



Flow Modeling in Liquid Composite Moulding Processes

Mohamed Hattabi & Jamal Echaabi

*Equipe de Recherche Appliquée sur les Polymères, Département de Génie Mécanique,
Ecole Nationale Supérieure d'Electricité et de Mécanique (ENSEM)
Université Hassan II Aïn Chok, BP 8118, Oasis, Casablanca, Maroc.*

Abdeghani Saouab

*Laboratoire de Mécanique Physique et Géosciences du Havre, Université du Havre,
25, rue Philippe Lebon, BP 540, 76058 Le Havre Cedex, France.*

Keywords: Liquid composites moulding, Numerical simulation, Flow front, permeability, Capillary number.

Abstract

The aim of this work is to present a numerical method based on the finite difference approach used to analyze the isothermal flows in the LCM processes in particular RTM unsaturated zone and capillary effect in processes and its derivatives. The numerical results obtained are compared with numerical results from the literature and with the experimental results obtained using an experimental device that we have developed. The application of our work within the framework of the RTM process and its derivatives contributes in particular to optimizing the mould dimensioning and to the analysis of particular defects due to presence of void. Indeed; the optimization of the quality of the parts remains a crucial point to study. The knowledge of the permeability of the fibrous reinforcements is necessary to simulate and optimise the RTM process. In our case, the analysis of the kinetics of the front permits to identify the permeability tensor and underlines an unsaturated zone which has been characterized by capillary pressure, the presence of the void and the relative permeability.

1. Introduction

Moulding of composite materials by LCM (Liquid Composite molding) is a technique that is being increasingly used in the industry. It's based on the principle of injecting a thermoset resin into a closed mould containing a fibrous reinforcement. It includes two sub-families: RTM processes (Resin Transfer Molding) and its derivatives and the infusion processes and its derivatives. In the first, the reinforcement is impregnated by the resin in a transfer mode and in the second by an infusion mode. The objective in this paper is to present a numerical and experimental modelling of the LCM processes. The numerical methods of modeling most

met in the literature are based on an approach of the Finite Element Method/Control Volume (FEM/CV) technique [1-3]. This type of approach seems well adapted to manufacture parts with complex configurations, but only an approximate position of the flow front is obtained during the filling and this method requires, at each step of time, a calculation on a grid of the whole mould. Contrary to this approach, we adopt in this work a numerical method based on a finite difference with curvilinear grid, which can better describe the progression of the flow front of the matter and whose remeshing process at every moment remains limited simply to the saturated part of the mould [4]. As a result, this effect depends primarily on the moulding parameters used such as [5]: pressure or flow rate of injection, the system temperature (resin and reinforcement), the fluid injected, the nature of the reinforcement and its oiling as well as the compression rate of the reinforcement. Concerning the microscopic aspect of this flow, the resin (while flowing) fills the empty space between the wicks, impregnating the mono filaments (inter wicks). This leads to two types of flow in addition to the presence of the bubbles (of air) as discussed by [6,7]. More experimental work is necessary to appreciate these two types of flow in order to identify the key parameters of LCM processes, which will allow the control of health matter of the elaborated parts. Thus more studies must be undertaken on the influence of the macroscopic parameters such as pressure, viscosity, temperature, compression rate reinforcement and the microscopic parameters such as the oiling of the reinforcement, the proportion of porosity and the grammage of the reinforcement. To appreciate the influence of some parameters mentioned, we discuss in this work the experimental results obtained on the mat type reinforcement and we interpret the observed phenomena.

2. The physical process and the mathematical models

On the macroscopic scale, the flow of the resin through a fibrous reinforcement is governed by the equation of continuity and Darcy's law:

$$\begin{cases} \text{div}(\vec{V}) = 0 \\ \vec{V} = -\frac{\overline{K}}{\mu} \text{grad}(P) \end{cases} \quad (1)$$

μ is the viscosity of the resin, \vec{V} the flow velocity vector and \overline{K} the permeability tensor (in principal axes):

$$\overline{K} = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix}_{(x_p, y_p)} \quad (2)$$

(x_p, y_p) is the principal reference. Since the flow of the resin is supposed to be incompressible, the substitution of the Darcy's law in equation of continuity leads to:

$$\frac{\partial}{\partial x} \left(\frac{K_x}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{K_y}{\mu} \frac{\partial P}{\partial y} \right) = 0 \quad (3)$$

The simulation of the mould filling under these conditions is controlled by the equation (3) whose solution is obtained by digital processing according to an iterative resolution. The boundary conditions are taken as follows:

- At the injection gates :

$$P = P_{inj} \quad \text{or} \quad Q = Q_{inj}$$

Where P_{inj} and Q_{inj} are respectively the pressure of injection applied and the flow injection rate.

