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A New Model for the Simulation and Improvement of Resin Transfer Molding Process

A. SAAD*¹, A. ECHCHELH¹, M. HATTABI², M. EL GANAOU³

Laboratory of electrical engineering and energetic systems

Faculty of Sciences BOP: 133, Ibn Tofail University, Kenitra, Morocco.

Applied research team on polymers, Department of mechanical engineering,

ENSEM, Hassan II University, POB: 8118, Oasis, Casablanca, Morocco.

Université Henri Poincaré, LERMAB, Institut Carnot, Nancy, France.

*Corresponding author Email: saad_aouatif@yahoo.fr

Abstract

In the current work, first of all, a general theoretical two-phase model was proposed to simulate the flow in the resin transfer molding RTM. This model has been widely used in geologic media and petroleum reservoirs and satisfied results have been given. The similarity between these medium and our composite domain either in heterogeneity or in fluid flow has motivated this choice. Based on multiphase darcy's law, the model has been developed to simulate the saturation distribution for two compressible immiscible phases which are resin and the air, it may control the formation of the void in composite material. Then, a particular case of the model was simulated numerically which is well known as the buckley-levrett model. Using the first time the control volume-finite element CV/FEM method, the results of this study agree qualitatively with experimental and numerical findings.

Keywords

Two Phases; Resin Transfer Molding RTM; Multiphase Darcy's Law; Buckley-leveret Model; Control Volume Finite-element Method CV/FEM

Introduction

Resin Transfer Molding (RTM) is a closed molding process in which a thermosetting resin is injected into a preplaced fiber preform. RTM offers the promise of producing low cost composite parts with complex structures and large near net shapes. Relatively fast cycle times with good surface definition and appearance are easily achievable. For these reasons, this process has gained the attention of composite manufacturers especially in automotive industries (Owen et al., 1991), and the subject of numerous experimental and numerical studies has been done (Hattabi et al., 2005, 2008; Saouab et al.,

2006; Samir et al. 2009, 2011). Nevertheless, almost all of these numerical studies have considered the problem as a one phase flow model which takes into account only the resin flow, therefore all parameters determined rely on this phase. While in reality, RTM is a technique where the motion of two phases plays significant role and affects the process parameters. The motivation for the research work presented in this paper arises from the need to develop an efficient and accurate model for RTM. This model accounts for the multiphase nature and more other singularities of this process, and in the same time the presence and the interaction of the two different phases are taken into consideration; liquid (resin) and gas (air), which can also be useful to treat the formation and migration of the void that affects the quality and the performance of the composite material. The two-phase general model developed in our work is extrapolated from soil mechanics (Bastian, 1999; Chen et al., 1994, 2006; Douglas et al., 1987; Geiger et al., 2003; Webb, 2006), which enable us to treat the case where one or the two phases are compressible, the permeability dependence on saturation, and even, the fiber porosity time-dependent. In spite of the obvious advantages offered by the two-phase model, few researches (Chui et al., 1997; Pillai et al., 1996) have been performed in this direction.

Aiming to test the validity of our model, a particular case of the filling process was simulated numerically, based on the assumption that both of the two phases are incompressible, which is well known as the Buckley-levrett model (Chui et al. 1997), the originality of this study was from the implementation of the CV/FEM methods to track the flow in the molding. A

node-centred control volume coupled with a finite element method has been depicted on an unstructured triangular grid which can be used to accurately and efficiently model multi-phase flow in porous media (Timooei, 2005; Chen, 2006). The results of our simulation are qualitatively quite the same with experimental (Hattabi et al., 2005, 2008; Saouab et al., 2006) and numerical findings (Samir et al., 2009, 2011).

Mathematical Model

The equations describing the flow of two compressible and immiscible fluids can be derived by combining Darcy’s law and mass conservation equation written for each phase individually. The phase flow equations are given in a fractional flow formulation, i.e, in terms of saturation and a global pressure. The main reason for this fractional flow approach is that efficient numerical methods can be devised to take advantage of many physical properties inherent to the flow equations.

