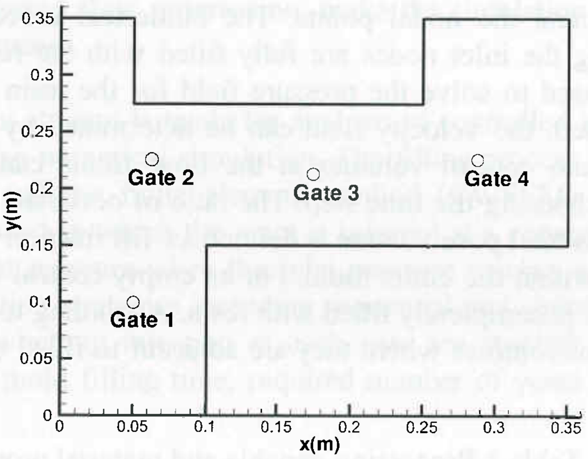
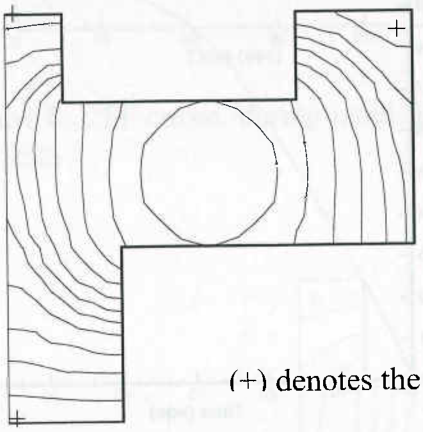


Figure 1 Geometric details of the mold.

The simulation results obtained from both injection strategies are shown in Figs. 2-5. Figs. 2-3 show the flow pattern during the mold filling. For both cases, only three vents are required which their location is shown in the figures. The mold filling can be properly illustrated using the cavity filled fraction (CFF) during mold filling, as demonstrated in Fig. 4. As expected, the CFF for constant flow rate strategy is linear representing that the volume of fluid entered into the mold are equal throughout the mold filling. For the case of constant pressure, mold filling is faster at early stages of the filling process and it quickly decreases with time. This is due to the large pressure gradient at the start of filling process which is a characteristic of constant pressure injection. Fig. 5 shows the inlet pressure for both constant pressure and flow rate strategies during mold filling. As expected, the inlet pressure for injection pressure is constant throughout the mold filling. As can be seen in Fig. 5, although the inlet pressure is very low at the early stage of filling process for constant flow rate injection, it exceeds from the maximum permissible inlet pressure near the end of mold filling. To overcome this problem, we have to reduce the flow rate which results in a longer mold filling time. In order to use from the benefit of low inlet pressure in the constant flow rate strategy, we introduce the switching injection strategy in which the injection is started with constant flow rate but it is switched to constant pressure when the inlet pressure reaches to the maximum permissible value. This enables us to start the mold filling at low pressure and reduce the risk of fiber mat deformation or washout near the gate while the mold filling time is still kept low.

For switching injection strategy in the case of a single gate, we choose a flow rate in such a way that its CFF curve approximately fits that of constant pressure strategy at the early stage of mold filling. For our case, the desired value of flow rate is $1.75 \times 10^{-6}$ $m^3$/sec which the CFF curve and inlet pressure during mold filling are shown in Figs. 4-5. The simulation results of switching injection strategy are also shown in Figs. 4-5. As shown in Fig. 4, mold filling time for switching strategy is approximately the same as the value obtained from the constant pressure (difference is less than 1%), however here, the inlet pressure and pressure gradient at the start of mold filling is low.



(+) denotes the vent location.

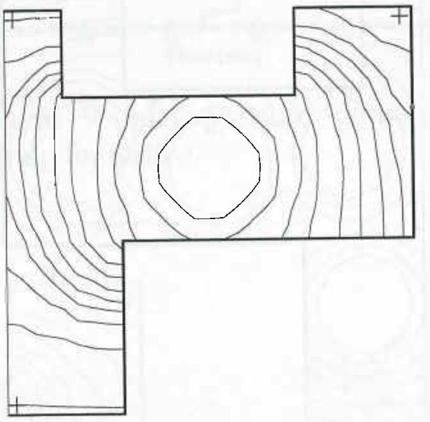
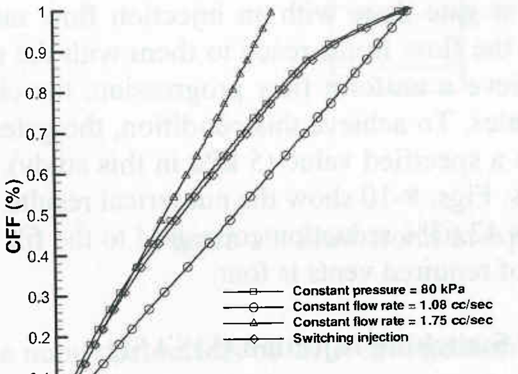


