Resin transfer molding process: a numerical and experimental investigation

Iran Rodrigues de Oliveira[1], Sandro Campos Amico[2], Jeferson Ávila Souza[3] and Antonio Gilson Barbosa de Lima[1]*
[1]Department of Mechanical Engineering, Federal University of Campina Grande, 58429-900, Campina Grande-PB, Brazil
[2]Department of Materials Engineering, Federal University of Rio Grande do Sul, 91501-970, Porto Alegre-RS, Brazil
[3]Department of Mechanical Engineering, Federal University of Rio Grande, 96201-900, Rio Grande-RS, Brazil

ABSTRACT
Resin Transfer Molding (RTM) is one of the composite manufacturing technique that consists in injecting a resin pre-catalysed thermosetting in a closed mold containing a dry fiber preform, where the resin is impregnated. In this sense, the aim of this research is to study theoretically and experimentally the RTM process. Experimental and simulations of the rectilinear infiltration of polyester resin (filled and non filled with $CaCO_3$) in mold with glass fiber preform were performed in cavity with dimensions 320 × 150 × 3.6 mm. Numerical results of the filling time and fluid front position over time were assessed by comparison with experimental data and good accuracy was obtained. It was verified that, the $CaCO_3$ content affect resin velocity during filling, the permeability of the reinforcement and resin viscosity, thus the filling time is affected strongly.

Keywords: RTM, fiber composite, PAM-RTM, simulations, experimental

1. INTRODUCTION

Composite material can be defined as a combination of two or more materials on a macroscale to form a useful material, often showing properties that none of the individual independent components shows [1]. Today, there are a wide variety of processing methods available to produce polymer matrix composites such as hand lay up, injection molding, filament winding, RTM and its variations (RTM light, VARTM, etc.)

RTM technique consists in positioning the preform (i.e. porous fibrous reinforcement in the shape of the piece) within the mold. The mold, containing the preform and moist air, is closed and resin is injected into the mold cavity until the fibrous reinforcement is fully impregnated. After resin curing, the mold is opened and the composite is removed from the mold. This composite may still require finishing operations and/or to go through a post-curing process. The RTM mold must have at least one inlet port for resin injection and one outlet to enable, during resin injection, the output of air from inside the mold.

For a good RTM molding, it is necessary to know and control different processes parameters such as fluid viscosity, injection pressure, volumetric fraction of fiber, temperature and permeability of the medium. The injection pressure and temperature

---

*Corresponding author. E-mail: gilson@dem.ufcg.edu.br gradient are the main factors [2], so their optimizations are desirable for a correct filling of the mold and high productivity. Nowadays, RTM is used by many industrial sectors such as automotive, aerospace, civil and sporting equipment [3].

Usually, composites manufacturing use particle-filled resins for different purposes, such as cost reduction, mechanical properties increase or flame resistance improvement. The resin's viscosity increasing due to addition of particles load contributes to slowing the flow of resin and is responsible for (i) the appearance of spots with low wettability, (ii) poor saturation of the fiber tows (iii) or longer production cycle time [4].

Due to large industrial applications several researchers have devoted attention to study experimentally the RTM process such as Amorim júnior et al. [5], Gerlach et al. [6], Haider et al. [7] and Gourichon et al. [8].

Haider et al. [7] report a study about the effects of controlled material and processing parameters on the pressure variations, process cycle times and ultimately on the surface quality of RTM molded components. According to authors resins with low profile additives (LPA) are used to reduce cure shrinkage and improve surface quality of the composite parts. However, little is known about the behaviour of low profile resins during RTM manufacturing and their ultimate effects on the surface quality of molded plaques.