The parabolic equation describing the fluid pressure p in the mold is then defined as:

$$(c_a S_a + c_r S_r) \frac{dp}{dt} + \nabla V_t = - \frac{\partial \phi p}{\partial t} + q(x, S_r) \tag{1}$$

$$\begin{aligned} \phi \frac{\partial S_r}{\partial t} + \nabla \left(f_r V_t - K \lambda_{af_r} g \delta p + K \lambda_{af_r} \frac{dp_c}{dS_r} \nabla S_r \right) \\ = -S_r \frac{\partial \phi p}{\partial t} + q_r \end{aligned} \tag{2}$$

In addition to the above system, a law of state is added to describe the behaviour of each phase:

$$S_r + S_a = 1 \tag{3}$$

Where $0 \leq S_r, S_a \leq 1$.

Equation (4) signifies that the two phases fill the entire pore of the porous media.

In these equations, subscript a and r refer respectively to air and resin, S is the saturation, K is the absolute permeability of the fiber mat, ϕ is the porosity of the media, and c is the compressibility of each phase, λ is the mobility, ρ is the density and g is the acceleration due to gravity.

With: $\frac{d}{dt} = \phi \frac{\partial}{\partial t} + \frac{V_a}{S_a} \nabla$.

$$G = \frac{\lambda_r \rho_r + \lambda_a \rho_a}{\lambda_t} g \tag{4}$$

In equations (1) and (2), the average fluid pressure p is given by:

$$p = \frac{1}{2}(p_r + p_a) \tag{5}$$

V_t is the total velocity:

$$V_t = V_r + V_a \tag{6}$$

The difference of pressures between the two phases,

named the capillary pressure p_c is given by:

$$p_c = p_a - p_r \tag{7}$$

λ_t is the total mobility:

$$\lambda_t = \lambda_r + \lambda_a = \frac{k_{r,r}(S_r)}{\mu_r} + \frac{k_{r,a}(S_a)}{\mu_a} \tag{8}$$

$k_{r,r}(S_r)$, $k_{r,a}(S_a)$ denote relative permeabilities which take values between 0 and 1, strongly depending on the saturation S_r and S_a . This dependence is not yet well established for general porous media, and the experimental research is therefore necessary to develop this relationship.

f_r represents the flow fraction function of the resin:

$$f_r = \frac{\lambda_r}{\lambda_t} = \frac{\frac{k_{r,r}(S_r)}{\mu_r}}{\frac{k_{r,r}(S_r)}{\mu_r} + \frac{k_{r,a}(S_a)}{\mu_a}} \tag{9}$$

In our two-phase model, it is considered that no phase transfer between the two fluids will occur. It’s also assumed that the capillary and the gravitational force can be neglected. Thus, the flow equations become:

$$\nabla V_t = 0 \tag{10}$$

$$V_t = -K \lambda_t \nabla p \tag{11}$$

$$\phi \frac{\partial S_r}{\partial t} + \nabla (f_r V_t) = 0 \tag{12}$$

This system is well known by the Buckley-levrett equation (Chui et al., 1997). It is more used in modelling the geologic media (Chen et al., 1994, Chui et al., 1997), and recently in few works in composite field (Chui et al., 1997).

The initial conditions are resin and air saturations. For the boundary conditions, a Dirichlet boundary condition of pressure at the inlet and the outlet gate:

$$p_{inlet} = p_{inj} \tag{13}$$

$$p_{front} = 0 \tag{14}$$

Whereas a Neumann boundary condition (no flow) is assumed at the other boundary:

$$v \cdot n = 0 \tag{15}$$

Where v is the velocity and n is the normal to the mold wall.

