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Numerical Simulation and Analysis of Flow in Resin Transfer Moulding Process

A. Saad[1,2]**, A. Echchelh**[1]**, M. Hattabi**[3]**, M. El Ganaoui**[4] **and F. Lahlou**[1]

Abstract: A modified finite element/control volume (FE/CV) method is used to solve the resin flow problem. Full advantage is taken of some of the intrinsic peculiar characteristics of the method, in particular, of its capability of eliminating the need to remesh continuously the resin-filled domain at each time step. The model leads to the numerical prediction of temperature, pressure distribution and flow front position with great accuracy, together with a precise representation of the thermal (spatio-temporal) behaviour of the resin inside the mould. The validity of such approach is validated by comparison with available analytical results. Results demonstrate that this modified method can reduce significantly the required resources (time and space memory). In turn, this allows to deal with problems of greater and more complex dimensions, mostly encountered in RTM application fields. From an application- oriented standpoint, it is shown how the developed code can be used to optimise the injection port location in the mould and lead to significant improvement of the composite production process.

Keywords: Resin transfer molding (RTM), modified control volume/finite element method CV/FEM, conjugate gradient.

Nomenclature

$\bar{\bar{K}}$	the permeability tensor of the perform.
P	pressure.
$\vec{V}$	volume-averaged Darcy's velocity.
μ	resin viscosity.
T	temperature.

[1] Laboratory of electrical engineering and energetic systems Faculty of Sciences BOP: 133, Ibn Tofail University, Kenitra, Morocco.
[2] Corresponding author Email: saad_aouatif@yahoo.fr
[3] Applied research team on polymers, Department of mechanical engineering, ENSEM, Hassan II University, POB: 8118, Oasis, Casablanca, Morocco.
[4] Universite de Lorraine, LERMAB/IUT Longwy, Institut Carnot, Nancy, France.

λ	effective thermal conductivity.
ρ	density.
C_p	heat capacity.
ΔH	reaction heat.
$\dot{G}$	reaction rate.
Q	resin flux.
ϕ	fibre porosity.
f	fill factor.
t	time.
L	length of the mold.
x, y	coordinate components in the domain of the mold.

Subscript

r	resin
f	fiber
inj	injection
m	mold

1 Introduction

Resin transfer moulding is one of the most efficient and attractive techniques for manufacturing of advanced fiber-reinforced composite materials ranging from small articles of simple shape, to large articles with complex shape and high structural performance characteristics [Raymer (1991); Beal].

The RTM process begins by placing reinforcement, in the form of properly oriented mats or fabrics, into a two-sided mold cavity. The mold is then closed and the resin is injected until the fibers are saturated and the mold is full. The resin is allowed to cure and the finished part is then removed from the mould and the process repeated. RTM employs four components: the mold, the reinforcement preform, the resin pump, and the resin (see Fig. 1).

The fact that this process uses a closed mold offers several advantages. First, complex shapes can be produced. Any variations in the geometry, such as ribs and areas of varying thickness, can be molded directly no matter where they are in the part. Second, the closed mould produces a smooth finish on both sides of the part. Third, emission of volatiles, such as styrene in polyester, is greatly reduced during processing [Potter (1997); Advani and Bruschke 1994)]. Finally, production rates can be high enough for automotive parts. These factors make RTM very attractive

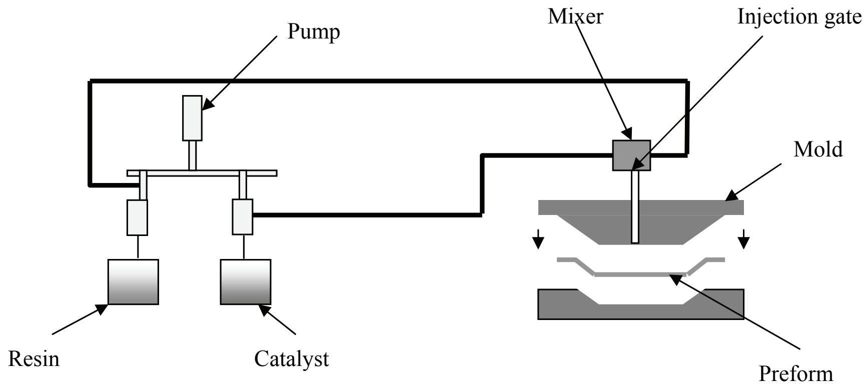


Figure 1: RTM materials

from both a production and economic standpoint, especially in automotive industries [Owen, Middleton and Hutcheon (1989); Owen, Rudd, Middleton, Kendall and Revill (1991)].