In addition to experimental studies, numerical analysis have been frequently used to predict the resin behavior within the preform/mold along the RTM process. For this purpose, there are different software dedicated exclusively to study RTM process such as PAM-RTM from ESI Group, the RTM-WORX from Polywork and the LIMS from the University of Delaware which are commonly used by industry for having a simple usage and focused only on this process. Further, there are non-dedicated commercial software commonly used to study CFD (*Computational Fluid Dynamics*) such as Ansys CFX® and FLUENT, both from ANSYS and Abaqus CFD from Simula Abaqus, which are simulation tools for fluid mechanics and heat transfer problems, capable of working with complex geometries and simulate the resin's advancement and curing within the mold. Several authors have studied the process of resin transfer molding by simulations, such as: Kuan et al. [9], Hattabi et al. [10], Machado et al. [11], Sánchez et al. [12] and Luz et al. [13].

Kuan et al. [9] reports that a control volume technique based on the finite difference method is used to characterize the flow behavior in resin transfer molding (RTM) of composite structures. Resin flow through fiber mats is modeled as a two-phase flow through porous media. The transient time terms are considered, and the concept of the volume fraction of fluid (VOF) is applied in order to accurately describe the behavior of the free boundary at the interface between the two fluids involved in the process, the resin and the air. Flow experiments in a transparent mold were performed to verify the numerical model. Experimental results on flow behavior of EPON 826 epoxy resin into irregular mold cavity with fiberglass mats agree well with the present numerical simulation. Several parametric studies using the developed model are conducted to investigate the effects of injection pressure and mold design on resin flow pattern, mold filling time, and pressure distribution inside the mold. Machado et al. [11] have used, the software Composite RTM Process 2 to simulate the injection of polyester resin in glass fibre reinforcements, in rectilinear and radial flow pattern. Simulations using polyester resin with $CaCO_3$ as filler were also performed. These simulations were compared to experimental and analytical results. The results were in agreement, within an expected error range, confirming that the flow may be analytically and numerically monitored.

Luiz et al. [13] discloses that it is possible to simulate the infiltration rectilinear in a porous mat of fibrous glass, using software PAM-RTM, and evaluate the influence of the parameters (viscosity of the resin, permeability of the medium and injection pressure) at speed of the RTM infiltration process.

In complement for these cited studies, this work aims to study a rectilinear infiltration in a glass fiber mat fibrous media by using simulation and experiments.

2. METHODOLOGY

2.1. EXPERIMENTAL STUDY

Experiments were performed injecting orthophthalic polyester resin in fiberglass mat for two different infiltration cases: Non-filled and $CaCO_3$ filled resin. Table 1 summarize informations about the studied cases and materials.

In these experiments it was used a RTM equipment shown in Fig 1.

The experiments were performed in a stainless steel RTM mold with cavity dimensions of 320 × 150 × 3.6 mm with the inlet and outlet points (vents) as shown in Figure 2. The mold has the top made of glass to enable viewing of the advance of fluid flow, and a camera positioned above the mold for monitoring this advance with the aid of a timer.

Figure 3 shows the calcium carbonate sample and Figure 4 shows the preform inserted in the mold. Detail about the equipment and experimental procedure can be found in the related literature [11, 13, 15].

Table 1 Cases studied in this work.

	Polyester resin		**Preform**		
Case	**$CaCO_3$ content (% mass/mass)**	**Density (kg/m^3)**	**Volumetric fraction (%)**	**Porosity**	**Glass fiber mat (g/m^2)**
1	0	1190	24	0.76	450
2	10	1260	24	0.76	450
3	20	1320	24	0.76	450
4	30	1380	24	0.76	450

