AN ORIGINAL PROCEDURE TO DETERMINE TRANSVERSE PERMEABILITY USING A MULTILAYER REINFORCEMENT IN RTM

Oliveira, Cristiano P., cristiano.oliveira78@gmail.com
Souza, Jeferson A., jasouza@furg.br
Isoldi, Liércio A., liercioisoldi@bol.com.br
Rocha, Luiz A. O., larocha@gmail.com
Escola de Engenharia, Universidade Federal de Rio Grande
Amico, Sandro C., amico@ufrgs.br
Silva, Rafael D. S., rafael.sonaglio@ufrgs.br
Departamento de Engenharia de Materiais, Universidade Federal do Rio Grande do Sul

Keywords: *Resin Transfer Molding; Numerical Simulation; Transverse Permeability*

Resin Transfer Molding (RTM) is a manufacturing process for polymer composites parts for a variety of uses. The numerical simulation of the resin flow into the mold can be used to minimize costs related to mold design and the manufacturing process itself. However, to obtain realistic results, accurate information about the resin and the reinforcement media are necessary. In the multilayer RTM, distinct porous media layers are stacked to obtain a final composite with better performance. For the numerical simulation of the multilayer RTM, transverse permeability (K_{zz}) data are necessary. This work proposes an original methodology to determine the transverse permeability in multilayer RTM composites, assuming that the in-plane permeabilities (K_{xx} and K_{yy}) are known and using this information, combined with experimental data obtained during mold filling. The motivation of this study is the fact that the transverse permeability is usually not available in the literature, being referred to as a difficult parameter to be directly determined using experiments.

1. INTRODUCTION

The RTM process is a manufacturing process in which a polymeric resin is injected into a closed metallic mold. This process has been used in the industry since the 1950s, however the production of pieces with the RTM process has increased significantly in recent years. This is mainly due to factors like good finishing in both sides of the parts with complex geometry, low operating costs and suitability to large scale production (Amico, 2005; Molina et al., 1994).

The automotive, aeronautic and aero-spatial industries are the most promising sectors to expand the use of the RTM process. In the automotive industry, for example, it is possible to produce a number of parts including panels, truck hoods and internal finishing pieces. Moreover, another advantage of the RTM process is that it is possible to use natural fibers, such as sisal (Amico, 2010), as reinforcement media, what is in accordance with the, current environmental tendencies of the society.

The RTM process (Fig. 1) can be summarized by three basic steps: pre-processing, injection and post-processing. In the pre-processing step, according to Amoring (2007), a preform (reinforcement in the shape of the part) is produced and positioned inside the mold, which is then closed. The second step is the injection itself. It is in this step that the resin will fill the mold, impregnating the reinforcement media. It is necessary at least one injection point and one outlet, however depending on the complexity of the piece, more injection and/or outlet points can be added to the mold. During this phase, the pressure and the resin advancement are constantly monitored. The third and last step is the post-processing. During this phase the resin will cure and cool down, and the mold will be disassembled (opened).

The reinforcement media used in the RTM process can be either a synthetic or natural fiber. Natural fibers are renewable and for this reason reduce the environmental impact of the final material. The search for reducing the environmental impact and costs and increasing performance leads, in some cases, to the use of hybrid or multilayer composites.

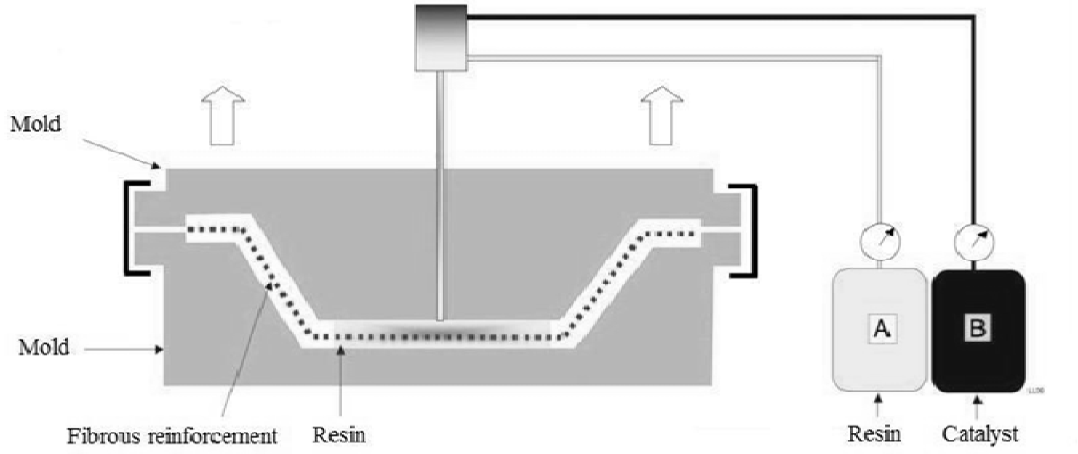

Figure 1 – RTM Process (LaurensvanLieshout, 2009)