The quality of the parts produced by the RTM process depends not only on the fiber preform and resin system, but also on the filling process itself. Inappropriate flow can lead to dry spot, take a long filling time, create high molding pressure, deform the mold, wash out the fiber preform and deform the fiber preform near the gate. These manufacturing variables are significantly influenced by fluid dynamic of the resin within the fiber preform. The fluid dynamic is largely affected by several parameters include the fiber type (distribution, orientation, surface treatment, etc. . .), the resin properties (viscosity, surface tension, etc. . .), filling and curing conditions (injection pressure, outlet pressure, resin/mold temperature), and interfacial properties (wetting fiber between resin and fiber, etc. . .).

It is therefore essential to optimize the processing conditions before fabrication of the mold. Recently, computer simulation has provided a time and cost effective tool for optimization of the process and offered important information to design the tooling and prediction of processing conditions.

Since the RTM flow front is a moving boundary problem, the numerical treatment of front position is an important issue in the simulation of filling process. 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 RTM [Coulter and Guceri (1988); Bruschke and Advani (1990); Chan and Hwang (1991); Um and Lee (1991); Young, Han, Fong, Lee and Liou (1991); Young, Rupel, Han, Lee and Liou (1991); Trochu, Gauvin, Gao (1993); Gauvin and Trochu (1993); Lee, Young and Lin (1994); Bruschke and Advani (1994); Yoo and Lee (1996); Mal, Couniot and Dupret (1998); Lin, Hahn, and Huh (1998); Lam, Joshi and Liu (2000); Shojaei, Ghaffarian and Karimian (2003) , (2004)]. A review on the modeling and simulation approaches in RTM process was presented by [Shojaei, Ghaffarian and Karimian (2003)]. Other researchers are interested on the enthalpy method considered as a fixed grid method in the resolution of phase change problems, particularly for directional crystal growth from the melt [El Ganaoui, Bontoux, Morvan (1999); El Ganaoui, Lamazouade, Bontoux and Morvan, (2002)]. 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 [Shojaei, Ghaffarian and Karimian (2003); Shojaei, Ghaffarian and Karimian (2004)]. In these techniques, a fixed grid approach is used in which there is no need to regenerate the mesh during the flow progression. This makes the simulation rapid and effective for complex geometries compared to moving grid approach.

This paper presents numerical simulations of isothermal and non isothermal mold filling process. Two computer codes are developed based on a modified control volume finite element method (CV/FEM) developed by [Saad, Echchelh, Hattabi and El Ganaoui (2011)]. The validation of both codes is evaluated by comparison with analytical solution. The numerical simulations of some mold geometries obtained by both codes are compared in terms of accuracy and CPU time.

2 Mathematical method

2.1 Resin flow through porous fiber perform

In our study we will be interested by a bi-dimensional simulation of the problem. Since the resin transfer molding is a process devoted to manufacture thin composite parts thus the resin flow has been modelled as a 2-D problem in the most simulations.