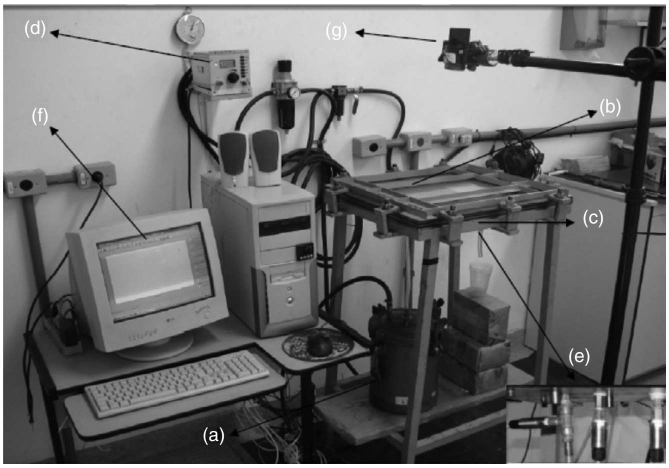


Figure 1 RTM experimental apparatus from LACOMP/UFRGS: (a) pressure vessel, (b) strengthened glass top mold, (c) steel lower mold, (d) pressure controller, (e) pressure transducers, (f) data acquisition system and (g) camera.

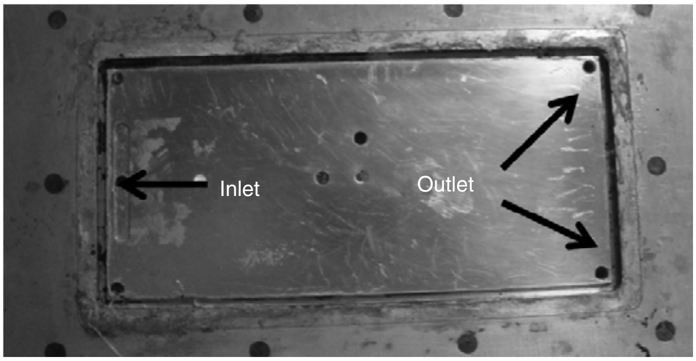


Figure 2 Stainless steel RTM mold without the preform and the top glass.

Figure 3 Calcium carbonate sample.

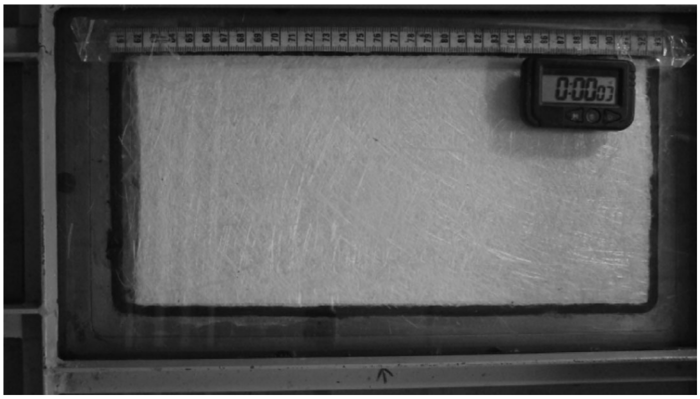


Figure 4 Preform inserted into the mold.

2.2. THEORETICAL STUDY

2.2.1. Mathematical modeling

In this research it was assumed an incompressible and newtonian fluid flow through a porous media. The mathematical model used is based on the Darcy`s law and is given as follows [7,16].

$$v = -\frac{1}{\mu} k \nabla P \tag{1}$$

And

$$\nabla . v = 0 \tag{2}$$

By combining these two equations, we get:

$$\nabla . \left(\frac{k}{\mu} \nabla P \right) = 0 \tag{3}$$

where v is the fluid velocity and vector P is the pressure.

2.2.2. Initial and boundary conditions

In this work, the following initial and boundary conditions were used.

a) Initial

The mold and preform are fully filled with moist air at prescribed gauge pressure (0.00 Pa).

b) Boundary conditions

b_1) Inlet port

At the inlet port, we use a prescribed gauge pressure as a function of time.

b_2) Mold wall

The mold wall was considered with non-flow, thus, pressure gradient is null.

b_3) Outlet port

In the outlet port we use a prescribed gauge pressure null.

b_4) Flow front

In the flow front position we consider that the gauge pressure is null along the filling process.

2.2.3. Numerical treatment

For obtain the numerical results, we use a PAM-RTM software. Herein we use a 2D mesh with dimensions 320 × 150 mm. In the mold, the rectangular region is specially designed to facilitate the formation of the linear profile of the resin forward advancement. This mold outline is required to be able, in laboratory experiments, to determinate the porous media permeability from the experimental data.