In the multilayer RTM, distinct porous media layers are stacked inside the mold that will be injected with the polymeric resin. In this process, one of the important control variables is the transverse permeability which is difficult to be obtained experimentally and normally not reported in the literature. The main motivation for the present this work focuses on the importance of the precise determination of the transverse permeability in multilayer reinforcements for the numerical modeling of the resin advance within the mold. Herein, an original methodology for the determination of transverse permeabilities using multilayered reinforcement media in the RTM process is proposed. The procedure combines experimental data (in-plane permeabilities and total filling time) and numerical simulation of the resin flow inside the mold cavity.

2. COMPUTATIONAL MODELING OF THE RTM PROCESS

Nearly all mathematical models used to describe the resin advance inside the mold in the RTM process are based on Darcy's Law for porous media. This can be mathematically expressed as

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

where V_i is the velocity [m/s], μ is the viscosity [Pa s], K_{ij} the permeability tensor [m^2] and P is the pressure [Pa]. The sub indexes *i* and *j* indicates the components of the Cartesian coordinate system.

The FLUENT® software was used for the numerical solution of the problem. This is a general CFD (Computational Fluid Dynamics) code in which the VOF (Volume of Fluid) method (Hirt and Nichols, 1981) was used for the multiphase (resin + air) flow solution inside the mold geometry.

According to Minussi (2007), Luoma and Voller (2000) and Maliska and Vasconcellos (1998), the VOF is a method to solve multiphase flows in which all fluids are immiscible. In the VOF method, the fluid phases are well defined, i.e., the phases are separated and the volume used (occupied) by one phase can not be used by another phase. The representation of the various phases within a unique volume (or element) is obtained by the definition of the volumetric phase fraction, *f*. Inside a volume, it is assumed that the fluid fractions, f_i, are continuous in space and time and that their sum is always equal to 1. Therefore, in the volumes with $0 < f_i < 1$, two or more phase coexist, if $f_i = 0$, the *i* phase does not exist in that volume, and if $f_i = 1$, only the *i* phase exists in that volume.

In the VOF method, the continuity, volumetric fraction and momentum equations form a system of partial differential equations given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V_i) = 0 \tag{2}$$

where ρ is the density [kg/m^3].

$$\frac{\partial(\rho f_i)}{\partial t} + \nabla \cdot (\rho f_i V_i) = 0 \quad (3)$$

where f_i is the volumetric fraction of the i phase, and

$$\frac{\partial(\rho V_i)}{\partial t} + \nabla \cdot (\rho V_i V_i) = -\nabla P + \nabla \cdot [\mu \tau_{ij}] + \rho g_i + F_i \quad (4)$$

where g_i is the gravity [m/s^2], τ_{ij} the stress tensor [Pa] and F_i the external force term [N].

In Eq. (4), F_i is used to include a resistive force due to the porous media in the momentum equation. This is actually the Darcy's Law, Eq. (1), written as

$$F_i = -\frac{\mu}{K_{ij}} V_i \quad (5)$$

Solution of Eqs. (1-4) results in the determination of the resin advance inside the mold cavity as a function of space and time. This information is important for both mold design and the manufacturing process itself.

3. POROUS MEDIA PERMEABILITY MEASUREMENTS

Permeability is the property used to evaluate the resistance imposed to the fluid flow by the porous media. For the precise prediction of the resin advance inside a RTM mold cavity, it is necessary to correctly evaluate the reinforcement permeability as well as the physical properties of the resin (Schimidt *et al.*, 2007). There are a number of studies about the permeability in reinforcement media for RTM and these works usually report the planar permeability measured following rectilinear or radial infiltrations (Alves, 2006; Calado *et al.* 1996). When the main goal of the work is to determine the properties of the reinforcement, a Newtonian fluid usually replaces the resin in the experiment (Schimidt et al., 2007). This procedure does not compromise the precision of the measurements and has two major advantages: low cost and easy handling.

