

Resin Transfer Molding Process: A Numerical Analysis

Iran Rodrigues de Oliveira^{1a}, Sandro Campos Amico^{2b},

Jeferson Ávila Souza^{3c}, Antonio Gilson Barbosa de Lima^{1b}

¹Department of Mechanical Engineering, Federal University of Campina Grande (UFCG), Zip Code 58429-900, Campina Grande-PB, Brazil.

²Department of Materials Engineering, Federal University of Rio Grande do Sul (UFRGS), Zip Code 91501-970, Porto Alegre-RS, Brazil.

³Department of Mechanical Engineering, Federal University of Rio Grande (FURG), Zip Code 96201-900, Rio Grande-RS, Brazil.

^arodrigues.iran@hotmail.com, ^bamico@ufrgs.br, ^cjasouza@furg.br, ^bgilson@dem.ufcg.edu.br

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Abstract. This work aims to investigate the infiltration of a CaCO₃ filled resin using experiments and the PAM-RTM software. A preform of glass fiber mat, with dimensions 320 x 150 x 3.6 mm, has been used for experiments conducted at room temperature, with injection pressure of 0.25bar. The resin contained 10 and 40% CaCO₃ content with particle size 38µm. The numerical results were evaluated by direct comparison with experimental data. The flat flow-front profile of the rectilinear flow was reached approximately halfway the length of the mold. It was observed, that the speed of the filling decreases with increasing CaCO₃ content and, the higher the amount of CaCO₃ in the resin, the lower the permeability of the reinforcement that is found. The reduction in permeability is due to the presence of calcium carbonate particles between the fibers, hindering the resin flow in the fibrous media. The computational fluid flow analysis with the PAM-RTM proved to be an accurate tool study for the processing of composite materials.

Introduction

The process of resin transfer molding offers many advantages over other manufacturing processes for composites, including low cost of skilled labor, tooling simple, time cycles satisfactory, fabrication of complex structures with quality, and do not require pre-impregnated, or prepreg. This process consists of injecting a thermoset resin through a fibrous media in a closed mold.

In the RTM process, there are some factors that should be known and controlled as the resin viscosity, injection pressure, content and arrangement of the fibers, porosity, process temperature and permeability of the porous media. The injection pressure and temperature gradient, for example, must be optimized so that the finishing of the composite and productivity is suitable [1].

In addition to experimental studies, numerical analysis software has frequently been used to predict the resin behavior within the preform/mold along the RTM process, evaluate the filling time (which should be less than the resin's gel time), evaluate deficient impregnation points and determine the resin injection points and vent ports [2]. 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. The non-dedicated commercial software commonly used to study CFD (*Computational Fluid Dynamics*) are 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, such as: Oliveira et al. [3]; Shi and Dong [4]; Saouab et al. [5]; Gelin et al. [6]; Sánchez et al. [7]; Jiang et al. [8]; Luz et al. [9]; Rudd [10] and Luz et al. [11].

In order to complement these cited studies, this work aims to simulate a resin rectilinear infiltration in a glass fiber mat fibrous media using the PAM-RTM software, and evaluate the influence of process parameters, such as resin viscosity, porous media permeability and CaCO₃ content, at the resin infiltration velocity in the porous media.

Methodology

For the numerical results validation, experiments were performed injecting orthophthalic polyester resin in fiberglass mat for two different infiltration cases:

- Filled resin with 10% CaCO₃, composite density $\rho = 1260 \text{ kg/m}^3$, fiber volume fraction $V_f = 30\%$, porosity $\phi = 0.7$;
- Filled resin with 40% CaCO₃, composite density $\rho = 1430 \text{ kg/m}^3$, fiber volume fraction $V_f = 30\%$, porosity $\phi = 0.7$;
- CaCO₃ granulometry $38\mu\text{m}$

In this work, we use a mold with dimensions $320 \times 150 \times 3.6 \text{ mm}$. 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. Detail about the equipment and experimental procedure can be found in [1, 6, 10,11]. The mesh obtained by PAM-RTM commercial code has 7077 elements and 3685 nodes, with better refinement in the zone near to the injection region.

In all simulations it was assumed an incompressible fluid flow through a porous medium. The numerical model used is based on Darcy's law, and is given as follows [1,10]:

$$\vec{v} = -\frac{1}{\mu}k\nabla P \quad (1)$$

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

where \vec{v} is the fluid velocity vector [m/s]; k is the porous media permeability [m²]; ∇P is the pressure gradient [Pa/m] and μ is the resin viscosity (considered as a Newtonian fluid) [Pa.s].

The model was solved using a non-conforming finite element approximation. The pressure is discontinuous along the inter-element boundaries except at the middle nodes, and filling factors are associated with the mesh elements [12]. Table 1 summarizes the initial and boundary conditions for the studied cases.