The relative permeability dependence of the saturation can be modelled as (Chui et al., 1997):

$$k_{r,a}(S_a) = S_a^2 \tag{16}$$

$$k_{r,r}(S_r) = S_r^2 \tag{17}$$

Numerical Procedure

Since the system of equation of the two-phase model is rearranged in such a way to have a form similar to that of the one phase model equation (Samir et al. 2009, 2011). To solve the Buckley-levrett system, many researches have been made based on level set method (Soukane et al., 2006), volume of fluid VOF, finite

difference and standard finite element method (Bruschke et al., Lin et.). In our study and contrarily to all methods used previously, the resin flow problem has been resolved by means of the control volume/finite element method (CV/FEM). This method was selected because of the advantage that this fixed mesh method eliminates the need for remeshing the resin-filled domain for each time step, thus the flow simulation for a complex geometry can be done rapidly and efficiently. Numerous studies have shown that CV/FEM simulations (chen et al., 1994; Shojaeia et al., 2003, 2004, 2006) yield very good results in comparison to traditional finite difference (Trochu et al., 1992; Hattabi et al., 2005, 2008) or finite element methods (Chang et al., 1998, 2003).

The use of the CV/FEM has many advantages. In particular:

- The geometric flexibility of the finite-element method allows for large variations in scale to be modelled efficiently.
- The parabolic equation for the fluid pressure and the hyperbolic conservation equation can be solved efficiently by the finite element method.

In addition to the geometric flexibility of using unstructured meshes, this method has the advantage that only the fluid pressure field needs to be computed by the finite element method.

Finite Element Method

The finite element method is used to approximate the spatial operators. This yields the fluid pressure at the nodes of the finite elements at each time step. The pressure is calculated using the Galerkin approach, and the governing equation of the flow model is:

$$\nabla(K\lambda_t \nabla p) = 0 \tag{18}$$

Using the procedure of Galerkin to this equation, we obtain:

$$\int_{\Omega} \nabla(K\lambda_t \nabla p) d\Omega = 0 \tag{19}$$

$$\int_{\Omega} K\lambda_t \nabla p \nabla \phi_i d\Omega = 0 \tag{20}$$

For all basis functions ϕ_i , the pressure p has the decomposition:

$$p(x, t) = \sum_{j=1}^n p_j(t) \phi_j(x) \tag{21}$$

The equations can then be written as follows:

$$[K_{ij}] \{p_j^e\} = 0 \tag{22}$$

With:

$$K_{ij} = \int_{\Omega} \lambda_t \nabla \phi_i \nabla \phi_j d\Omega = 0 \tag{23}$$

After the distribution of the pressure is determined in

the domain, the nodal fluid pressures can be differentiated to compute the total velocities at the centre of the finite elements, using Darcy’s law equation (eqt. 11).

Control Volume Technique

The control volume technique is a numerical approach to track flow front location in fluid dynamics problems involving flow with a free-surface (Chen et al., 2006)

In the control volume approach, the molding is first discretized into finite elements. By subdividing the elements into smaller sub-volumes, a control volume is constructed around each node (figure 1). The concept of fill factor is introduced to monitor the fluid volume in each control volume; and defined as the ratio of the fluid volume in the control volume to the total volume of the control volume. The fill factor takes values from 0 to 1, of which 0 represents that the control volume is empty and 1 when it is filled. The control volumes can be empty, partially filled, or completely filled. The numerical flow front is construction of the nodes that have partially filled control volumes. At each time step, fill factors are calculated based on the resin velocity and flow into each nodal control volume. If the resin does not gel, the flow front is thus updated until all the control volumes are full and the infiltration is complete.

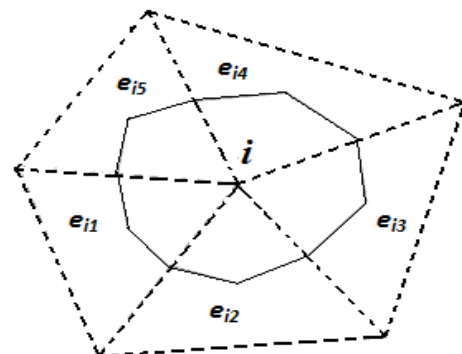


FIG. 1 ONE CONTROL VOLUME V_i AT THE NODE i , WITH TRIANGULAR ELEMENT $e_{i1} - e_{i5}$

There are two basic components to the control volume technique: (1) control volume formation, (2) flow front advancement.