The mould filling process is generally regarded as a process of flow through porous media from a macroscopic point of view. A schematic representation of mould filling is represented by figure 2. Thus, the momentum balance equation and the continuity equation of the resin flow can be written as:

$$\vec{V} = -\frac{\bar{\bar{K}}}{\mu}\nabla P \quad (1)$$

$$\nabla\vec{V} = 0 \quad (2)$$

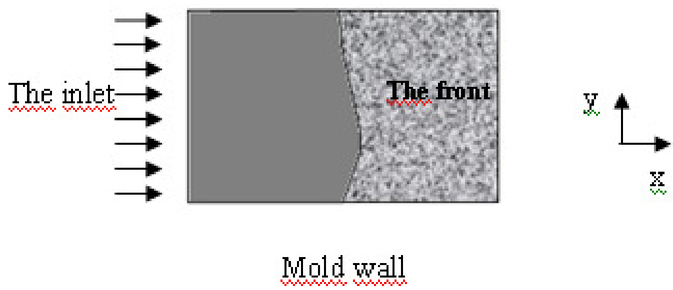


Figure 2: Schematic of the mold cavity and coordinate system

As a result, the flow equation is then obtained by substituting the expression for Darcy's velocity (Eq. (1)) in the equation for continuity (Eq. (2)):

$$\nabla(\frac{\bar{\bar{K}}}{\mu}\nabla.P) = 0 \tag{3}$$

Where $\vec{V}$ is the volume-averaged Darcy velocity, $\bar{\bar{K}}$ is the permeability tensor of the medium, μ is the viscosity, and P is the pore-averaged resin pressure.

The solution of this equation gives the pressure distribution and the fill fraction field; this will be done by employing an appropriate resolution procedure and having satisfied the following boundary conditions and constraints:

$$\begin{cases} P = P_{inj} & \text{at inlet gate} \\ P = P_{front} & \text{at the flow front} \\ \frac{\partial P}{\partial n} = 0 & \text{at the mould wall} \end{cases}$$

$$\begin{cases} P \geq 0 & \text{for all nodes} \\ P = 0 & \text{for all nodes where } 0 \leq f < 1 \\ 0 \leq f \leq 1 & \text{for all nodes} \end{cases}$$

f is a scalar parameter, called nodal fill fraction, shows the status of each control volume.

The resin viscosity is a function of temperature. It decreases when temperature increases, the viscosity equation used in this study is the widely used model given as [Gonzalez-Romero and Mascosko (1985)]:

$$\mu = \mu_0 . \exp(\frac{\alpha_T}{T}) \tag{4}$$

Where μ_0 and α_T are material properties.

2.2 Heat Transfer model

In general, the mold filling process is not an isothermal process. As the resin fills the mold, heat transfer takes place between the resins, fiber preform and mold walls. The heat transfer equation can be expressed as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} \left(\vec{V}.\nabla T\right) = \nabla\left(\lambda \nabla T\right) + \phi \Delta H \dot{G} \tag{5}$$

Where λ the effective thermal conductivity, ρ the density and Cp the specific heat capacity at constant pressure, ΔH is the reaction heat, ϕ is the porosity of the medium.

In our work, one considers the case studied by [Yu, Chiu, Ding and Lee (2000)]: of a resin with constant viscosity and no source of heat is observed, the equation (5) becomes:

$$\nabla\left(\lambda \nabla T\right) = 0 \tag{6}$$

Where the effective thermal conductivity λ may be expressed by the rule of mixture [Shojaei, Ghaffarian and Karimian (2003); Shojaei, Ghaffarian and Karimian (2004)].

The possible boundary conditions for temperature are:

$$\begin{cases} T = T_{inj} \\ T = T_f = Tm \\ T = T_m \end{cases}$$

3 Numerical procedure

In order to solve such moving boundary problems as the resin flow front advances using the traditional finite element method, it requires the computation domain redefinition and mesh regeneration. This leads to a large amount of computation time as the domain becomes complicated. Alternatively, the control volume finite element method [Shojaei, Ghaffarian and Karimian (2003); Shojaei, Ghaffarian and Karimian (2004)], which forms and solves a set of equations for nodal control volumes as if they were finite elements, does not require mesh regeneration. Thus, the computation is more efficient.

3.1 Description of the CV/FE approach

The control volume formulation is illustrated using the three-node triangular element configuration. As shown in Figure 3, each three-node triangular element is divided into three sub-areas by connecting the centroid to the midpoints of all three sides.

A control volume is composed of six sub-areas, which have a common node at the center of the control volume.

