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FLEXIBLE INJECTION: A NOVEL LCM TECHNOLOGY FOR LOW COST MANUFACTURING OF HIGH PERFORMANCE COMPOSITES. PART II – NUMERICAL MODEL

F. Trochu [1, 2], B. Touraine [1] and S. Soukane [1]

[1] *Chaire sur les Composites à Haute Performance (CCHP),*
Centre de recherches en plasturgie et composites (CREPEC), École Polytechnique de Montréal,
C.P. 6079, Station Centre-Ville Montréal (Québec), H3C 3A7
[2] *Corresponding author's Email:* trochu@polymtl.ca

SUMMARY: A novel technology based on *Liquid Composite Molding* was developed for low cost manufacturing of high-performance composites. The description of this new approach called *flexible injection* has shown that two main flows occur during the fabrication process: Stokes flow in the compaction chamber or upper cavity and Darcy's flow such as in resin infusion through the fibrous reinforcement contained in the lower cavity [1]. The algorithm to model this new process is based on the solution of these two flows that are coupled through the deformation of the membrane separating the upper and lower chambers [2]. Unlike in classical *Resin Transfer Molding* (RTM), which is basically governed only by the injection pressure or flow rate, flexible injection allows setting optimum values to several process parameters: the injection pressure such as in RTM, the vacuum pressure such as in *Vacuum Assisted Resin Infusion* (VARI), the compaction pressure, the thickness of the two chambers and the viscosity of the compaction fluid. This large number of control parameters gives a wider processing window, but it makes also more complex the understanding and control of the fabrication process. Numerical simulation is expected here to assist in finding the best ranges of process parameters so as to decrease fill times and improve part quality.

KEYWORDS: Liquid Composite Molding (LCM), flexible injection, flow simulation, Darcy's equation, Stokes flow

INTRODUCTION

This work presents a comparison between modeling and experimental results for model calibration. Both experimental analysis and numerical simulations for a test case show that the compaction fluid, once released, accelerates the impregnation of the fibrous reinforcement by the resin until the compaction fluid and resin fronts cross each other. Once the compaction fluid passes over the resin front, it compresses the dry reinforcement. This results in a lower permeability that slows the resin flow. Further investigation is therefore needed for process optimization.

A series of numerical simulations were carried out to reproduce experimental results for the injection of a random fiber mat contained in a transparent test mold. Simulation and experimental results match correctly, showing that flexible injection is faster not only for a compaction fluid of lower viscosity, but also, as expected, when the compaction pressure is larger. Indeed, this analysis has demonstrated that a compaction fluid of higher viscosity compresses the reinforcement more efficiently in the first compaction stage, but slows down the impregnation after the compaction fluid has crossed the resin front. The opposite behavior is observed for a fluid of lower viscosity. In order to find the optimum value of viscosity, a parametric study was carried out by numerical simulation. The effect of compaction pressure was also evaluated. This final conclusions confirm experimental results showing that flexible injection in a double cavity mold can be one order of magnitude faster than classical RTM.

ANALYSIS OF FLEXIBLE INJECTION

In order to simulate properly the injection stage of this new process, one has first to identify the different types of flow occurring. From the numerical point of view, it is appropriate to differentiate between four main types of flow:

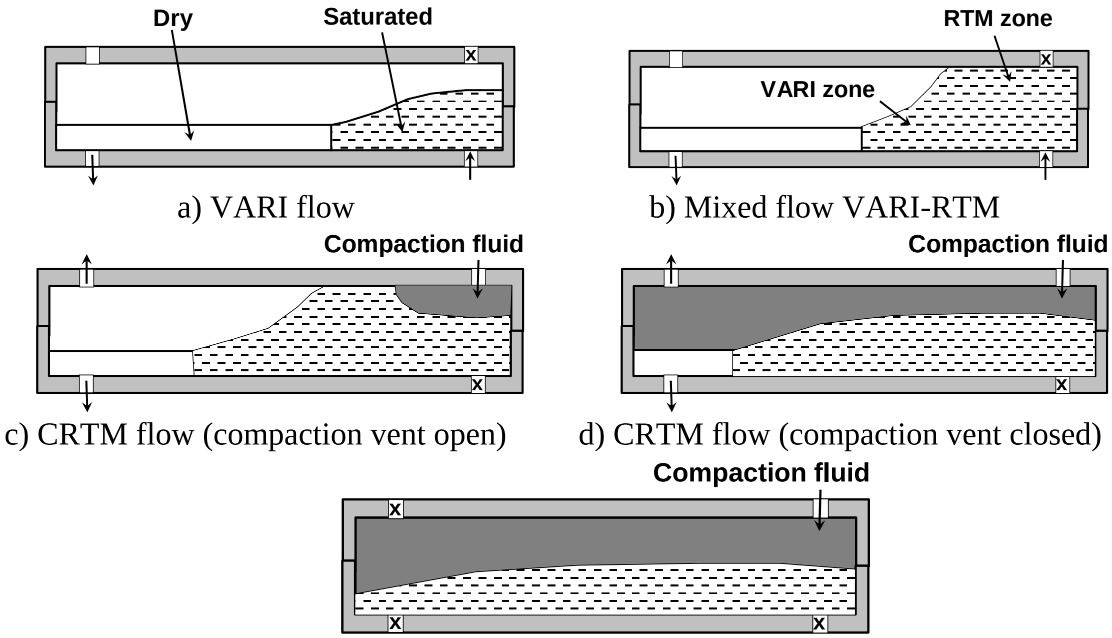
1. The first type of flow occurs at the beginning of the process and is analogous to Vacuum Assisted Resin Infusion (VARI) (see Fig. 1a). The resin injected in the lower cavity deforms the reinforcement that swells until it reaches the mold cover.

