COMPUTATIONAL MODELLING OF THE RESIN TRANSFER MOLDING PROCESS

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Abstract. *The Resin Transfer Molding, or RTM, process has recently become one of the most important processes of fiber reinforced composites manufacturing. The process consists essentially of three stages: "an arrangement of fiber mats in a mold cavity, a mold filling by a polymeric resin and a curing phase". Most of the difficulties of incorporating RTM occur during the filling stage. To create an acceptable composite part the preform must be completely impregnated with resin. The conditions which most strongly influence the flow are mold geometry, resin rheology, preform permeability, and location of the injection ports and vents. There are different types of RTM process, e.g. RTM Light or VARTM, employed in accordance with the final desired characteristics and properties of composite components. Besides, RTM may also be carried out using multilayers, with distinct characteristics. The numerical simulation of the mold filling stage becomes an important tool which helps the mold designer to understand the process parameters. Considering the fibrous preform as a porous media, the phenomenon can be modeled by Darcy's law to describe resin flow. This study used two commercial softwares, FLUENT® and PAM-RTM®. FLUENT® is a general Computational Fluid Dynamics (CFD) code, based on Finite Volume Method (FVM). It applies the Volume of Fluid (VOF) method to solve the filling problem because it does not have a specific RTM module. PAM-RTM® is a specific package for RTM problems, based on the Finite Element Method (FEM). These tools were applied to simulate numerically several RTM examples of the resin flow into the mold and the results for both softwares were compared with previous works.*

Keywords: *Resin Transfer Molding; Numerical Simulation; FLUENT®; PAM-RTM®.*

1. INTRODUCTION

Resin transfer molding is a process for the manufacturing of fiber-reinforced composites. In recent years, liquid composite molding processes (LCM) and, particularly, resin transfer molding (RTM), are growing in importance in industrial sectors like aerospace and automotive (Sánchez *et al.* (2007)). Based on the work of Lee *et al* (2002), Liu *et al.* (2007) and Schmidt *et al* (2007), the RTM has been an industrial process since the 50's, however in recent years the production of parts through this process has increased significantly, mainly due to factors such as good finish on parts of complex geometry, low operational cost and the possibility of large scale production with lower environmental impact.

In the RTM process, composite parts are produced by the impregnation of a fibrous preform with a polymeric resin in a closed metallic mold (view Fig. 1). According to Schmidt *et al.* (2007), the molding involves the injection of a pre-catalyzed liquid resin into a closed mold containing a dry fibrous reinforcement and subsequent curing of the resin. For a successful molding, the residual air within the fibrous media must be totally eliminated. However, defects in the molded components can occur, for example, due to the partial impregnation of the reinforcement or the formation of micro-voids during infiltration.

In accordance with Amorim, (2007), the processing of RTM may seem a simple two steps process: preform preparation, followed by injection and curing of the resin, but this does not imply that this is an easy task. When a composite part is produced by RTM, in addition to the definition of design parameters (e.g. size, shape, weight, load) it is also necessary to verify if this part can be actually produced by RTM, considering factors like permeability, density and type of resin.

According to Jinlian *et al.* (2004), previous research revealed that the presence of voids is very undesirable and causes a deleterious effect on the mechanical properties of the product, such as inter-laminar shear strength, compressive strength, impact resistance and fatigue life. The research also revealed that void formation and development is correlated to injection pressure, outlet pressure, resin properties (viscosity, surface tension) and fabric characteristics (e.g. type and orientation of fibers, surface treatment).