- At the mould wall: $\left. \frac{\partial P}{\partial n} \right|_{wall} = 0$
- At the flow front : $P_{front} = P_{atm}$.

n being the normal direction within the wall.

3. Resolution procedure

The major difficulty in this problem does not lie so much in the numerical resolution of the elliptic equation (3), but rather in the fact that the geometry of the field of resolution varies during time. Indeed at every time step, this equation must be resolved in the saturated part of the mould. A spatial discretisation is chosen by means of a system of curvilinear coordinates adapted to the complex shape of the domain where the lines of the meshing coincide with the material front and the line of injection [4].

4. Experimental apparatus

The developed installation enables us to carry out a central injection on a parallelepiped cavity whose

dimensions are: $(270 \times 270 \times 3.4) \text{ mm}^3$. The mould consists of a lower part made of steel bottom and a glass or Plexi-glass top which makes it possible to visually follow the progression of the flow front. Injection is done by means of a buzzard placed at the centre of the mould and connected with a jack by a flexible hose equipped with a distributor to evacuate the air bubbles. The hydraulic jack containing the glycerine is activated by a drive machine. The fluid impregnates the reinforcement placed inside the cavity before being evacuated by a vent placed on the lower part of the mould.

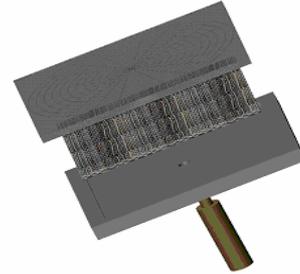


Figure 1: Assembly for radial injection (2D).

5. Results and conclusion

Figure 2 shows, progress in the course of time of the two beams and offers a comparison between the numerical and the experimental results. A perfect agreement is obtained between the results of our numerical simulation and the experimental results. The efficiency of the numerical model developed in the treatment of the front in this type of flow is noticed. An excellent reproduction of the front shape is obtained, together with precision in the position.

The results of figure 3 describe the variation of the ratio K_{unsat} / K_{sat} of the permeability in unsaturated and saturated modes according to the flow front for two different porosities. This variation of permeability can be explained by a nonlinear behaviour of Darcy's law, and also by a non saturation of the porous medium. As soon as the front exceeds the position corresponding to the middle of the mould, we observe a zone where the flow becomes stable and this for both porosities. This can be explained by the presence of a transient mode at the beginning of the injection.

It is then necessary to take into account the effect of capillarity which cannot be ignored. Capillarity emerges in LCM processes because of the unsaturated impregnation of the reinforcement. As a result, the rigorous precise description of the flow near the front cannot be treated only on the basis of Darcy's law.

The notion of saturation allows to describe in more detail the progressive impregnation of a fibrous perform with a fluid. In fact within this framework, permeability always plays a central part, but it is expressed this time according to the saturation of the

porous medium. It evolves between two extreme values: unsaturated (K_{unsat}) and saturated (K_{sat}) permeability. The permeability can be redefined as a function of saturation (relative permeability) and of intrinsic of sizes of the medium (geometrical permeability).

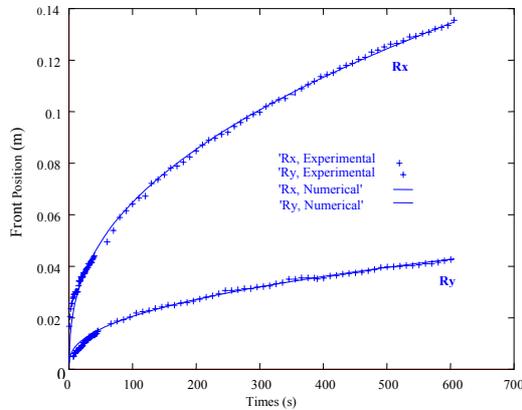


Figure 2: Kinetics of the front ($R_x(t)$, $R_y(t)$) in central injection.