Table 1 - Initial and boundary conditions for the studied cases.

Filled resin with 10% CaCO ₃	Filled resin with 40% CaCO ₃
$P_{\text{inlet}} \rightarrow$ varying from 0 to 22900 Pa (manometric)	$P_{\text{inlet}} \rightarrow$ varying from 0 to 20300 Pa (manometric)
Wall \rightarrow zero pressure gradient	Wall \rightarrow zero pressure gradient
$P_{\text{front flow}} = 0 \text{ Pa}$ (manometric)	$P_{\text{front flow}} = 0 \text{ Pa}$ (manometric)
$T_{\text{resin,inlet}} = 289.5 \text{ K}$	$T_{\text{resin,inlet}} = 289.3 \text{ K}$

Results and Discussion

Table 2 shows results for viscosity and permeability as a function of calcium carbonate content and injection pressure. It is observed that the addition of CaCO₃ affects slightly the permeability and increases the viscosity. It is realized that the higher the concentration of CaCO₃ in the resin,

modifies slightly the permeability due to the inherent characteristics of the experimental method used for estimation of this parameter (rectilinear flow) and so varying the properties of the fibrous reinforcement.

Table 2 – Viscosity and permeability data for each experiment.

	Viscosity (cP)	Maximum injection pressure (bar)	Permeability ($\times 10^{-10} \text{ m}^2$)
10% CaCO ₃	962	0.229	1.77
40% CaCO ₃	2113	0.200	1.78

With the increasing in fluid viscosity, increases the filling time (the time for completion of the fibrous media with resin) as show in Table 3, where the experimental results are compared with the PAM-RTM numerical solution.

Table 3 – Filling time for experimental and numeric results.

	Filling time (s)		
	Experimental	Numerical	Error
10% CaCO ₃	850	852	0.3%
40% CaCO ₃	380	383	0.7%

Figs. 1 and 2 illustrate the pressure behavior within the preform for the filling times $t = 8020 \text{ s}$ (10% CaCO₃) and $t = 7896 \text{ s}$ (40% CaCO₃). It is perceived that the injection pressure obtained by the PAM-RTM numeric solution approaches the experimental results obtained for both cases. We can see that the higher pressure occurs of 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.

The flow front advance in the 10% CaCO₃ case during the resin injection is shown in Fig.2. The rectilinear flow front profile has occurred at approximately half the 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 form 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, the results of the flow front position were compared with experimental data, as shown in Figs. 3, 4 and 5. Results show that the PAM-RTM numerical solution is in good agreement with experimental results. A large error is observed in the nonlinear (close to the injection 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 is specified at the borders of the injection hole. Besides, the permeability was determined based on the 1D rectilinear flow ($t > 100\text{s}$) [1,6,9,10].