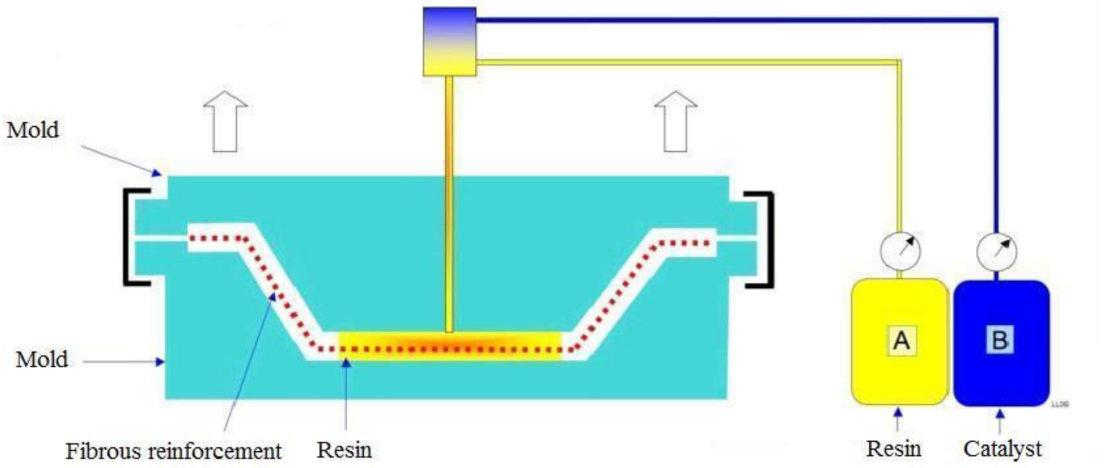

Figure 1 – Mold being impregnated by the resin during the RTM process.

According to Shojaei (2006), the main objectives of carrying out numerical simulations of the RTM process are to determine the progression of the flow, the location of the flow front line and the regions of possible void formation enabling an efficient mold design. For this reason, numerical simulation is a powerful tool in RTM, reducing times and costs and enabling process optimization. Shin *et al.* (2006) states that accurate prediction of flow advancement is of great use for saving processing time and enhancing product properties of the final part.

Depending on the characteristics of the final composite, it may be necessary to use multilayer reinforced media. In these cases, two or more layers of fibrous reinforcements, with different porosity and/or permeability, are used in the preform. Multilayer reinforced media is usually used when faster flow or better overall performance of the composite is needed.

In this work, a new analytical and numerical model of the resin flow in the RTM process with multilayer reinforcement media problems are presented and several example problems were solved. The new analytical model was developed in accordance with Bruschke *et al.* (1992), Calado and Advani (1996), Chen et al. (2004), Song *et al.* (2007) and Souza et al. (2008). The numerical modelling is based on the work of Silva et al. (2008) and Ribeiro et al. (2007).

2 ANALYTICAL MODELLING

According to Souza *et al.* (2008), the inner mold volume, which is to be impregnated with the resin, is considered a porous medium and the Darcy's law formulation may be used to determine resin transport through the mold. Experimental observations performed by Darcy showed that the fluid velocity through a column of porous material is proportional to the pressure gradient along the column. The mathematical formulation for this phenomenon may be expressed as:

$$\mathrm{V_i} = -\frac{\mathrm{K_{ij}}}{\mu}\nabla \mathrm{P} \tag{1}$$

where $V_i$is the velocity of the resin flow [m/s], μ the viscosity of the fluid [Pa s], K_{ij} the permeability tensor of the porous medium, P_i is the pressure and the indexes i, j = 1,2 or 3 represent the components of the coordinate system.

Considering the continuity equation for an incompressible fluid one have:

$$\mathrm{div\,V_i} = 0 \tag{2}$$

Combining Eqs. 1 and 2:

$$\text{div}\left(\frac{K_{ij}}{\mu}\cdot\nabla P_i\right) = 0 \tag{3}$$

According to Song *et al.* (2007):

$$Q_1 + Q_1^t = Q_2 - Q_1^t \tag{4}$$

$$Q_2 + Q_3^t = Q_3 - Q_3^t \tag{5}$$

where Q_i is the in-plane volumetric flow rate and Q_i^t is the transverse flow rate in the free surface of the *i*th layer. Song *et al*. (2007) also states that the unidirectional flow in each layer (see Fig. 2) can be calculated as:

$$\overline{u_1} = \frac{Q_1 + Q_1^t}{A_1} = u_1\varepsilon_1 \tag{6}$$

$$\overline{u_2} = \frac{Q_2 - Q_1^t - Q_3^t}{A_2} = u_2\varepsilon_2 \tag{7}$$

$$\overline{u_3} = \frac{Q_3 + Q_3^t}{A_3} = u_3\varepsilon_3 \tag{8}$$

where $\overline{u_i}$ is the average velocity.

Assuming that the pressure profile is linear in each region filled with resin, as proposed by Bruschke *et al.* (1992) and Calado *et al.* (1996):

$$P_1 = \frac{P_0\cdot(x_2 - x_1)}{2\cdot x_2} \tag{9}$$

$$P_3 = \frac{P_0\cdot(x_2 - x_3)}{2\cdot x_2} \tag{10}$$

where P_0 is initial pressure and P_1, P_3 is the time dependent pressure in layer 1 and 3 respectively.