1) Control Volume Formation

The molding cavity is first discretized using finite elements, and then each individual element is further divided into sub-volumes; each of which is associated with one of the nodes on the element (figure 1). The number of the sub-volumes is equal to that of nodes in the element. The control volume

for a particular node is composed of all of the sub-volumes associated with that node.

2) Flow Front Advancement

The concept of fill factor introduced in one-phase model to monitor the progression of the flow front is replaced in our two-phase model by the saturation S_r of the wetting phase (resin).

The equation that leads to updating the saturation S_r is the same as it describes the mass conservation of the resin:

$$\phi \frac{\partial S_r}{\partial t} + \nabla(f_r V_t) = 0 \tag{24}$$

After calculating the total velocity, this one is introduced in the equation (24) to determine the saturation for the next iteration. The integration of equation (24) over an arbitrary volume V_i and the application of the divergence theorem yields:

$$\phi \int_{V_i} \frac{\partial S_r}{\partial t} dV_i = - \int_{V_i} (f_r V_t) dV_t \tag{25}$$

Within each control volume V_i , S_r is constant. Discretization of Equation (25) using Euler's method leads to:

$$S_{ri}^{n+1} = S_{ri}^n + \frac{\Delta t}{\phi A_i} \sum_j^k (f_{rj} V_{tj} n_j) \tag{26}$$

Where \sum_j^k is the summation over all segments j belonging to the control volume, Δt is the time step, A_i is the area of the control volume and n_j is the outward normal vector to segment j .

The saturation S_r takes values from 0 to 1, where 0 represents totally empty and 1 totally full. When the control volume is partially full, the saturation S_r varies between 0 and 1. The numerical flow front is construction of the nodes that have partially full control volumes as shown in fig. 2.

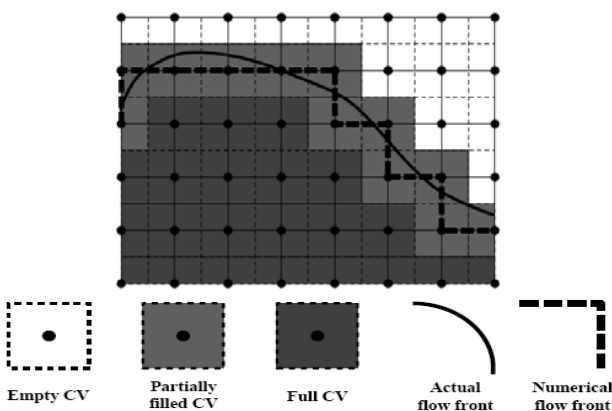


FIG. 2 NUMERICAL AND ACTUAL FLOW FRONT

3) Time Step Calculation

The time step for the next iteration must be calculated before the solution can proceed. The

optimal time step would be when the fluid just fills one control volume. If a larger step was chosen, the flow front would over-run the control volume and result in a loss of mass from the system.

The flow charts of the numerical schemes developed in this study are illustrated in fig. 3.