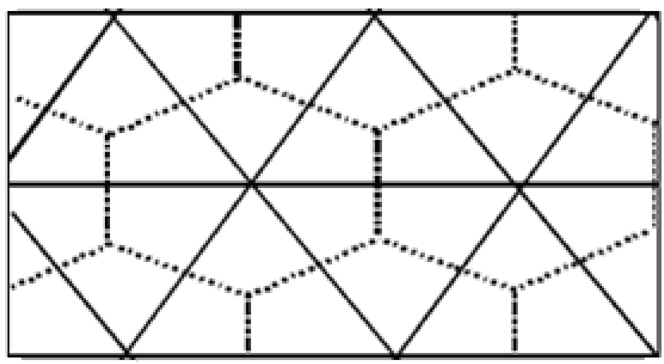


Figure 3: The formation of control volume boundary

At the flow front, a parameter f is used to represent the status of each control volume in the flow domain. If the control volume has not been occupied by the fluid, f is equal to zero. If the control volume is partially filled, f is equal to the volume fraction of the fluid occupying the control volume. f factor is set to 1 if the volume is completely filled by advancing fluid. The control volumes with f values varying between 0 and 1 are considered flow front elements. The pressure in these partially filled flow front control volumes is set to the ambient pressure. With the aforementioned boundary conditions, the set of linear algebraic equations can be solved to determine the pressure field at each time step during mold filling. Based on the calculated pressure field, the velocity field can then be computed using Darcy's law.

3.2 Galerkin Finite Element Formulation

In this approach, the finite element method is used to approximate the fluid pressure field at the nodes of the finite elements at each time step. The pressure is calculated using the Galerkin procedure, applied to the equation (3) as follows:

$$\int_{\Omega} \phi \nabla \left(K \nabla P \right) d\Omega = 0 \tag{7}$$

$$-\int_{\Omega} \nabla\phi\,(K\nabla P)\,d\Omega + \int_{\Gamma} \phi\,(K\nabla P)\,.\vec{n}d\Gamma = 0 \tag{8}$$

Where $\Omega = \bigcup_{i=1}^{k} \Omega_i$, Ω_i is the domain of one element and k is the number of all elements.

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

$$P(x,y,t) = \sum_{j=1}^{n} P_j(t)\phi_j(x,y) \tag{9}$$

The equations can then be written as follows:

$$\left[K_{ij}^e\right]\left\{P_j^e\right\} = \left\{f_i^e\right\} \quad i,j = 1,......,n \tag{10}$$

With:

$$K_{ij}^e = \int_{\Omega_e} \nabla\phi_i \nabla\phi_j d\Omega = 0$$

and

$$f_i^e = \int_{\Gamma_e} \phi\,(K\nabla P)\,.\vec{n}d\Gamma \tag{11}$$

Equation (10) is the working equation to solve the nodal pressure and can be applied to all elements within the solution domain yielding a set of linear algebraic equations by applying an appropriate assembly procedure. In matrix notation, it can be expressed as:

$$AP = F \tag{12}$$

Using calculated pressure, the velocities are then calculated at the centroid of each element using Darcy's law (eqt.2). After the velocity of the resin is obtained, the control volume technique is used to track the flow front position.

3.3 Flow front advancement

After the flow rates into each control volume have been deduced from velocities, the fill factors can be updated. The time step for the next iteration must be calculated before the solution can proceed. The optimal time step would be where the fluid just fills one control volume (eqt. 13):

$$\Delta t_{=}\ \min \frac{(1-f_n)V_n}{Q_n} \tag{13}$$

Given the current time step (Δt), the fill factors from the previous step (f_n^i), the calculated flow rate (Q_n), and the volume of each control volume (V_n), the new fill factors can be calculated with:

$$f_n^{i+1} = f_n^i + \frac{\Delta t \, Q_n}{V_n} \tag{14}$$

Where f_n is the fill factor, Δt is the time step, V_n is the volume of the control volume, and the superscripts i indicate time level.