Also, average transverse permeability was proposed by Chen *et al.* (2004) and Song and Yong (2007) as:

$$K_1^t = \frac{h_1 + h_2}{\frac{h_1}{K_{yy}^1} + \frac{h_2}{K_{yy}^2}} \tag{11}$$

$$K_3^t = \frac{h_3 + h_2}{\frac{h_3}{K_{yy}^3} + \frac{h_2}{K_{yy}^2}} \tag{12}$$

where h is the layer thickness (Fig. 2), and K_{xx}, K_{yy} are the transverse permeabilities.

Based on Darcy's law, in-plane and transverse volumetric flow rates in Fig. 2 may be described as:

$$Q_1 = \frac{2K_{xx}^1 P_0 A_1}{\mu x_1} \tag{13}$$

$$Q_2 = \frac{2K_{xx}^2 P_0 A_2}{\mu x_2} \tag{14}$$

$$Q_3 = \frac{2K_{xx}^3 P_0 A_3}{\mu x_3} \tag{15}$$

$$Q_1^t = \frac{2K_1^t P_1 (x_2 - x_1)}{\mu (h_1 + h_2)} \tag{16}$$

$$Q_3^t = \frac{2K_3^t P_3 (x_2 - x_3)}{\mu (h_3 + h_2)} \tag{17}$$

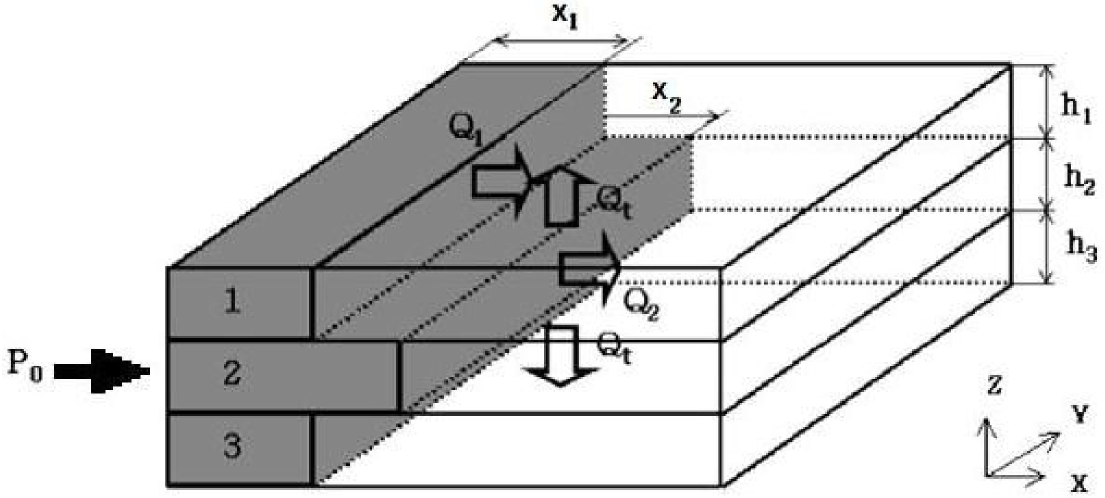

Figure 2 – Schematic diagram of flow advancement through the preform with sandwich structure (Song 2007)

Combining Eqs. 6, 9, 11, 13 and 16, one have:

$$x_1 = \frac{2K_{xx}^1 P_0 t}{\mu \varepsilon_1 x_1} + \frac{K_1^t P_0 (x_2 - x_1)^2 t}{\mu \varepsilon_1 (h_1 + h_2) h_1 x_2} \tag{18}$$

Similarly, combining the Eqs. 7, 9-12, 16 and 17:

$$x_2 = \frac{2K_{xx}^2 P_0 t}{\mu \varepsilon_2 x_2} - \frac{K_1^t P_0 (x_2 - x_1)^2 t}{\mu \varepsilon_2 (h_1 + h_2) h_2 x_2} - \frac{K_3^t P_0 (x_2 - x_3)^2 t}{\mu \varepsilon_2 (h_3 + h_2) h_2 x_2} \tag{19}$$

and Eqs. 8, 10, 12, 15 and 17:

$$x_3 = \frac{2K_{xx}^3 P_0 t}{\mu \varepsilon_3 x_3} + \frac{K_3^t P_0 (x_2 - x_3)^2 t}{\mu \varepsilon_3 (h_3 + h_2) h_3 x_2} \tag{20}$$

where $\varepsilon_{1,}$ $\varepsilon_{2,}$ ε_3 is the porosity in each layer, respectively.