Figure 2 Flow fronts at equal time intervals of 20 sec for constant pressure injection (80 kPa)

Figure 3 Flow fronts at equal time intervals of 20 sec for constant flow rate (1.08 cc/sec)



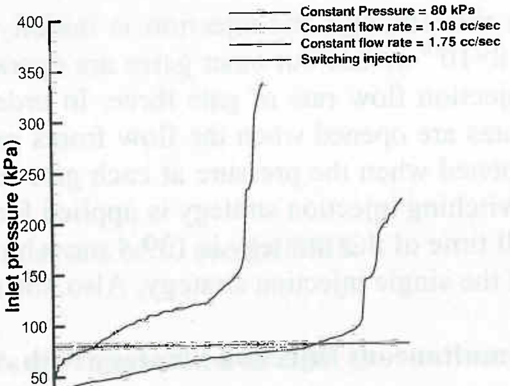


Figure 4 CFF curves during mold filling for different single injection strategies

Figure 5 Inlet pressure during mold filling for different single injection

## Simultaneous Injection Strategy with Maximum Injection Value (SISMIV)

For this case, all injection gates are opened and the resin is injected with a constant pressure injection of 80 kPa at each gate. The simulation results are shown in Figs. 6-7. As can be seen in the figures, the mold filling time is 52.8 sec while nine vents are required to prevent the air entrapment. The comparison between the results obtained by the single and simultaneous injection strategies shows that a filling time reduction of 78.3% is achieved by the SISMIV, but the number of required vents are increased. It seems that the SISMIV is the fastest way to fill the mold for a fixed number of gates and the single injection strategy is the slowest one. Since the air entrapment in the SISMIV can be occurred due to the merging of flow fronts coming from the gates, it can be prevented by managing the injection strategy for each gate. To do this, two different injection strategies including sequential injection and simultaneous adjusted injection strategy combined with the switching injection strategy for each gate are numerically studied.

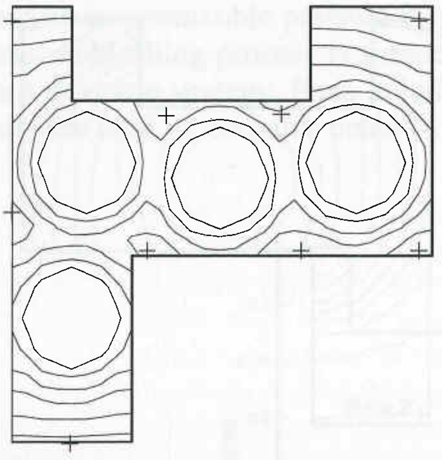


Figure 6 Flow fronts at equal time intervals of 6 sec for SISMIV (80 kPa)

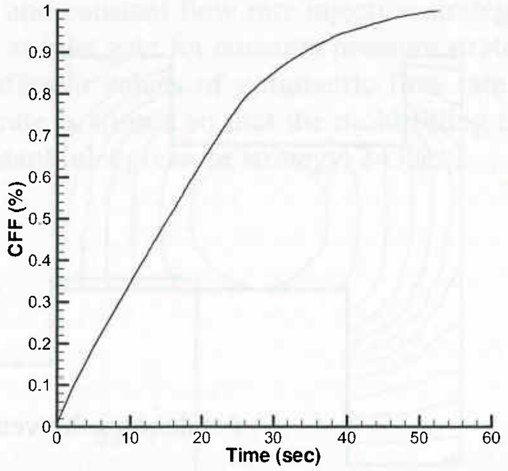


Figure 7 CFF curve during mold filling for SISMIV (80 kPa)

**Sequential Switching Injection Strategy (SSIS)**

In this strategy, the injection is initially started at gate three with an injection flow rate of $1.8\times10^{-6}$ $m^3$/sec but other gates are opened when the flow fronts reach to them with the same injection flow rate of gate three. In order to achieve a uniform flow progression, the closed gates are opened when the flow fronts pass the gates. To achieve this condition, the gates are opened when the pressure at each gate reaches to a specified value (5 kPa in this study). The switching injection strategy is applied for all gates. Figs. 8-10 show the numerical results. The fill time of this strategy is 139.4 sec which shows 42.63% reduction compared to the fill time of the single injection strategy. Also, the number of required vents is four.