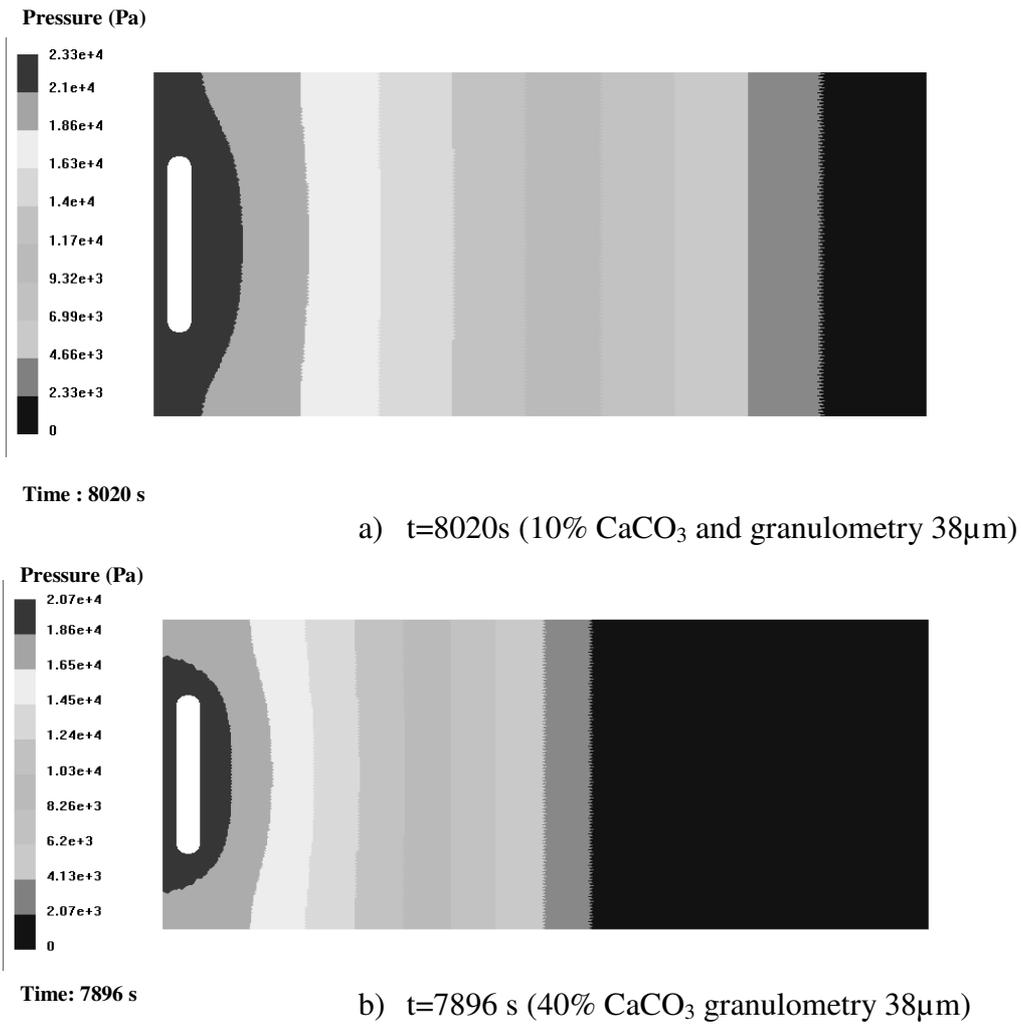


Figure1- Pressure field obtained with PAM-RTM software.

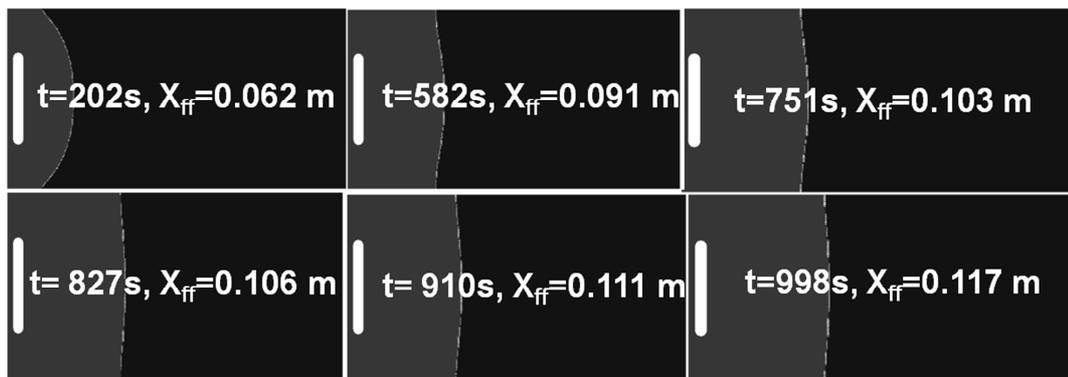


Figure 2 - PAM-RTM simulation for the front flow in the case 10% CaCO_3 and granulometry $38\mu\text{m}$ at different times.

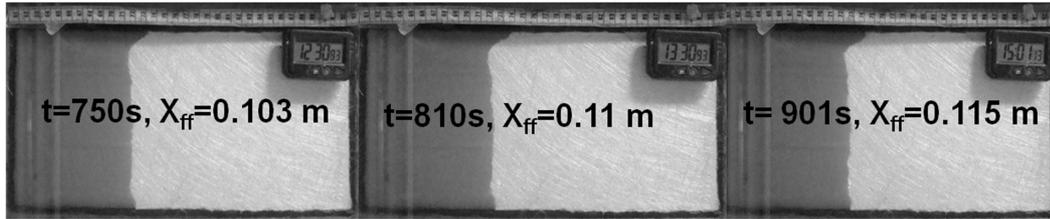


Figure 3 - Experimental front flow in the filled resin case 10% CaCO₃ and granulometry 38μm at different times.