The mesh has 7077 elements and 3685 nodes, with better refinement in the zone near to the injection region. Figure 5 illustrates the mesh used in the simulation.

The model was solved using a non-conforming finite element approximation. In this numerical procedure, the pressure is discontinuous along the inter-element boundaries except at the middle nodes, and filling factors are associated with the mesh elements [6, 13]. Table 2 summarizes the initial and boundary conditions for the studied cases.

The porous media permeability was obtained by fitting the numerical data with the experimental data of the filling time.

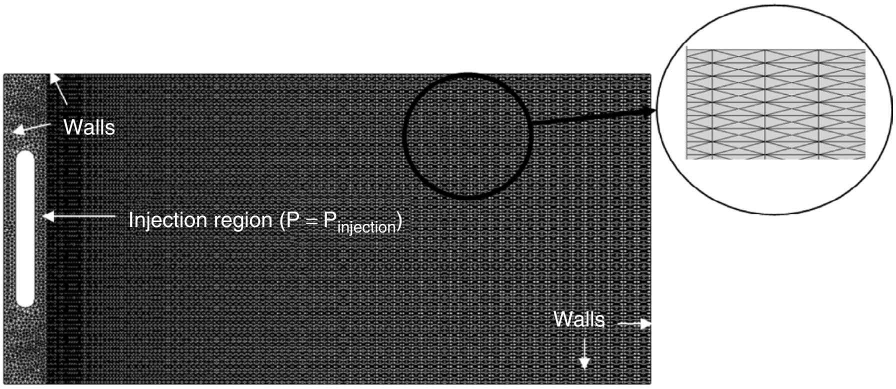


Figure 5 2D mesh used at the computational simulations with PAM-RTM.

Table 2 Filling time and physical parameters as a function of $CaCO_3$ content.

$CaCO_3$ content (% mass/mass)	Viscosity (cP)	Permeability ($10^{-10}m^2$)	Mobility (m^2/Pa.s)	Filling Time (s)
30	1352.53	5.50	5.72×10^{-13}	718
20	1414.46	3.00	2.22×10^{-13}	614
10	962.37	6.00	4.24×10^{-13}	2984
0	330.32	3.50	1.26×10^{-13}	1758

3. RESULTS AND DISCUSSIONS

Table 2 shows the differents parameters varying with the $CaCO_3$ content. It is observed that the resin viscosity increase with the increase of $CaCO_3$ content, thus, increasing the filling time i.e. the time for completion the fibrous media with resin. This is due to the presence of calcium carbonate particles among the fibers, hindering the resin flow through the fibrous media. For the cases with 20 and 30% $CaCO_3$ content, there was an agglomeration of particles at the beginning, thereby making it difficult to fill the mold. Then the case was considered caught when resin speed was less than 0.1 mm/s.

The linear relationship between the flow front position (x_{ff}^2) and filling time for all the cases is shown in the Figure 6. These lines behaviors indicated a linear relation between the position and time, allowing the Eq.(4) to be applied, thus, and to determine permeability of the fibrous media and fluid phase mobility resin.

The flow front advance case in the 0% $CaCO_3$, during the resin injection is shown in Figure 7. The rectilinear flow front profile has occurred at approximately half length of the mold. Initially, at the region close to the injection port, the flow has 2D characteristics and the flow front assumes a ring (radial) shape in the main flow direction. When the pressure gradient become linear, the flow front tends to become rectilinear (1D).