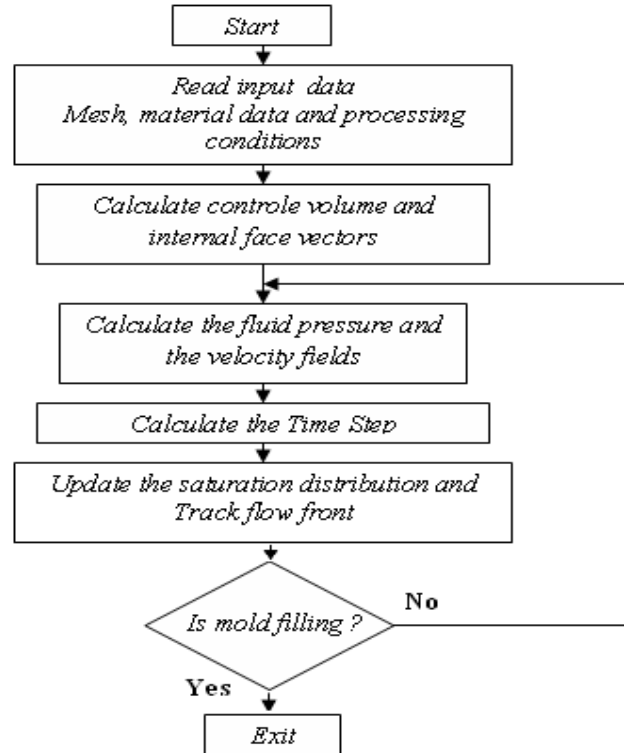


FIG. 3 FLOW CHART OF THE NUMERICAL PROCEDURE OF FE/CV TECHNIQUE

Results and discussion

In the simulation of the RTM filling process, the resin is injected into a square molding cavity (4000 × 4000) mm², and the inlet condition can be either a constant volumetric flow rate or a constant injection pressure for the resin. Here constant pressure is taken as the inlet boundary condition. The details of the numerical procedure are described by the flow chart in figure 3. The physical properties of the fiber mats and resin are listed in table 1.

TABLE 1 PHYSICAL PROPERTIES OF FIBER AND PROCESSING CONDITIONS USED IN NUMERICAL STUDY

RTM parameters		
Permeability	$K_{xx} = 10^{-9}$	$K_{yy} = 10^9$
Resin viscosity	$\mu_r = 0.05 \text{ Pa}\cdot\text{s}$	
Air viscosity	$\mu_a = 1.8 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$	
Injection pressure	$p_{inj} = 4 \times 10^5 \text{ Pa}$	
Porosity	$\Phi = 0,696$	

When the molding is completely filled, the saturation S_r is the same in all nodes and equal to 1. Then the equation (18) is reduced to the one considered in one-

phase flow (Hattabi et al., 2005, 2008; Samir et al., 2009, 2011), therefore it has the same solution given in (Cai) by:

$$p(x) = p_0 \left(1 - \frac{x}{x_f(t)}\right) \tag{27}$$

Where P_0 is the pressure at the inlet, x is the flow front position.

Figure 4 shows a comparison between our numerical result and the analytical result of pressure presented in equation (28). An excellent agreement is observed.

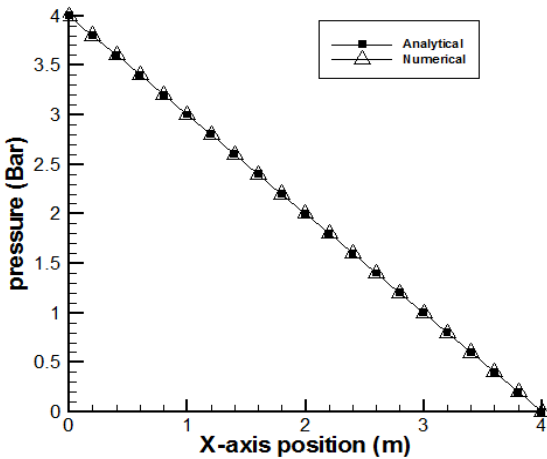


FIG. 4 PRESSURE VARIATION OVER THE MOLD LENGTH

Figure 5 is a classical observation that comes to reinforcing the validity of the present model, in addition, it has been demonstrated that the viscosity is among other parameters that affect the cycle time of the process. Indeed, the time of filling increases with high resin viscosity. So, in order to optimize the production cost, it's recommended to minimize the time of the cycle by using a not very viscous resin.