The transverse permeability (Visconti et al. 2003; Ballata et al. 1999) is an important property to be determined when the study focuses in parts where the transverse width can not be neglected and the resin flow is tree-dimensional. However, its measurement is difficult if compared with the measurement of the planar permeability and, due to this reason, the number of works found in the literature reporting about this permeability is small. The transverse permeability is also important for the modeling of the resin flow in a multilayered reinforcement. In this case, the transverse flow between different layers must be correctly quantified and this can not be carried out unless the permeability in the transverse direction is known.

In the present work, a new iterative algorithm is proposed for the prediction of the transverse permeability in multilayered RTM. The procedure combines experimental data (in-plane permeabilities and total filling time) and numerical simulation of the resin flow inside the mold cavity.

4. DETERMINATION OF THE TRANSVERSE PERMEABILITY

The proposed numerical/experimental procedure for the determination of the transverse permeability uses experimental data for the in-plane permeabilities and mold filling times with successive (iterative) numerical solutions of the resin flow considering a known multilayered reinforcement porous media. The in-plane permeability of each layer is measured in a single layer experiment (homogeneous reinforcement) and considered to remain unaltered in the multilayer assemble for an equivalent fiber content. The transverse permeability is then calculated by an iterative procedure given by:

(i) estimate K_{zz};
(ii) calculate (numerically) the filling time;
(iii) compare experimental (t_{exp}) and numerical (t_{num}) filling time
  if / $t_{exp} - t_{num}$/ < tolerance → **end** simulation
  else return to step 1

Steps (i) to (iii) are repeated until the determination of the transverse permeability in which the numerically predicted filling time equals (within a defined tolerance) the measured experimental time.

5. RESULTS

In the present analysis, a two-layer reinforcement media is used to demonstrate the transverse permeability determination. The mold geometry is presented in Fig. 2. This geometry was discretized and the 3D problem was solved using the FLUENT® software. A detailed description of the numerical simulation using this geometry for a single layer problem is found in Oliveira et al. (2009).

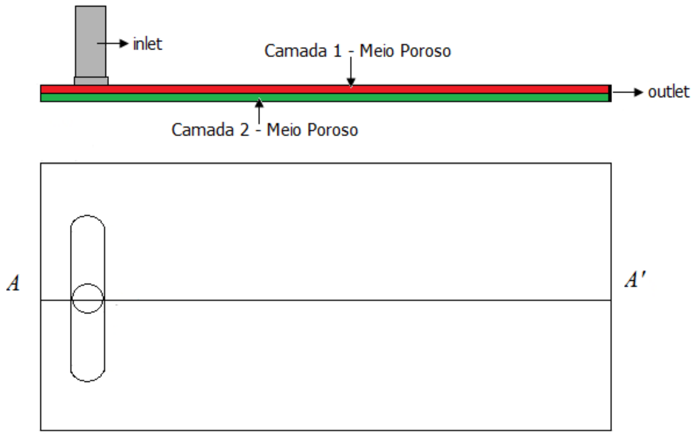

Figure 2 – Schematic representation of the two-layer reinforcement media

In a preliminary study, two identical layers (with homogeneous reinforcement properties) were considered. The numerical and experimental solutions were used to adjust the model and set up the problem for the multilayer solution. Glass fiber was used as reinforcement media with constant permeability ($K_{xx} = K_{yy} = K_{zz} = 1.12 \times 10^{-9}$ m^2) and porosity ($\varepsilon = 0.811$). Soybean oil (density $\rho = 919$ kg/m3 and viscosity $\mu = 0.065$ Pa s) was injected at constant pressure $P_0 = 0.054$ bar and the characteristics of the fluid were considered constant in all analysis.

Experimental and numerical results for the two-layer homogeneous problem are shown in Fig. 3. In this figure, the resin front line position (x_f) is plotted as a function of time (t) along the symmetry line *AA'*. Both curves showed the same tendency and good agreement. The total filling time, which is later used for the transverse permeability (K_{zz}) determination, presented good agreement reaching $((t_{exp} - t_{num})/t_{exp} \sim 0.28)$.

The K_{zz} determination procedure is demonstrated in the following section by solving two case studies, detailed below.