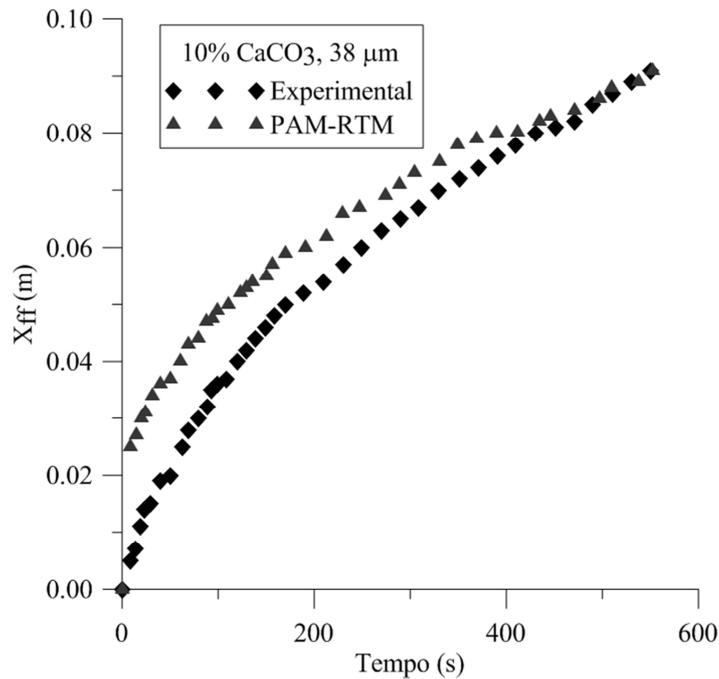


Figure 4 - Resin position inside the mold versus time for the case 10% CaCO₃ and granulometry 38μm.

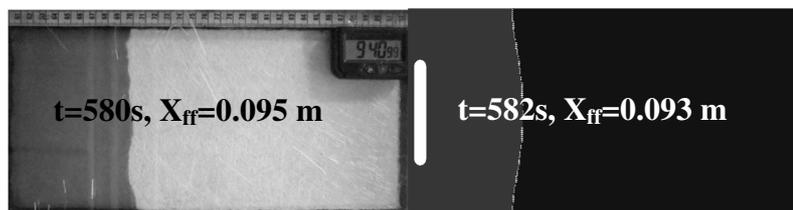


Figure 5 - Comparative of the experimental data (a) and PAM-RTM solution (b) for the fluid flow front for the filled resin case (10% CaCO₃ and granulometry 38μm).

Comparing the PAM-RTM results with the experimental data for the time 580 s for the filled resin (10% CaCO₃ with granulometry 38μm) and filled resin cases (Figs. 2, 3 and 5), we can observe the effect of adding calcium carbonate in the filling time, the higher the CaCO₃ concentration in the resin, the higher the filling time. This is due to the presence of calcium carbonate particles among the fibers, hindering the resin flow through the fibrous media.

Conclusions

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

a) The computational model represented well the physics of the problem, it was possible to simulate the total resin filling time for both cases (10 and 40% CaCO₃) cases and predict the fluid flow front profile in the mold.

b) Addition of CaCO₃ modifies the permeability values, increases viscosity and the filling time.

c) Numerical results showed good agreement with the experimental data in terms of front flow position, filling time and injection pressure.

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References

- [1] F. F. Luz: "Comparative Analysis of Fluid Flow in Experiments Using RTM Commercial Applications" Master`s Thesis. Federal University of Rio Grande do Sul, Brazil, 2011. (In Portuguese)
- [2] R. Stewart: *Reinf. Plast.*, Vol. 46 (2002), n.6, p.36-39.
- [3] I. R. Oliveira, S. C. Amico, F. F. Luz, J. A. Souza, R. Barcella and A. G. B. Lima: *Defect Diffusion Forum*, Vol. 334-335 (2013).
- [4] A. Shi and X. Dong,: *Finite Elem. Analy. Des.* Vol.47 (2011), n.7, p.764-770.
- [5] A. Saouab, J. Bréard, P. Lory, B. Gardarein and G. Bouquet: *Comp. Sci. Technol.* Vol. 61(2001), n.3, p.445-451.
- [6] J. C. Gelin, A. Cherouat, P. Boisse, and H. Sabhi: *Comp. Sci. Technol.* Vo. 56 (1996), n.7, p.711-718.
- [7] F. Sánchez, J. A. García, L. Gascón and F. Chinesta: *Comput. Meth. Appl. Mech. Eng.* Vol.196 (2007), n.21-24, p. 2300-2312.
- [8] S. Jiang, L. Yang, S. Alsoliby and G. Zhou: *Comp. Sci. Technol.*, Vol.67 (2007), n.15-16, p.3316-3322.
- [9] F. F. Luz, S. C. Amico, A. L. Lima, E. S. Barbosa and A. G. B. Lima: *Defect Diffusion Forum*, Vol 326-328 (2012).
- [10] C. D.Rudd, K. N. LAC and C. G. E. Mangin: *Liquid Moulding, Structural Reaction Injection Moulding and Related Processing Techniques*. Woodhead, Publishing Limited, 1997.
- [11] F. F. Luz, S. C. Amico, J. A. Souza, E. S. Barbosa and A. G. B. Lima, in: *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).
- [12] PAM-RTM – User`s Guide & Tutorials, 2009.