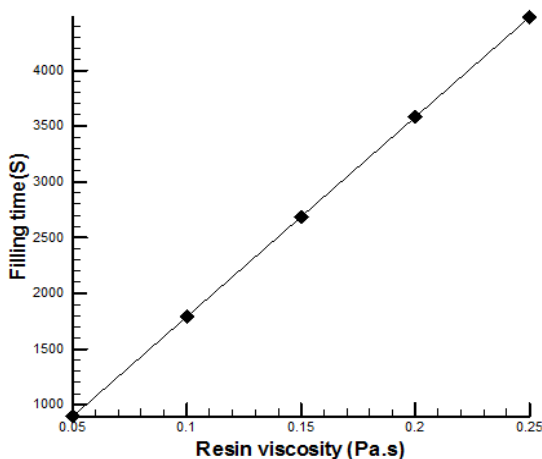


FIG. 5 EVOLUTION OF MOLD TIME FILLING TIME WITH RESIN VISCOSITY

The front position presented in figure 6 has a quadratic pattern in the course of the time, with confirms for another time the conformity of the model with the previous findings (Saad et al., 2011, 2012;

Samir et al., 2009, 2011).

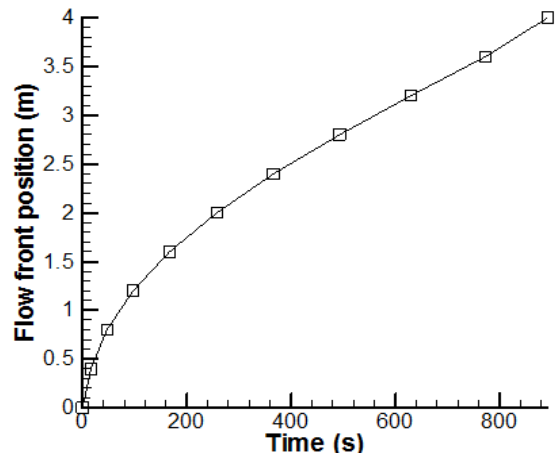


FIG. 6 FRONT POSITION VARIATION WITH TIME

In this model, the total time of the filing becomes higher 895.39 s as compared with the model of one phase flow 500.58 s (figure 7), because in our model both the motion of resin and air are taken into account, and this increment is principally due to the resistance proved by air to the resin advancement.

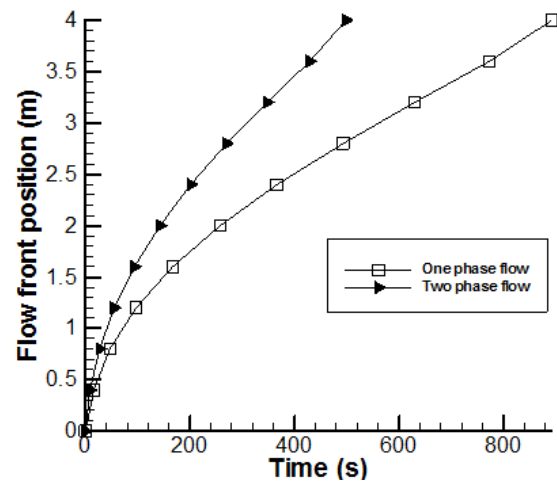


FIG. 7 FRONT POSITION COMPARISON BETWEEN TWO MODELS

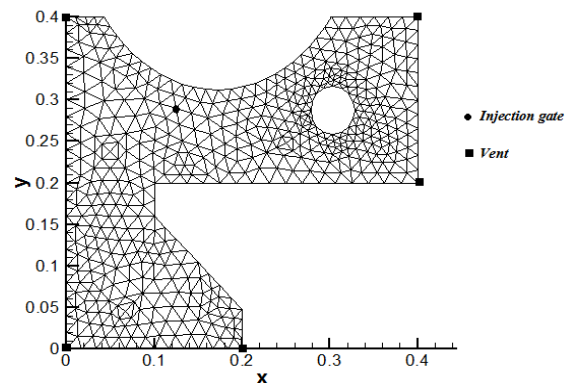


FIG. 8 SCHEMATIC OF THE COMPLEX MOULD GEOMETRY WITH SINGLE GATE AND BOUNDARY CONDITIONS

The modelling of complex geometry is a more realistic concern in RTM application field, that's why it is

intended to simulate with our model the filling of a complex shape, which has the specificity including an insert inside the piece. The filling of the mould has been done under constant injection pressure with only a single gate injection, and five events where the pressure is equal to zero (fig. 8).