Finally, solving Eqs. 19-21 simultaneously, it is possible to describe the resin flow advance into a mold with three layers.

3. NUMERICAL MODELLING

The numerical modelling of the mold filling was performed with the FLUENT® package and PAM-RTM®.

The PAM-RTM® is a specific software for RTM simulations. This computational package is based on Finite Element Method (FEM) and employ the Darcy´s Law to treat the porous medium problem.

The FLUENT® package is a general CFD software, where the Darcy´s Law and the Volume of Fluid (VOF) method are used to simulate RTM cases.

In the VOF method, the momentum, continuity and volume fraction equations must be solved simultaneously. The FLUENT® software includes a module for the solution of problems with two or more immiscible fluids where the position of the interface between the fluids is of interest. A single set of momentum equations is applied to both fluids, and the volume fraction of each fluid in every computational cell is tracked throughout the domain (Silva et al., 2008).

For the RTM process, the two phases involved in the problem are the resin (liquid phase) and the air (gaseous phase). Thus, the model is composed of the continuity equation, given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V_i) = 0 \tag{21}$$

the equation for the resin volume fraction f, defined by:

$$\frac{\partial (\rho f)}{\partial t} + \nabla \cdot (\rho f V_i) = 0 \tag{22}$$

and the momentum equation, given by:

$$\frac{\partial (\rho V_i)}{\partial t} + \nabla \cdot (\rho V_i V_i) = -\nabla P + \nabla \cdot \left[\mu \tau_{ij}\right] + \rho g_i + F_i \tag{23}$$

being ρ the specific mass, t the time, τ_{ij} the stress tensor, g_i the gravitational acceleration vector and F_i the external force.

As already mentioned, the reinforcement media inside the mold cavity may be considered a porous media. In FLUENT®, porous media are modeled by adding a source term to the standard momentum equations such as:

$$\mathrm{F_i} = -\frac{\mu}{\mathrm{K_{ij}}}\mathrm{V_i} \tag{24}$$

Combining Eqs. (23) and (24) and considering that F_i is very large – since K_{ij} is very small ($\sim$ 1 x 10^{-10}) – it is possible to simplify Eq. (23) as follows:

$$\nabla \mathrm{P} = -\frac{\mu}{\mathrm{K_{ij}}}\mathrm{V_i} \tag{25}$$

It is important to bear in mind that Eq. (25) represents Darcy’s Law in the same way as Eq. (1).

More information about the numerical simulation of the RTM process with this package can be found in Ribeiro *et al.* (2007) and Silva *et al.* (2008).

4. RESULTS

To demonstrate the validity and effectiveness of the developed analytical and numerical models presented in this work, some examples of RTM problems were studied: a) an isotropic rectilinear flow considering a preform with only one layer, b) an isotropic rectilinear flow considering a multilayer perform and c) a rectilinear flow considering a multilayer preform, with different permeability and porosity.

The inlet gate is placed in the left face and the outlet in the right face (Fig. 3), and the discretization of the computational domain was performed with triangular volumes (Fig. 4).