2. When the resin comes in contact with the upper cavity, the flow in Fig. 1b presents downstream the characteristics of VARI and upstream near the injection port of RTM, although this RTM flow occurs in a larger gap than the nominal part thickness.

3. When the preset quantity of resin required to impregnate the reinforcement has been injected, Fig. 1c shows the new type of flow that occurs after the resin injection port is closed and the compaction fluid inlet gate opened. The compaction fluid compresses the reinforcement like in Compression RTM, and accelerates resin impregnation in the fibrous reinforcement. This type of flow can also be considered as analogous to VARI from the modeling point of view, but with a different pressure imposed on the membrane than the atmospheric pressure.

4. Since the compaction fluid fills the upper cavity much faster than the resin can impregnate the reinforcement contained in the lower cavity, the vent of the compaction chamber is attained in Fig. 1d before total impregnation of the preform. The compaction outlet is then closed, which causes an increase of pressure in the compaction chamber.

5. Finally, in the last stage of the process, a consolidation flow under constant pressure occurs in the compaction chamber as shown in Fig. 1e.



a) VARI flow
b) Mixed flow VARI-RTM
c) CRTM flow (compaction vent open)
d) CRTM flow (compaction vent closed)
e) Flow caused by consolidation of the reinforcement

Fig. 1 Analysis of flexible injection from the modeling point of view.

MATHEMATICAL MODEL

Since there is no reinforcement in the compaction chamber, a Stokes type of flow occurs in the compaction chamber. Therefore two different flow modes, Stokes and VARI with a modified Darcy's equation, are required with appropriate boundary conditions to describe the successive stages of flexible injection.

Stokes Flow

If v denotes the velocity of fluid particles and p the pressure field, Stokes flow is governed by the following equations:

$$2\mu\, div(\varepsilon(v)) - \nabla p = 0 \qquad (1a)$$
$$div(v) = 0 \qquad (1b)$$

where μ is the viscosity of the compaction fluid and $\varepsilon(v)$ is the strain rate tensor:

$$\varepsilon(v) = \frac{1}{2}\left(\nabla v + {}^{t}\nabla v\right) \qquad (2)$$

The incompressibility condition *div(v)* = 0 introduces a constraint and an additional equation to solve Stokes problem with the boundary conditions of Fig. 2:

- imposed pressure on Γ_{P1} and Γ_{P2}, the vent and inlet gate of the compaction chamber,

- null velocity on Γ_{V2} (no-slip boundary condition),
- imposed velocity on Γ_{V1} (defined by the deformation of the membrane during resin injection).

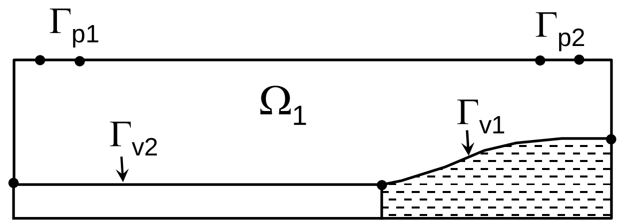


Fig. 2 Stokes domain Ω_1 definition and corresponding boundary conditions.

Modified Darcy's Equation

It is classical to model a vacuum driven infusion flow with a modified Darcy's equation that takes into account the compression and relaxation of the porous medium. If $\vec{v}_s$ is the velocity of the solid phase during deformation of the fibrous reinforcement, $[\mathbf{K}]$ is the permeability tensor of the porous medium, ϕ its porosity, μ_r the resin viscosity and p the pore pressure, the general mass conservation equation in a compressible porous medium writes as follows when the velocity of the liquid phase is given by Darcy's law:

$$div\left(\frac{[\mathbf{K}]}{\mu_r}\langle\nabla p\rangle\right) = div\left(\vec{v}_s\right) \tag{3}$$

In order to solve Eqn. 3 in the saturated reinforcement, another equation is needed relating the velocity $\vec{v}_s$ of the solid phase with the pore pressure p. This equation is provided by Terzaghi's law, which states that the total stress σ in a saturated porous medium is the sum of the effective stress σ' on the solid phase plus the pore pressure:

$$\sigma_{ij} = \sigma'_{ij} + \delta_{ij} p \tag{4}$$

The quasi-static equilibrium condition in the saturated porous medium writes then as follows:

$$div(\sigma'_{ij} + \delta_{ij} p) = 0 \tag{5}$$

Assuming that the fiber displacements are small, one can relate the stress to the displacement by Hooke's law:

$$\sigma'_{ij} = E_{ijkl}\varepsilon_{kl} \tag{6}$$

where E_{ijkl} are the terms of the elasticity tensor E, $\varepsilon = \frac{1}{2}\left(\nabla u + \nabla u^T\right)$ is the deformation tensor and u represents the displacement vector of the fibers.

Finally, if I denotes the identity matrix, the mechanical equilibrium of a saturated porous medium couples the hydrostatic fluid pressure p with the displacement of the fibers in the general equation

$$div\left(\frac{1}{2}E:\left(\nabla u+\nabla u^{T}\right)+pI\right)=0 \tag{7}$$

NUMERICAL SIMULATION OF FLEXIBLE INJECTION

A coupled finite element approximation of Eqn. 7 together with Stokes boundary value problem governed by Eqn. 1 and 2 yields a numerical solution of flexible injection in the transient one-dimensional case. A special bubble element was used with interpolating polynomials of degree 1 to solve Stokes equation. A series of numerical results will be shown during the conference.

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