To validate the simulation obtained with PAM-RTM, results of the flow front position at differents moments were compared with experimental data, as shown in Figures 8, 9 and 10. Figure 8 shows the numerical flow front positions along the fibrous media for different processing times. In this case, resin is not filled with $CaCO_{3.}$ Figure 9 and 10 show the experimental and numerical flow front positions as a function of time for the case 30% $CaCO_3$ content. Results show that the PAM-RTM numerical solution is in good agreement with experimental results. Small errors are observed in the nonlinear (close to the injection

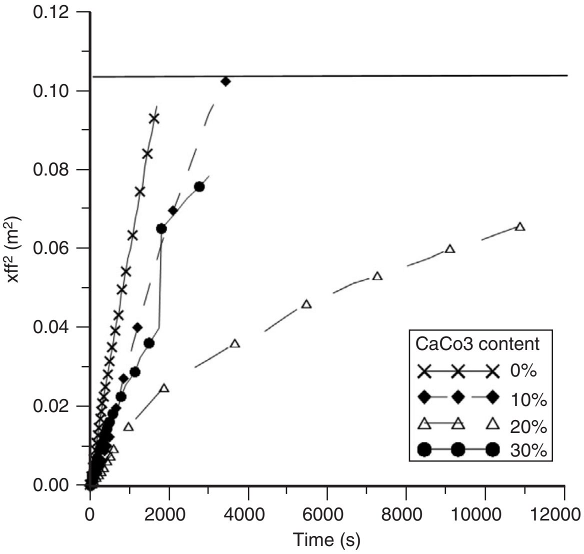


Figure 6 Linear relationship between the flow front position (x_{ff}^2) and filling time for all the cases.

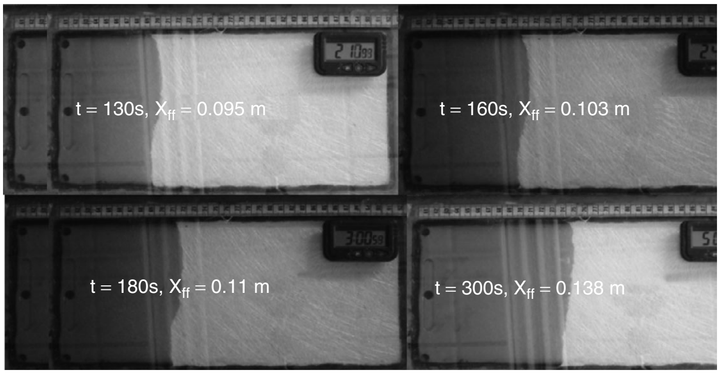


Figure 7 Flow front position (Experimental) in the non-filled resin case (0% $CaCO_3$ content) at different times.

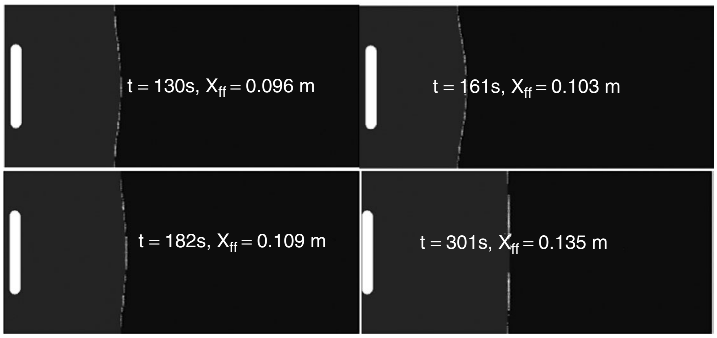


Figure 8 Flow front position (PAM-RTM simulation) in the case 0% $CaCO_3$ content at different times.

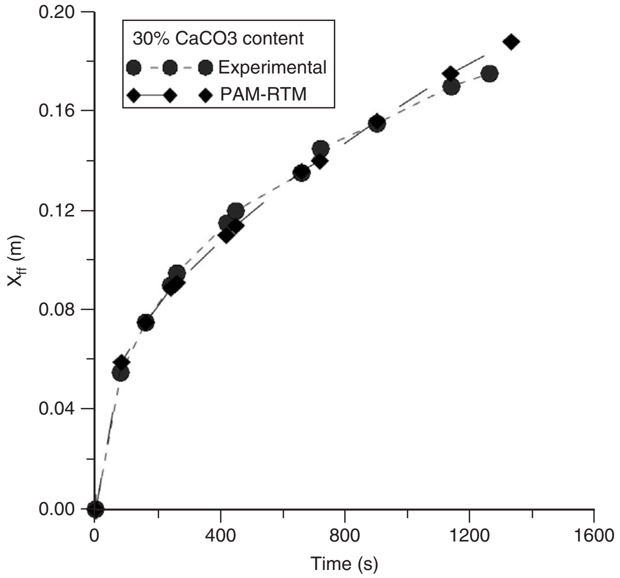


Figure 9 Resin front position versus time for the case 30% $CaCO_3$ content.