**Simultaneous Injection Strategy with Adjusted Switching Injection (SISASI)**

In order to reduce the need for vents in the SISMIV, the resin is injected simultaneously through the gates with an adjusted flow rate within the permissible injection value for each gate. Adjusting the flow rate makes a uniform filling pattern and prevents the air entrapment remarkably. In our standard molding conditions, four different values of flow rate are chosen as: $1.2\times10^{-6}$ $m^3$/sec for gate one, $0.3\times10^{-6}$ $m^3$/sec for gate two, $1.8\times10^{-6}$ $m^3$/sec for gate three and $0.7\times10^{-6}$ $m^3$/sec for gate four. These flow rates are obtained by trial and error using the numerical code used in this study, but they can be optimized by an optimization method. Switching injection strategy is also used for all gates. Simulation results of this strategy are shown in Figs. 11-13. For this case, mold filling time is 84.6 sec that shows 65.2% reduction with respect to fill time of single injection strategy. The number of required vents is reduced to four compared with nine in the SISMIV.

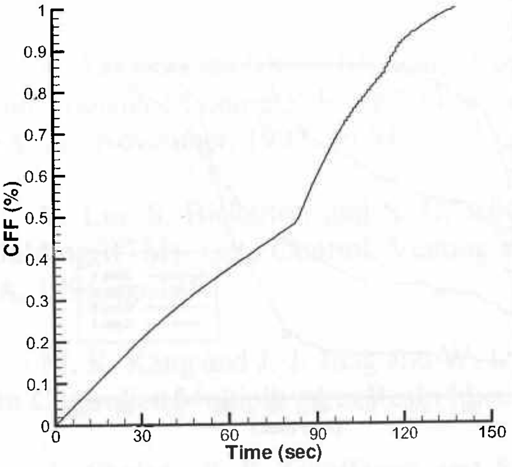


Figure 8 CFF curve during mold filling for SSIS

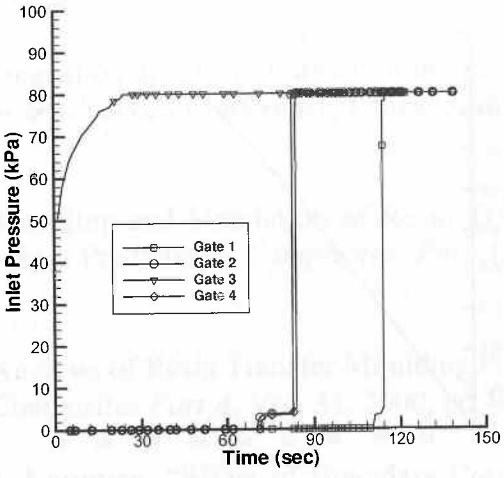


Figure 9 Inlet pressure during mold filling for SSIS

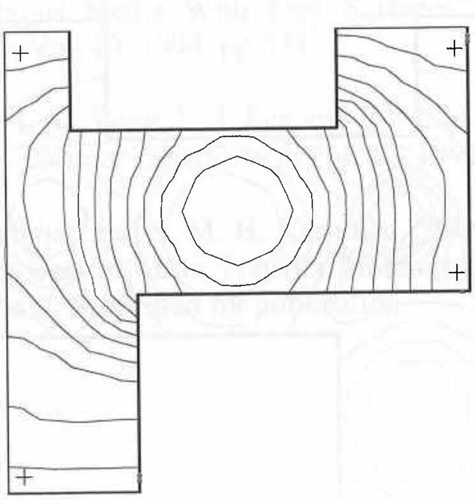


Figure 10 Flow fronts at equal time intervals of 10 sec for SSIS.

The numerical results of different injection strategies are summarized in Table 2.

Table 2 Number of required vents and mold filling time for different injection strategies

| Injection Strategy | Number of required vents | Mold filling time (sec) | Reduction in fill time with respect to single injection (%) |
|---|---|---|---|
| **Single injection** | 3 | 243 | — |
| **SSIS** | 4 | 139.3 | 42.63% |
| **SISASI** | 4 | 84.6 | 65.2% |
| **SISMIV** | 9 | 52.8 | 78.3% |

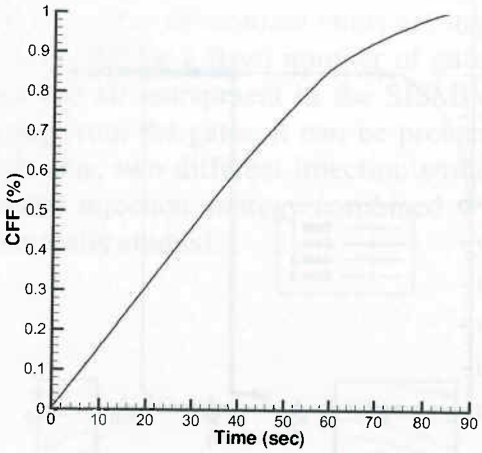


Figure 11 CFF curve during mold filling for SISASI.