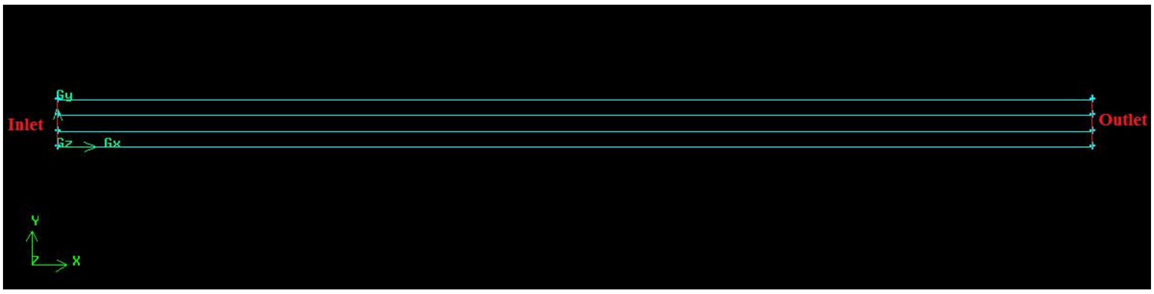

Figure 3 – Boundary Conditions

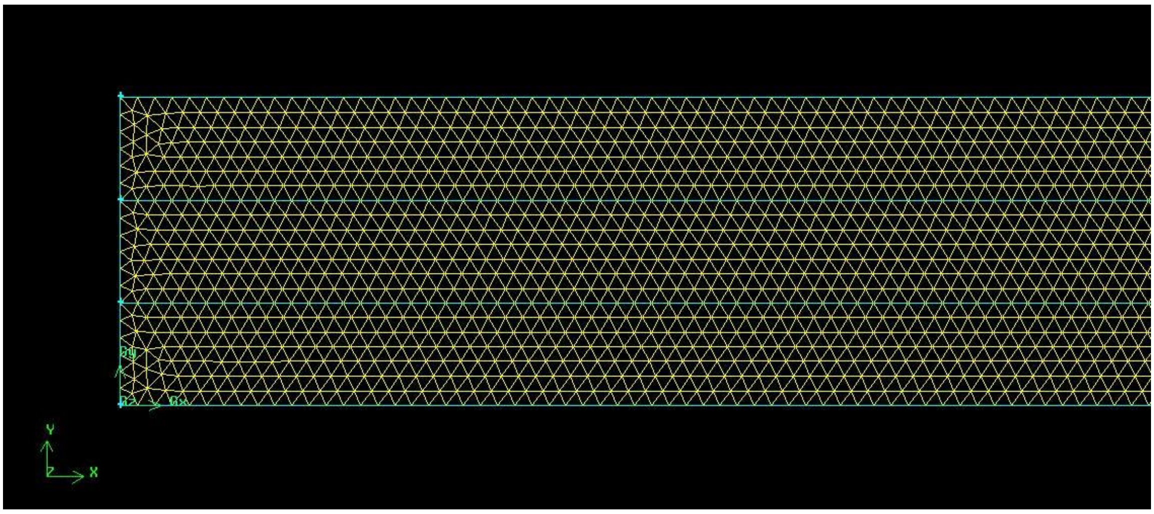

Figure 4 – Discretization of the geometry

4.1 ISOTROPIC RECTILINEAR FLOW – ONE LAYER

The geometry used to perform the simulation is shown in Fig. 3 where $K_{xx} = K_{yy} = 12.4\text{x}10^{-10} m^2$ are the permeability, $\mu = 9.70\text{x}10^{-2} Pa \cdot s$ the viscosity, $\varepsilon = 71.30\text{x}10^{-2}$ the porosity, h = 0.009 m the layer thickness, $x_f = 0.20\ m$ the resin front line final position, $P_0 = 0.10\text{x}10^5\ Pa$ the injection pressure and $\rho = 920.00\ kg/m^3$ the resin density.

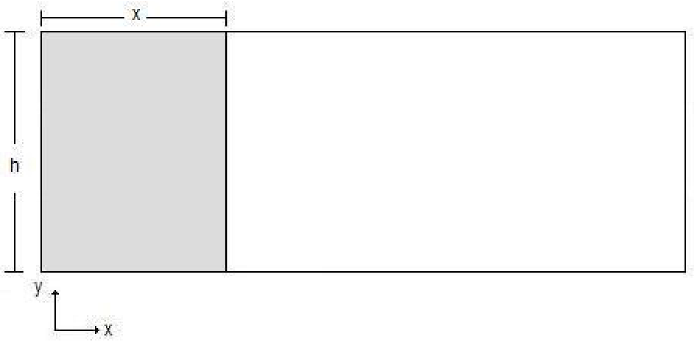

Figure 5 – Rectilinear flow geometry

The results obtained for this example is shown in Fig. 4. The analytical solution for this kind of rectilinear flow may be found in Hattabi et al. (2008) and Jinlian et al. (2004). Comparing the results obtained with the analytical solution and those with the numerical solution in this figure, it is possible to notice a perfect agreement. Therefore, the FLUENT® and PAM-RTM® packages were able to determine the flow front as a function of time in rectilinear RTM problems.