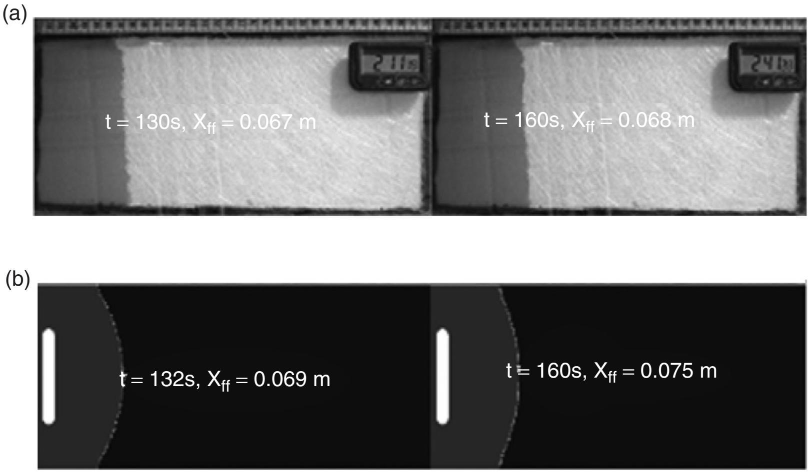


Figure 10 Comparative of the flow front position for the filled resin case (30% $CaCO_3$ content). (a) experimental data and (b) PAM-RTM solution.

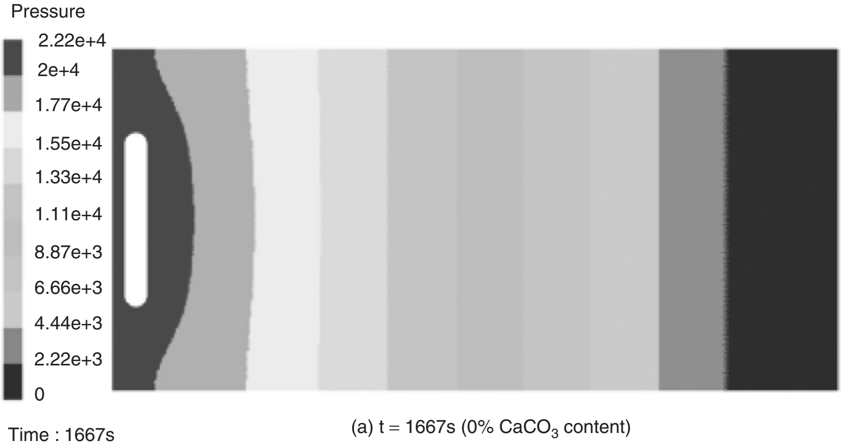
section) region. The difference is probably due to the 3D characteristic of the experimental setup on which the injection is performed through the bottom of the mold while in the numerical solution prescribed pressure was specified at the borders of the injection hole. Besides, the permeability was determined based on the 1D rectilinear flow (t>190s) [1, 11, 14, 15].

Table 3 shows the experimental results of the filling time and flow front position compared with the PAM-RTM numeric solution. From the analysis of this table we can see that a good agreement was obtained in all simulated cases.