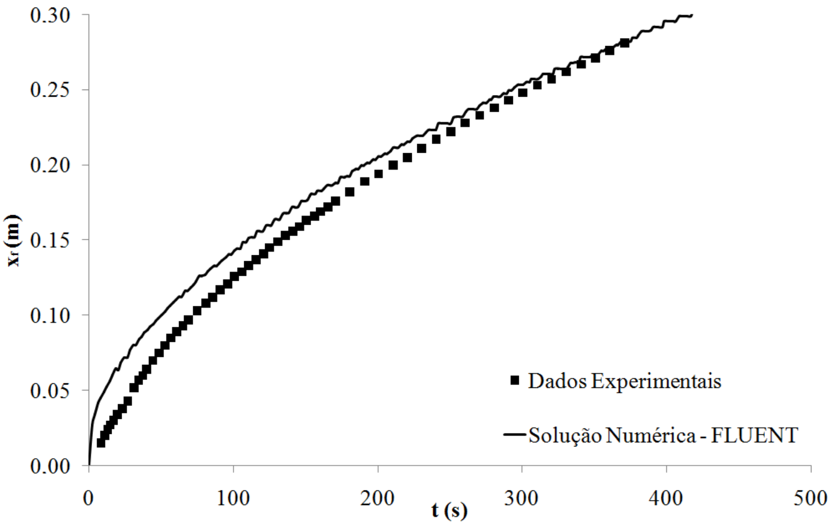

Figure 3 – Homogeneous solution for the two-layer case

5.1. ***Case study 1***:

In the first solution, the reinforcement media is built with two distinct layers: polypropylene fiber (layer 1) and glass fiber (layer 2). The permeability of each layer was obtained experimentally in single layer runs and assumed to remain unchanged in the two-layer assemble (because the fiber content in that layer is constant). Tab. 1 displays the injection pressure and properties of the resin and reinforcement.

Table 1 – Operating conditions and physical properties used in *Case study 1*

Layer	$K_{xx} = K_{yy}$ [m²]	μ[Pa · s]	ε	P_0[bar]
1	1.40 x 10^{-9}	0.065	0.811	0.0525
2	2.09 x 10^{-9}	0.065	0.803	0.0525

The determination of the K_{zz} starts with an initial guess (K_{zz} = 2.21 x 10^{-9} m²). The algorithm presented in section 4 is then used to calculate a K_{zz} value that, when used in the numerical model, will allow the numerical determination of a filling time equal (within a tolerance) to the experimental filling time. In the present solution, convergence was reached when the error was smaller than 4%. The four iterations performed are shown in Tab. 2.

Table 2 – Iterative determination o K_{zz} – *Case study 1*

Iteration	K_{zz}[m²]	t_{num} [s]	t_{exp} [s]	% Error*
1	2.21 x 10^{-9}	209.32	190.43	9.92%
2	2.35 x 10^{-9}	207.39		8.91%
3	2.35 x 10^{-8}	199.23		4.62%
4	3.53 x 10^{-7}	197.04		3.47%
* % Error = 100 x (t_{num} - t_{exp})/t_{num}				

It can be observed from the data in Tab. 2 that the transverse permeability is an important parameter for the numerical modeling of the resin injection in RTM problems. From the experimental data it is possible to estimate an in-plane effective permeability K_{eff}. This K_{eff} is obtained based on the experimental data for x_f as a function of the filling time observed considering the superior layer (the actual visible layer in the experiment). K_{eff} is different from the in-plane permeability of each layer and is expected that it could contain some information about the transverse permeability, i.e. a relationship between K_{eff} and K_{zz} can be expected. In the present solution, the transverse permeability is approximately 150 times the effective permeability (K_{eff} = 2.35 x 10^{-9} m²).

The numerical and experimental solutions for the two-layer case is shown in Fig. 4. In this solution, the calculated K_{zz} = 3.53 x 10^{-7} m² was used in the numerical simulation. All other parameters and properties are given in Tab. 1.