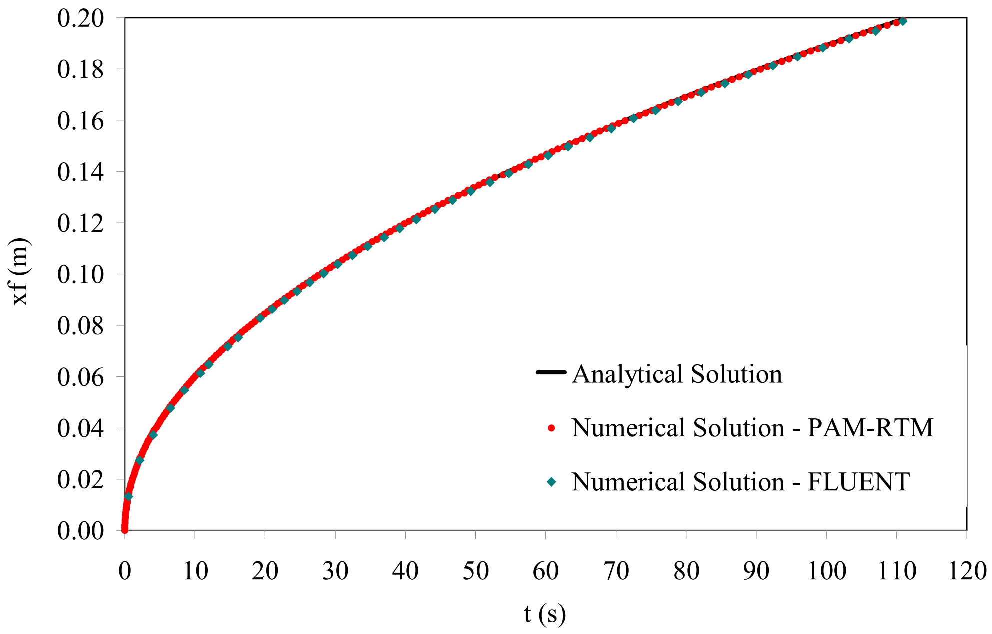

Figure 6 – Rectilinear flow solution: One layer.

4.2 ISOTROPIC RECTILINEAR FLOW – MULTILAYER

In this case, the same mold of the previous example was used, but now the mold was divided into three layers of the same thickness. The properties used are shown in Tab. 1 and the results are presented in Fig. 5.

Table 1 – Properties used in the isotropic multilayer problem

Layer	$K_{xx}(\text{x}10^{-10}m^2)$	$K_{yy}(\text{x}10^{-10}m^2)$	$\mu(\text{x}10^{-2}Pa \cdot s)$	$\varepsilon(\text{x}10^{-2})$	$P_0(\text{x}10^5 Pa)$	$h(m)$
1;2;3	12.4 x 10^{-10}	12.4 x 10^{-10}	9.70	71.30	0.10	0.003

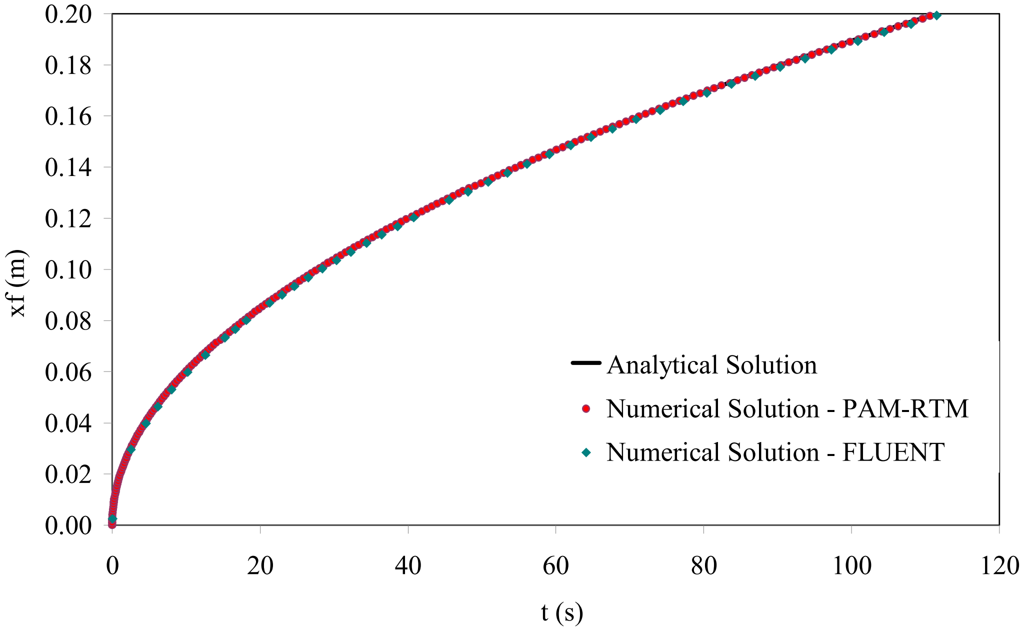

Figure 7 – Rectilinear flow – multilayer.