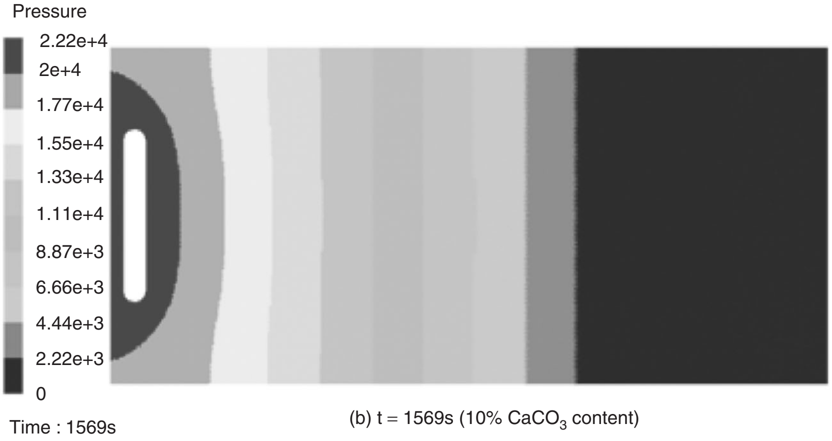
Table 3 Filling time and flow front position experimental and numeric results.

$CaCO_3$ content (%)	Filling time (s)			Flow front position (m)		
	Experimental	Numerical	Error	Experimental	Numerical	Error
30	718	718	0.0%	0.14	0.14	0.0%
20	614	618	0.6%	0.09	0.10	5.0%
10	2984	3065	0.2%	0.32	0.32	0.0%
0	1758	1756	0.1%	0.32	0.32	0.0%

Figure 11 illustrate the pressure behavior within the preform at differents filling times t = 1607 s (0% $CaCO_3$ content), t = 1577 s (10% $CaCO_3$ content), t = 1569s (20% $CaCO_3$ content) and t = 1577 s (30% $CaCO_3$ content), respectively. It is verified that the injection pressure obtained by the PAM-RTM numeric solution approaches to the experimental results obtained for the different cases (Figure 12). We can see that the higher pressure occurs in the injection port and lower pressure is verified in the vent port, as expected, because maximum and minimum pressures correspond to boundary conditions for the studied physical problem.



(a) t = 1667s (0% $CaCO_3$ content)



(b) t = 1569s (10% $CaCO_3$ content)

Figure 11 (*Continued*)

(c) t = 1577s (20% $CaCO_3$ content)

(d) t = 1577s (30% $CaCO_3$ content)

Figure 11 Pressure field obtained with PAM-RTM at differents filling time.

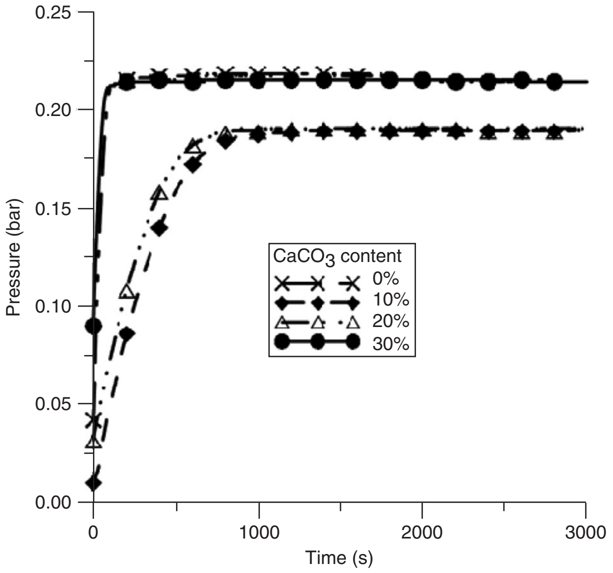


Figure 12 Injection pressure (at inlet port) versus filling time.

4. CONCLUSIONS

This paper provides numerical and experimental information about RTM process. The PAM-RTM commercial software has been applied to simulate resin flow in fibrous porous media. Through the numerical and experimental results it can be concluded that:

- The computational model represented well the physics of the problem; it was possible to simulate the total resin filling time for cases in study and predict the fluid flow front profile in the mold.
- Addition of $CaCO_3$ amending the permeability values, increases viscosity and the filling time. The numerical results showed good agreement with the experimental data in terms of front flow position, filling time and injection pressure.