Despite the fact that the control volume finite element approach led to a reduction in the simulation time with regard to other pioneers methods, it need some additional computational efforts to rapidly solve the mold filling stage. In order to achieve more computational economy, we developed an optimization strategy to enhance the CV/FE method [Saad, Echchelh, Hattabi and El Ganaoui (2011)]. Our approach was accomplished in two steps; the first concern the modification of the conventional control volume finite element CV/FEM and the second the implementation in the modified code of an adapted conjugate gradient to the compressed sparse row storage scheme CSR.

4 Results and discussion

4.1 Validation

The simulation results of the developed computer code, is compared with analytical solutions of some simple geometries for which the exact solution are known [Chang (2003)].

The analytical solutions for the location of flow front, pressure distribution and mould filling time for the cases of constant injecting pressure are given respectively by the equations (15), (16) and (17), the details of derivations are given by[Cai (1992)]:

$$x_f = \sqrt{\frac{2KP_0 t_f}{\phi \, \mu}} \tag{15}$$

$$P(x) = P_0 \left(1 - \frac{x}{x_f(t)}\right) \tag{16}$$

$$t_f = \frac{\phi \, \mu L^2}{2KP_0} \tag{17}$$

In witch, L is the length of the mould, x_f denotes the location of the flow front at time t_f, K is the permeability.

The cavity used in this example is a square mould with the dimensions (400x400) mm^2, the resin is injected at the left surface of the rectangular mould and air is removed from the right surface resulting in 1-D flow. The details of physical properties of the fiber mats and resin used in our simulation are listed in table 1.

Table 1: Physical properties of fiber and processing conditions used in numerical study.

RTM parameters	**Value**
P_{inj}.	1.5×10^5 Pa
K_{xx}= K_{yy}	10^{-10} m^2
μ	0.4 Pa.s
Φ	0,5
k_f	0.0335W/m.K
k_r	0.168 W/m.K
C_{pf}	670 J/kg.K
C_{pr}	1680 J/kg.K

Figures (4.a) and (4.b) illustrate analytical and numerical results of our code with modified CV/FEM for the flow front location and pressure distribution during mould filling under the constant injection pressure. An excellent agreement is observed between our numerical results, the numerical results of [Samir, Hattabi, Echaabi, Saouab and Park (2009); Samir, Hattabi, Echaabi (2011)] and the analytical results for this test problem.

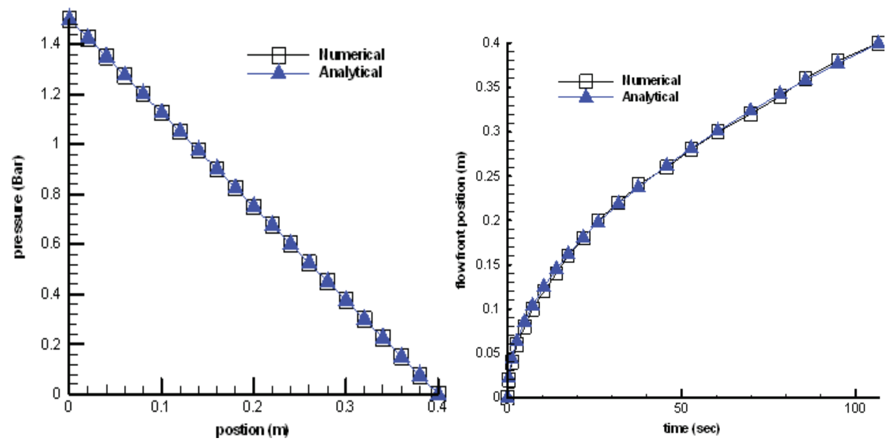
4.2 Simulation time and memory gain

We give here a comparison in the execution time of the code firstly computed with the modified control volume finite element approach to the code with conventional method in the two case isothermal and non isothermal simulation (figure 5), and secondly between the codes resolved by standard conjugate gradient and modified conjugate gradient (table 2).

The both codes are executed sequentially on a personal computer Intel Pentium-IV 3.4 GHz processor with 504 Mo of RAM.