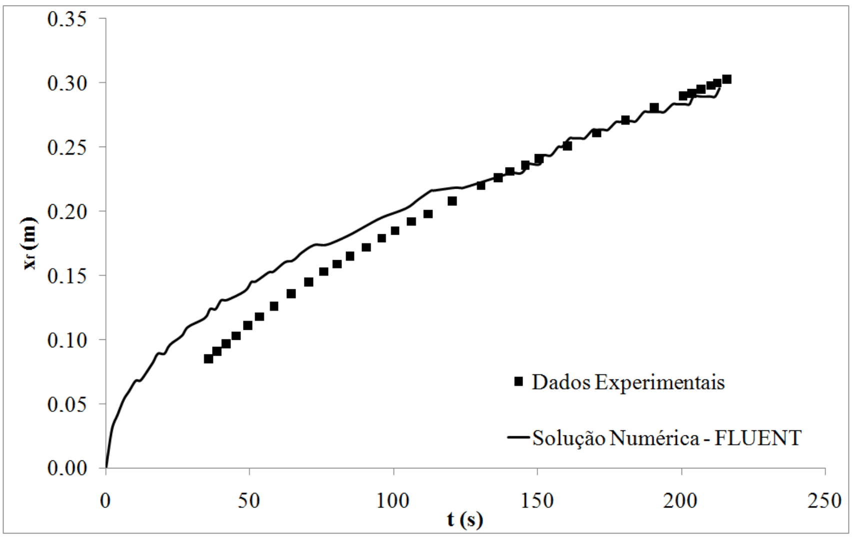

Figure 4 – Numerical and experimental results for *Case study 1*

5.2. *Case study 2*:

The methodology used in this case is identical to the procedure used in *Case study 1*. However, a different method was used for the determination of the in-plane permeability of the different layers. The method used by Oliveira (2010) allows a better estimation of the $\%V_f$ of each reinforcement layer. The $\%V_f$ obtained by this method is the actual $\%V_f$ due to the fact that it is assumed that the calculated $\%V_f$ gives the exact fiber volume fraction of the reinforcement.

The same two-layer reinforcement was used, with the first layer polypropylene fiber and, the other, glass fiber. The parameters used in this simulation are presented in Tab. 3.

Table 3 – Operating conditions and physical properties used in *Case study 2*

Layer	$K_{xx} = K_{yy}\ [m^2]$	$\mu [Pa \cdot s]$	ε	$P_0 [bar]$
1	3.50×10^{-9}	0.633	0.862	0.0762
2	2.76×10^{-10}	0.633	0.694	0.0762

In this case a better agreement between the numerical and experimental filling time was obtained, i.e., the numerical solution performed with the calculated K_{zz} determined a filling time much closer to the experimental filling time than the results obtained in *Case study 1*. Table 4 summarizes the 6 iterations used to determine the transverse permeability, K_{zz}. The convergence was assumed when an error smaller then 1% was obtained.

Table 4 – Iterative determination o K_{zz} – *Case study 2*

Iteration	$K_{zz} [m^2]$	t_{num} **[s]**	t_{exp} **[s]**	**% Error***
1	2.23×10^{-9}	142.15	157.11	9.12%
2	3.50×10^{-8}	134.93		13.13%
3	7.43×10^{-10}	150.52		7.37%
4	2.23×10^{-10}	164.18		4.97%
5	3.19×10^{-10}	162.25		3.73%
6	4.46×10^{-10}	157.11		0.45%
* Error = $(t_{num} - t_{exp})/t_{num}$				

The numerical and experimental solutions for *Case study 2* are plotted in Fig. 5.

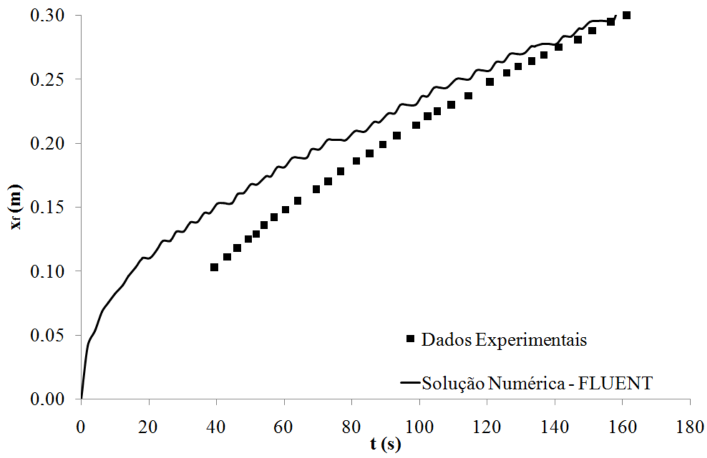

Figure 5 – Numerical and experimental results for *Case study 2*

Again, the calculated K_{zz} and the experimental K_{eff} were compared, however a very different value was obtained. In *Case study 2*, the calculated transverse permeability is approximated five times smaller than the effective permeability ($K_{eff} = 2.23 \times 10^{-9}\ m^2$). This unexpected result suggests that a relationship between K_{zz} and K_{eff} does not appear to exist, although it is necessary to highlight that this may have been a consequence of the distinct procedure used to calculate $\%V_f$ in cases 1 and 2. More experiments are been carried out to further investigate the relationship between K_{zz} and K_{eff} and these results will be discussed in a future work.