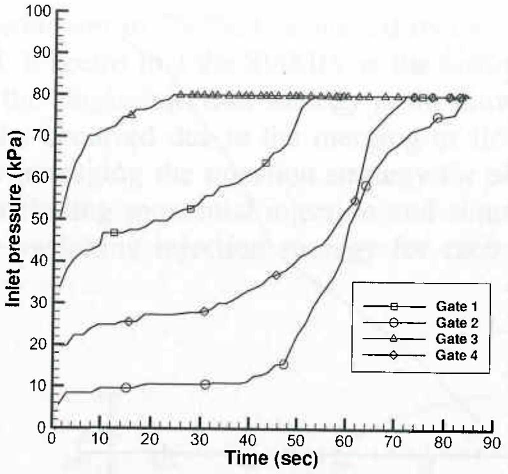


Figure 12 Inlet pressure during mold filling for SISASI.

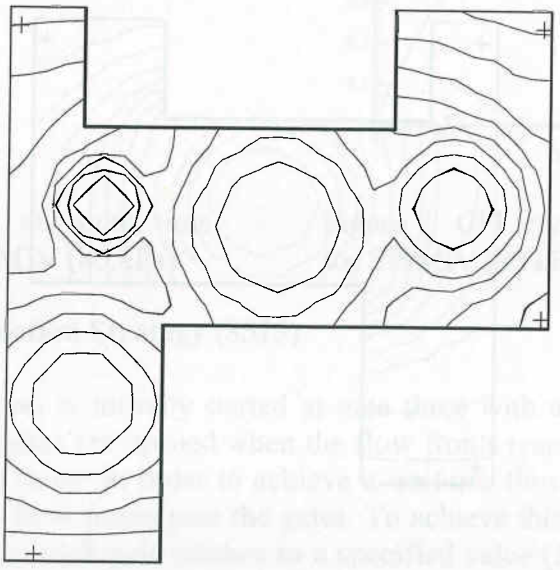


Figure 13 Flow fronts at equal time intervals of 10 sec for SISASI.

## CONCLUSIONS

Injection strategies to enhance the flow during mold filling process and prevent dry spots formation have been investigated using the computer code developed in this study to simulate the filling process with controlled multiple gates. The switching injection strategy has been introduced and its advantages during mold filling have been presented. Applying both switching injection and adjusting the injection value in multiple gate has been found to be an effective method for decreasing the mold filling time, lowering inlet pressure at early stages of mold filling and reducing the need for further vents. These results further emphasize that the numerical simulation can be a time and cost effective tool for proper design of process variables for a desired injection strategy. Of course, the optimized process variables can be achieved by employing numerical simulation combined with a proper optimization technique.

## REFERENCES

1. A. W. Chan and R. J. Morgan, "Resin Impregnation and Void Formation in Enhanced Resin Transfer Molding Scheme", *Proc. of The 8-th Advanced Conference*, Chicago, Illinois, USA, 2-5 November, 1992, pp.69.

2. B. Liu, S. Bickerton and S. G. Advani, "Modeling and Simulation of Resin Transfer Moulding(RTM)- Gate Control, Venting and Dry Spot Prediction", *Composites Part A*, Vol. 27A, 1996, pp.135.

3. M. K. Kang and J. J. Jung and W. I. Lee, "Analysis of Resin Transfer Moulding Process with Controlled Multiple gates Resin Injection", *Composites Part A*, Vol. 31, 2000, pp.407.

4. A. Shojaei, S. R. Ghaffarian and S. M. H. Karimian, "Effect of Boundary Condition Type on Mold Filling in RTM Process", *Proc. Of The Second Asian-Australasian Conference on Composite Materials:(ACCM-2000),* Kyongju, Korea, Vol. 1, 2000, pp.173.

5. M. V. Bruschke and S. G. Advani, "A Numerical Approach to Model Non-Isothermal Viscous Flow Through Fibrous Media With Free Surfaces", *International Journal For Numerical Methods in Fluids*, Vol. 19, 1994, pp.575.

6. W. B. Young, K. Han, L. H. Fong, L. J. Lee and M. Liou, "Flow Simulation in Molds With Preplaced Fiber Mats", *Polymer Composites*, Vol. 12, 1991, pp.391.

7. A. Shojaei, S. R. Ghaffarian and S. M. H. Karimian, "Numerical Simulation of Three-Dimensional Mold Filling Process in Resin Transfer Molding Using Quasi-Steady State and Partial Saturation Formulations", Submitted for publication.