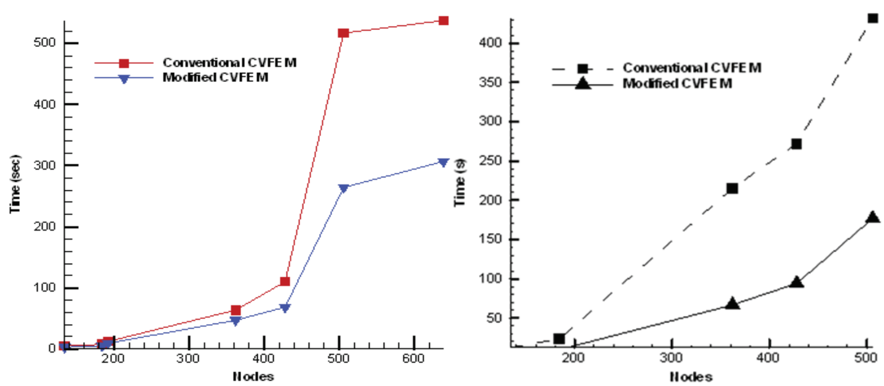
One can conclude from these results that the time of simulation is many orders smaller when using the modified CV/FEM, and the time of execution is also very reduced by using the modified conjugate gradient algorithm.

One can conclude that our optimization approach speeds up the RTM execution code by many order of magnitude than the standard one, and this is become as important as the number of nodes grows and the dimension of the domain increases.



(a) (b)

Figure 4: (a) Inlet pressure at different position of the mould, (b) Flow front position at different filling time of the process.



(a) (b)

Figure 5: Execution time of code with modified and standard finite element/ control volume method CV/FEM (a) isothermal (b) non isothermal.

Figure 6 shows that the compressed-storage scheme contributes to a large reduction in memory usage, which becomes more important when the dimension of the calculation domain increases. Thus, adoption of our algorithm will allow us to bypass (in future simulations) limitations in terms of available computer resources so that

Table 2: Execution time of code with modified and standard conjugate gradient algorithm

	Time (h)			
Nodes	Standard conjugate gradient		Modified conjugate gradient	
	Isothermal	Non isothermal	Isothermal	Non isothermal
639	00:05:07.30	00:05:56.02	00:00:35.13	00:00:48.70
1002	00:28:46.44	00:34:24.08	00:02:06.92	00:02:49:49
1232	00:56:27.14	00:53:30.47	00:03:49.46	00:05:02.64
1927	02:51:07.11	03:05:45.23	00:13:34:30	00:17:14.55

our results will be more reliable and realistic.

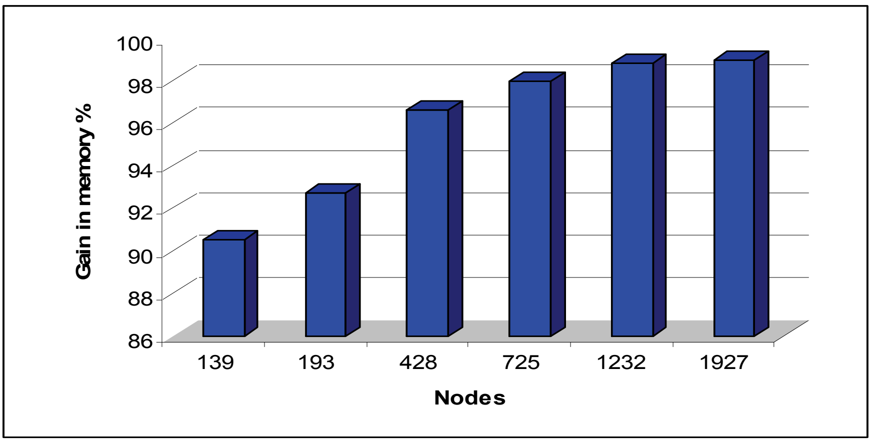


Figure 6: Gain in memory occupation (%) for different mold dimensions.

4.3 Process optimisation by numerical simulation

4.3.1 Multiple injection gates

A more effective method to economize energy by reducing the time of the process is employed in this study; this is done by enhancing the flow using multiple injection gates. In this method, all the injection gates are opened simultaneously. Since each gate fills a smaller volume than the gate in a single gate injection should, the filling time can be reduced. Figure (7 a-b) shows a comparison in the filling strategy of a complex shaped mold with single and multiple injection gates. Indeed, the filling time with a single injection gate is **54.84 s** whereas it is reduced to only **15.98 s** in the case of multiple injection gates, this shows that the later strategy reduces the filling time by 71% compared to the single gate injection with the same injection pressure.