The distribution of pressure in the course of molding filling is also affected in the current model (figure 9). This confirms again the importance of taking into consideration the motion of the two phases (resin and air) in order to define more precisely all process parameters that allow a final product with high performance and low cost.

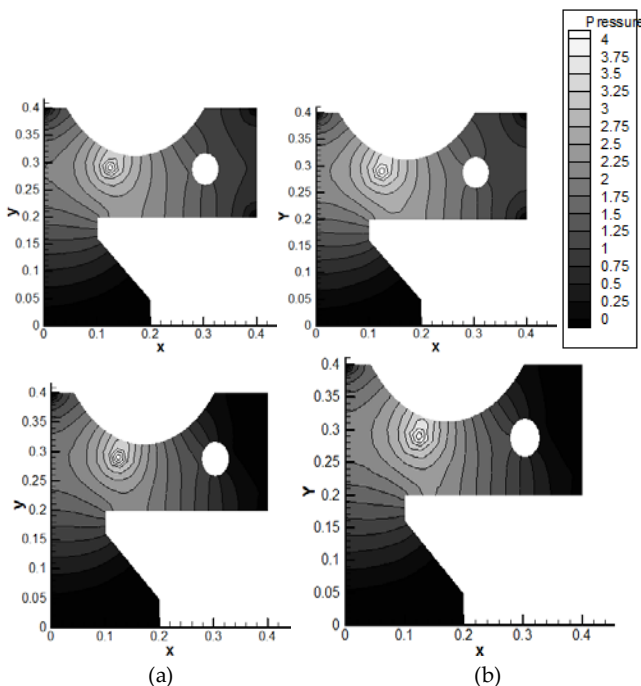


FIG. 9 NUMERICAL PRESSURE DISTRIBUTION IN (a) ONE PHASE FLOW (b) TWO PHASES FLOW

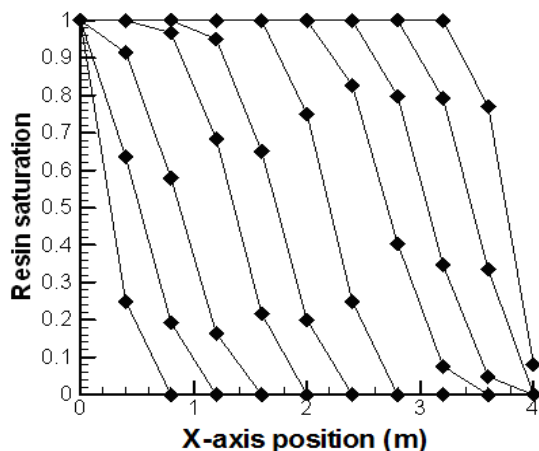


FIG. 10 RESIN SATURATION PROFILE AT DIFFERENT TIME

Figure 10 shows the saturation profile as a function of the distance from inlet, at various time of filling, and this result agree well with the saturation pattern of

Chang et al. At the initial time, the saturation is equal to one just at the inlet gate and zero at the flow front. The flow field expands gradually during the filling process, and the wetting phase saturation S_r increases gradually from 0 to the final steady state value 1, to completely fill the entire molding. This implies that the voids will disappear if the resin is continuously filled.

Conclusion and outlook

The theoretical general model seems to be promising in the simulation of resin transfer molding, since it takes into consideration almost all particularity of RTM filling process. This constatation comes from the fact that the Buckley-levrett model, a particular case of this model, gave a satisfied result in the case of two incompressible steady states problem.

The main result of this work is that the Buckley-levrett model presented in a form similar to that of a one phase model, can be resolved by the CV/FEM method to predict accurately all process variables. Furthermore, the control volume finite element method applied for the first time to a two-phase flow model allows one to predict with a cost-effective tool and a high accuracy the pressure evolution over the saturated region of the mould at each time step and to track the flow front position during molding filling, and the pressure can be also investigated in molding with simple and complex geometries including inserts.

To improve the usefulness of this model, it is suggested in the next work, to simulate numerically this theoretical model, by taking into account the compressibility of the two phases.

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