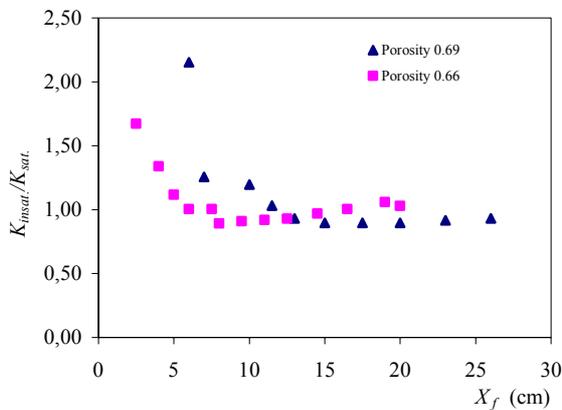


Figure 3: The permeability Evolution vs of the flow front.

Relative permeability is defined as being functions of saturation that lie between 0 and 1 values. The concept of relative permeability intervenes in the flows in porous medium in the presence of air bubbles. It explains why that in addition to the resistance of the porous matrix, one of the phases can constitute an obstacle to the displacement of the other phase figure 4.

We can choose for relative permeability a law of power of the following form:

$$K = k_{relative}(S)K_{geometrical}$$

$$K = \left[S + (1 - S) \left(\frac{K_{unsat}}{K_{satur}} \right)^\lambda \right]^{-\lambda} K_{geometrical} \quad (4)$$

$$\text{With } k_{relative} = \left[S + (1 - S) \left(\frac{K_{unsat}}{K_{satur}} \right)^\lambda \right]^{-\lambda}$$

Where λ is a constant of fitting.

The dependence of permeability with the degree of saturation (S) has often been discussed in the field of the soil mechanics as well as the LCM process [5]. Our first results obtained within this framework, show that the ratio K_{unsat}/K_{sat} extends from 0.8 to 0.9 respectively for porosities of 0.66 and 0.69.

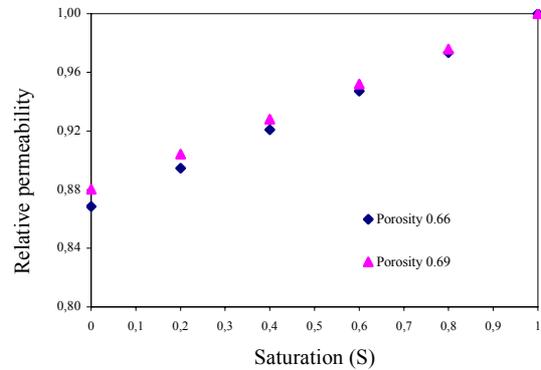


Figure 4: Profile of relative permeability vs saturation

The results of the numerical simulations show a perfect agreement with the analytical, experimental and numerical results in the literature. We note the effectiveness of the numerical model developed in the treatment of a front of this type of flow. An excellent reproduction of the front shape as well as a good precision in its positioning are obtained. The experimental apparatus developed enables us to study some moulding parameters. The ratio between saturated and unsaturated permeability has been identified and used to characterise their difference. As has been observed in the soil mechanics, unsaturated permeability is always lower than saturated permeability. In the light of these results, the dependence of permeability on the degree of saturation should not be neglected.

Reference

- [1] Brusckhe M. V. & Advani S. G., "A finite element/control volume approach to mold filling in anisotropic porous media", *Polymer composites*, 11 (6), pp. 398-405, 1990.
- [2] Shojaei A., Ghaffarian S.R. & Karimian S.M.H., "Numerical simulation of three-dimensional mold filling process in resin transfer molding using quasi-steady state and partial saturation formulations", *Composites Science and Technology*, 62 (6), pp. 861-879, 2002.
- [3] Liu X.L., "Isothermal flow simulation of liquid composite molding", *Composites Part A*, 31 (12), pp. 1295-1302, 2000.
- [4] Hattabi M., Snake I., Echaabi J. & Bensalah M.O., "Flow front simulation in the liquid composite molding processes.", *Compte Rendue de Mécanique*, Ed. Elsevier 333 (7), pp. 585-59, 2005.
- [5] Hattabi M., Bensalah M.O., Echaabi J. & A. Saouab, Analysis of Isothermal Flow in Liquid Composite Molding, *ASME, Journal of Fluids Engineering*, Accepted.
- [6] Patel N. & L. James Lee, "Modeling of void formation and removal in liquid composite molding. Part II: Model development and implementation", *Polymer Composites*, 17(1), pp. 104-114, 1996.
- [7] Hattabi M., Echaabi J., Bensalah M. O., J. Bréard & A. Saouab, "Analyzes flow during on-line Injections and Radial Application in the Measure of Permeability", *Journal of Reinforced Plastics and Composites*, 24 pp. 1909-1920, 2005.