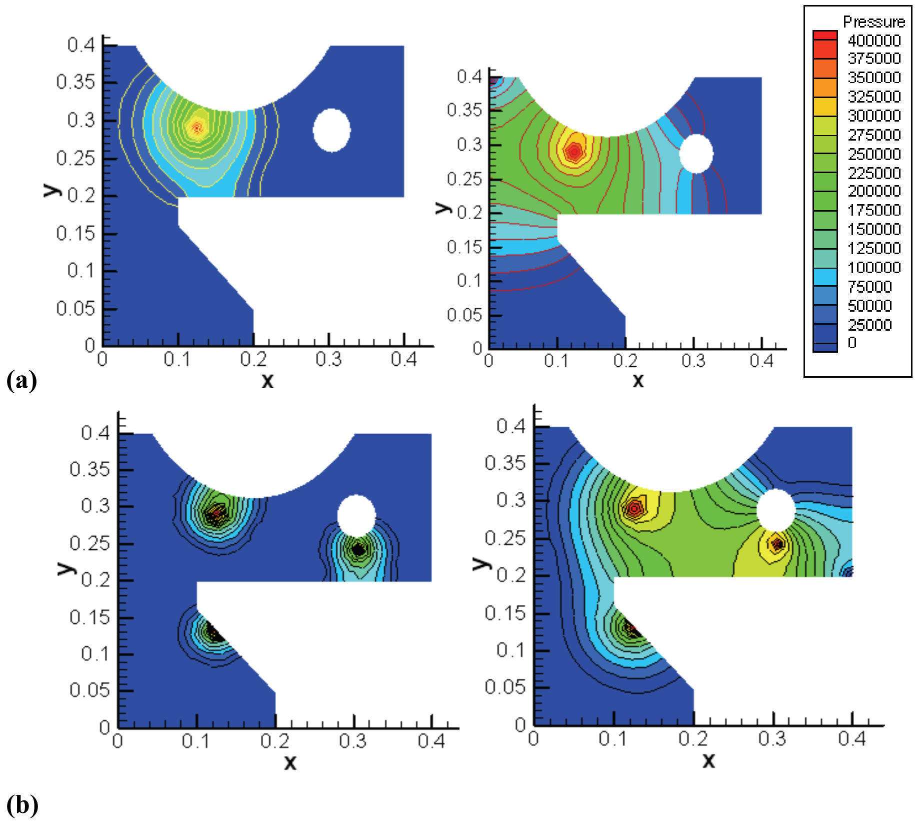


Figure 7: Mold filling patterns: (a) single injection gate (b) multiple injection gates.

4.3.2 Reinforcement thickness variation

In resin transfer molding (RTM), the plates employed often consist of reinforcements with a variable number of plies and stacking sequences. A correct simulation of this process requires taking into account all these parameters.

In our work, we will compare the impact of reinforcement thickness variation on flow front location in the course of the time. One considers a square mold (4000x4000) mm^2 with two different reinforcement thicknesses as shown in figure (8).

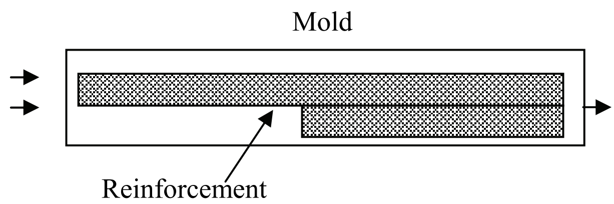


Figure 8: Mold with reinforcement with two different thickness.