The results in Fig. 5, when compared to those in Fig. 4, show that the analytical solution (Eq. 18-20) developed in this work, when simplified for an isotropic case, can perfectly reproduce the behavior of the isotropic rectilinear flow. Besides, the results show that FLUENT® and PAM-RTM® are able to correctly simulate RTM multilayer problems.

4.3 RECTILINEAR FLOW – MULTILAYER

Finally, a RTM multilayer example where the layers have different properties was analyzed, comparing the analytical solution, represented by the set of equations presented in section 2.1, and the numerical solutions obtained with FLUENT® and PAM-RTM®. The properties and the analyzed geometry are shown in Tab. 2 and Fig. 6, respectively. In all cases, a triangular 16810-element mesh was used.

Table 2 – Properties used in the multilayer problem.

	$K_{xx}(\text{x}10^{-10}m^2)$	$K_{yy}(\text{x}10^{-10}m^2)$	$\mu(\text{x}10^{-2}Pa\cdot s)$	$\varepsilon(\text{x}10^{-2})$	$P_0(\text{x}10^5Pa)$	$h(m)$
1	12.4 x 10^{-10}	1.16 x 10^{-10}	9.70	71.30	0.10	0.003
2	57.8 x 10^{-10}	4.98 x 10^{-10}	9.70	61.30	0.10	0.003
3	12.4 x 10^{-10}	1.16 x 10^{-10}	9.70	71.30	0.10	0.003

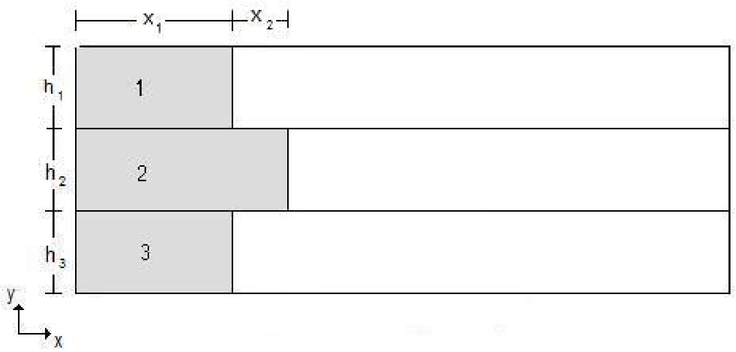

Figure 8 – Geometry for the multilayer problem (side view).

Comparison between the numerical solution and the analytical solution for layers 1 and 2 are presented in Figs. 7 and Fig. 8, respectively. In Fig. 7 it can be seen that the results from the numerical models have a good agreement with the analytical model. Here Fluent® obtained the best results of the PAM-RTM®.

In Fig. 7, the results for layer 2 have shown a good agreement between analytical and numerical model, although in this case, the PAM-RTM® obtained the best results.