5. CONCLUSIONS

The present work proposed an original methodology for the determination of transverse permeabilities using multilayered reinforcement media in the RTM process. This procedure combines experimental data (in-plane permeabilities and total filling time) and numerical results of the simulated resin flow inside the mold cavity.

The transverse permeability can be experimentally determined, although it is much easier to measure the in-plane permeabilities only. In the proposed method, only the in-plane permeabilities need to be experimentally determined and the transverse permeability is numerically obtained by a iterative algorithm.

It was also investigated a possible relationship between the transverse permeability and the experimental effective permeability. The already obtained results did not indicate a correlation between these two parameters, however more experiments are necessary to investigate this issue.

6. ACKNOWLEDGEMENTS

The authors are thankful to CAPES, CNPq and FAPERGS for the financial support.

7. REFERENCES

Alves, A.L.S. “Processamento de Placas Compósitas pela Técnica de Moldagem por Infusão de Resina de Seemann”. Dissertação (Mestrado em Ciências e Engenharia Metalúrgica e de Materiais) – Programa de Pós-Graduação em Engenharia Metalúrgica e de Materiais, UFRJ, Rio de Janeiro, 2006.

Amico, S.C., 2005, “Novo processo de fabricação de compósitos para indústria”. Revista Ciência Hoje, 219 p.55.

Amico, S. C. “Vegetable fibers as multifunctional materials”, Revista Matéria, 15 (2): 386-395, 2010..

Amorim Jr. W.F. “Processamento de Placa Espessa de Compósito Através de Moldagem por Transferência de Resina”. Tese (Doutorado em Ciências e Engenharia Metalúrgica e de Materiais) – Programa de Pós-Graduação em Engenharia Metalúrgica e de Materiais, UFRJ, Rio de Janeiro, 2007.

Ballata, W.O.; Walsh, S.M.; Advani, S. “Determination of the Transverse Permeability of a Fiber Preform”, Journal of Reinforced Plastics and Composites 18:1450, 1999.

Calado, V.M.A.; Advani, S.G. “Effective average permeability of multilayer performs in resin transfer molding”, Compos Sci Technol 56(5): 519-31, 1996.

Hirt, C.W.; Nichols, B.D. “Volume of Fluid (VOF) method for dynamics of free boundaries”, J. Comput. Phys. 39 (1981) 201±225, 1981.

Luoma, J. A.; Voller, V. R., 2000, “An explicit scheme for tracking the filling front during polymer mold filling”, Applied Mathematical Modelling 24 , 575-590

Maliska, C. R.; Vasconcellos, J. F. V. de, 1998, "An unstructured finite volume procedure for simulating flows with moving fronts", Computer Methods in Applied Mechanics and Engineering, vol.182, pp. 401-420.

Minussi, R. B. “Rompimento de Barreiras – Análise Experimental e Numérica na Previsão de Velocidades de Propagação de Frentes de Material Hiperconcentrado” Dissertação (Mestrado em Engenharia Mecânica) – Programa de Pós-Graduação em Engenharia Mecânica, Universidade Estadual Paulista, São Paulo 2007.

Molina, G.; Boero, G.; Smeriglio, P. “Resin transfer molding for car body parts – An integrated approach using CAE methodology”, Journal of Reinforced Plastics and Composites, 13 (8): 681-697, 1994.

Oliveira, C.P.; Souza, J.A.; Isoldi, L.A.; Rocha, L.A.O.; Amico, S.C.; Silva, R.D.S.; “Computational Modeling of the Multilayer RTM Process”, in 30º CILAMCE, Búzios, RJ, 2009.

Oliveira, C. P. “Modelagem Numérica do Transporte de Resinas em um Meio Poroso Aplicado ao Processo de RTM” Dissertação (Mestrado em Modelagem Computacional) – Programa de Pós-Graduação em Modelagem Computacional, Universidade Federal do Rio Grande, Rio Grande 2010.

Schimidt, T.M., Goss, T.M., Ornaghi Jr. H.L., Amico, S.C., 2007, "Determinação da Permeabilidade de Reforços Fibrosos no Processo de Moldagem por Transferência de Resina", in Carbono 2007 – IV Congresso Brasileiro de Carbono, Gramado.

Visconti, I.C.; Langella, A., Durante, M. “Analysis of Transversal Permeability for Different Types of Glass Fiber Reinforcement”, Applied Composite Materials 10: 119-127, 2003.

Wu, X.; Li, J.; Shenoi, R.A.; “Measurement of braided preform permeability”, Composites Science and Technology 66 3064–3069 (2006).

8. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.