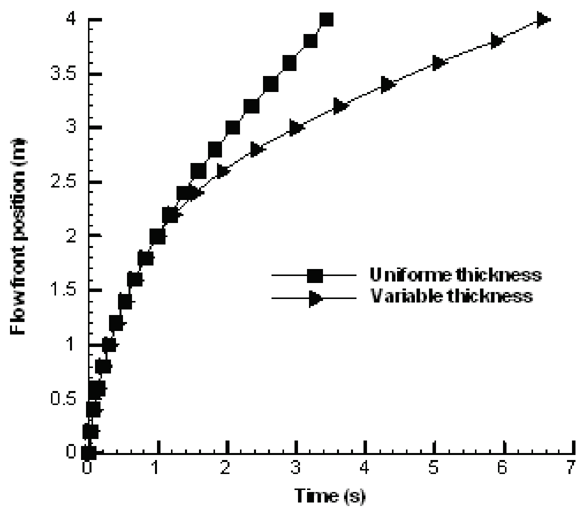


Figure 9: Comparison of flow front position in a mold with variable and uniform reinforcement thickness (Thickness 1 < Thickness 2)

One can deduce from the results presented in figure (9) that in the mold with variable thickness of reinforcement, the flow front is retarded with regards to the one with uniform thickness of reinforcement, indeed the flow front in the first case reaches the outlet of the mold while in the later is still inside the mold. This finally leads to an increase in the time of the process "the cycle time", where it is found that this time is equal to 1613.6s with variable thickness against 807.09s in the case of uniform thickness.

This increase in the process time is principally due to the fact that when the thickness of the reinforcement is increased the volume of the total pore in the mold decreases when the mold is closed, by consequent the permeability of the reinforcement become smaller leading automatically to increase the resistance proved by the fiber to the flow advancement and thus to an increase in the time of mold filling [Saad, Echchelh, Hattabi and El Ganaoui (2012)].

The optimization of injection gate positioning by numerical simulation becomes an important issue that have be done before the mold is built, because it reduce the cycle time of the process and thus the total cost of composites parts manufacturing.

In our study one consider the filling of a square mould using four injection gates (see fig. 10), their positioning in the mold play an important role on the cycle time, numerical simulation allows predicting the optimal position of these injection ports. Here we give different statements of mold filling with two different thicknesses (thickness 1<thickness 2).

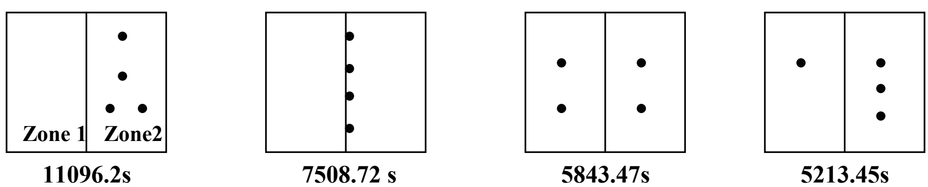


Figure 10: Mold filling time with multiple injection ports in different position in the mould

One can conclude from these results that the time of filling for the same cavity of the mold with the same processing conditions: injection pressure (4 bar), four injection ports, four vents, and by varying only the injection port replacement the time of filling is reduced to the half by comparison to the first case. This result highlights the interest of the numerical simulation in the optimization of cycle time and consequently to reduce processing cost of the composite part

Furthermore, our developed algorithm allows to predict with a high accuracy the temperature evolution over the saturated region of the mold at each time step, the heat transfer can be also investigated in molds with simple and complex geometries, that contain inserts, and the injection of resin can be accomplished either through one injection or multiple injection ports in order to reduce cycle time of all the process.

5 Conclusion

A computer code has been developed to simulate the two-dimensional mold filling in RTM. The resulting computer code allows one to analyze the resin flow, pressure and temperature distributions in the mold cavity. This information is helpful to design of tooling and processing conditions before the mold is built. The simulation results obtained by the code have been compared with analytical solutions and an excellent agreement is observed. The examples presented in this paper illustrate the flexibility and effectiveness of the developed computer codes for the simulation of complicated mold cavity including inserts.

These results can be generalised in further study to the development of three dimensional RTM simulation in which the use of conventional CV/FEM with classical resolution algorithm led to a high computation time reducing the applicability and practicality of 3-D simulations.

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