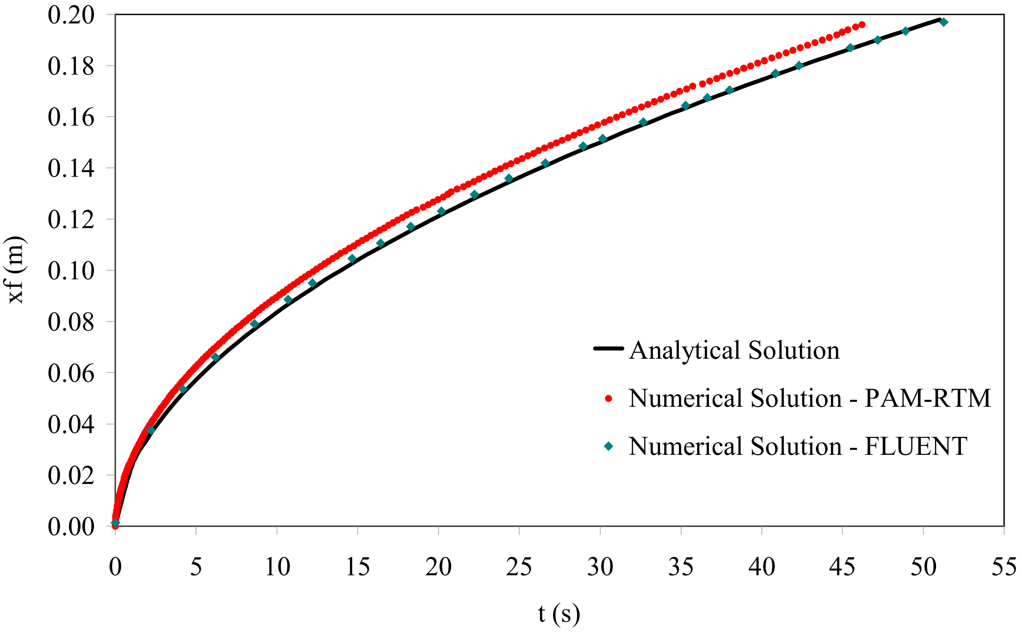

Figure 9 – Flow front in layer 1.

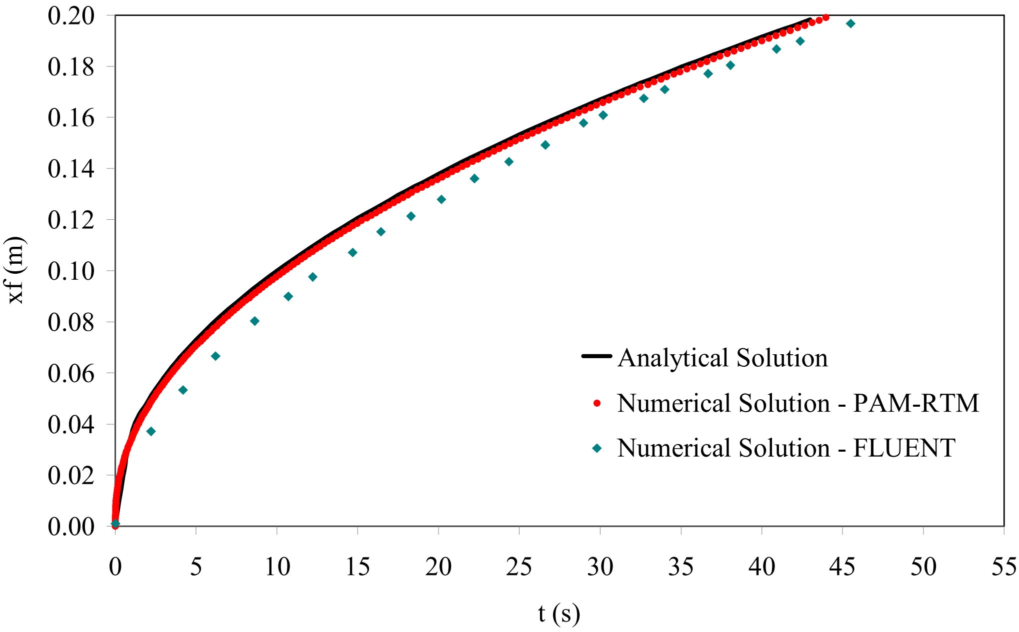

Figure 10 – Flow front in layer 2.

5. CONCLUSIONS

This work presents an analytical formulation and a numerical model (developed in FLUENT® package) for multilayer Resin Transfer Molding process. Firstly, an isotropic rectilinear example was solved. The results obtained with analytical formulation and with FLUENT® are in agreement with those generated by PAM-RTM® software (an specific code for RTM simulations). After that, the same problem was considered like a multilayer one, but considering the same properties and characteristics for each layer. The results are the same to the previous problem, what was already expected. Finally, a multilayer RTM problem was analyzed, showing the validity and effectiveness of the analytical formulation presented and the numerical model developed. Comparing the results generated by FLUENT® and the analytical formulation, differences of 0.49% (in layer 1) and 3.65% (in layer 2) were founded. And when the PAM-RTM® and FLUENT® results were compared, differences of 10.93% (in layer 1) and 5.55% (in layer 2) were encountered.

Therefore, it is possible to observe that the FLUENT® package, a general Computational Fluid Dynamics code, is able to solve the multilayer RTM problems presented in this work. Besides, the analytical formulation presented shows consistent results both for isotropic rectilinear RTM problems as for multilayer rectilinear RTM problems.

6. ACKNOWLEDGEMENTS

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