ACKNOWLEDGEMENTS

The authors thanks to CNPq and CAPES for financial support, as well as to researchers referenced that with your research, helped in its improvement.

REFERENCES

[1] C. D. Rudd, A. C. Long, K. N. Kendall, and C. Mangin, *Liquid moulding technologies*,1a ed., Woodhead Publishing Limited, Cambridge England, 1997.

[2] D. A. Steenkamer, The influence of preform design and manufacturing issues on the processing and performance of resin transfer molded composites. Publishing House University of Delaware, 1994.

[3] K. T. Hsiao, Simulation-based liquid injection control (SLIC): Methodology and applications in RTM and VARTM. University of Delaware, *Center for Composite Materials*, 2003.

[4] D. Lefevre, S. Comos-Cardona Binétruy, and P. Krowczak, Modelling the flow of particle-filled resin through a fibrous perform in liquid composite molding technologies, *Applied Science Manufacturing*, 2007, Vol. 38 (10), 2154–2163.

[5] W. F. Amorim Júnior, G. Q. Chaves, V. M. A. Calado, and F. L. Bastian, Processing thick composite board by resin transfer molding. *Revista Matéria*, 2006, Vol. 11 (3), 316–323.

[6] R. Gerlach, C. R. Sivion, N. Petrinic, and J. Wiegand, Experimental characterisation and constitutive modelling of RTM-6 resin under impact loading. *Polymer*, 2008, Vol. 49 (11), 2728–2737.

[7] M. Haider, P. Hubert, and L. lessard, An experimental investigation of class a surface finish of composites made by the resin transfer molding process. *Composites Science and Technology*, 2007, Vol. 67 (15–16), 3176–3186.

[8] B. Gourichon, C. Binetruy and, P. Krawczak, Experimental investigation of high fiber tow count fabric unsaturation during RTM. *Composites Science and Technolog*y, 2007, Vol. 66 (7–8), 976–982.

[9] Y. Kuan and, A. S. ElGizawy, Numerical Characterization of mold injection in resin transfer molding process, *Advances in Polymer Technology*, 2000, Vol. 19 (3), 173–179.

[10] M. Hattabi, J. Echaabi and, O. Bensalah, Numerical and experimental analysis of the resin transfer molding process, *Korea&Australia Rheology Journal*, 2008, Vol. 20 (1), 7–14.

[11] G. L. P. Machado, A. C. Garay, P. B. Roese, T. M. Schmidt, J. A. Souza, and S. C. Amico, Numerical Simulation of Infiltration in Manufacturing Process for Composite RTM. *X CBpol-Brazilian Congress of Polymers*, 2009.

[12] F. Sánchez, J. A. García, L. Gascón and, F. Chinesta, Towards an efficient numerical treatment of the transport problems in the resin transfer molding simulation. *Computer Methods in Applied Mechanics and Engineering*. 2007, Vol. 196 (21–24), 2300–2312.

[13] F. F. Luz, S. C. Amico, J. A. Souza, E. S. Barbosa, and A. G. B. Lima, *Numerical Analysis of Heat and Mass Transfer in Porous Media*, edited by J. M. P. Q. Delgado, Antonio Gilson Barbosa de Lima and Marta Vázquez da Silva, Springer, Heidelberg (2012).

[14] J.A. Destephen, and K. J. Choi, Modeling of filtration processes of fibrous filter media. *Separations Technology*. 1996, Vol. 6 (1), 55–67.

[15] A. C. Garay, V. Heck, A. J. Zattera, J. A. Souza, and S. C. Amico, Influence of calcium carbonate on RTM and RTM light processing and properties of molded composites. *Journal of Reinforced Plastics Composites*, 2011, Vol. 30 (7), 1213–1221.

[16] PAM-RTM – *User`s Guide & Tutorials*, 2009.