APPLICATION OF THE COMPUTATIONAL MODELING IN THE RESIN TRANSFER MOLDING (RTM) PROCESS: A CASE STUDY OF A MARINE PROPELLER

Joseane da Silva Porto, joseaneclmd@gmail.com
Max Letzow, max.letzow@bol.com.br
Elizaldo Domingues dos Santos, elizaldosantos@furg.br
Jeferson Avila Souza, jasouza@furg.br
Liércio André Isoldi, liercioisoldi@furg.br
Escola de Engenharia - Universidade Federal do Rio Grande (FURG) - Av. Itália km 8, CEP 96203-900 Rio Grande-RS, Brazil

Sandro Campos Amico, amico@ufrgs.br
Escola de Engenharia - Universidade Federal do Rio Grande do Sul (UFRGS)

Abstract. *This work presents one example of how the computational modeling can help in the Resin Transfer Molding (RTM) process when it is applied to the production of parts with complex geometry, such as the marine propellers. This manufacture process of composite material parts consists in the injection of a polymeric resin into a closed mold where a fibrous reinforcement is previously placed. The numerical simulation of the RTM process can be considered as the resin flow through a porous media. This computational model was developed in the FLUENT package, which is based on the Finite Volume Method (FVM), and was applied to study a propeller for naval propulsion. As the propeller has a complex format, the use of computational approach as a preliminar step in the manufacturing process is very important for the correct definition of the inlet and outlet nozzles. So, it is possible to design an efficient mold, avoinding extras costs related with the mold redesign, the resin waste and the increase of injection time. The results showed that an inadequate positioning of the mold outlet nozzles causes an increase about 10% and 2% in the production time and in the resin amount, respectively, for obtaining the marine propeller by RTM process.*

Keywords*: Resin Transfer Molding (RTM), Polymeric Composite Materials, Computational Modeling, FLUENT.*

1. INTRODUCTION

A composite material is defined, basically, as a combination of two or more materials in a macroscopic scale generating a new material. A typical composite material is formed by suspended inclusions in a matrix. These inclusions (fibers or particles) provide the mechanical characteristics to composite material, while the matrix (resin) is responsible to transfer the mechanical loads for the inclusions and protect them from the external environment (Isoldi, 2008).

Nowadays the naval industry increasingly employs the polymeric composites to manufacture various parts, such as: hulls and decks of boats, chimneys and propellers. This trend impels the search for new technologies, as the use of computational modelling, to help in the reduction of time and costs of the fabrication processes and further enabling to obtain parts with better quality.

In accordance with Lin et al. (2008) most of propellers for marine propulsion are still produced of mettalic materials, as bronze or steel. However, the advantages of replacing the metallic material by polymeric composite material are that the latter is lighter and more corrosion resistant. Another important advantage is that the deformation of the composite propeller can be controlled to improve its performance. Therefore the use of polymeric composite materials for naval applications, more specifically for the marine propellers, allows to produce parts with complex geometries and with certain specific properties.

Among the different manufacturing processes of polymeric composite material parts, it is possible to highlight the Resin Transfer Molding (RTM) process which produces parts with best characteristics and properties if compared with those produced by other fabrication techniques (Fortuna, 2000). The process mainly consists of two steps. The mold filling step involves injecting a thermosetting resin mixed with catalyst and initiators into a net-shaped mold cavity containing a dry fibrous unit, called the preform. The resin-catalyst mixture permeates through the porous network formed by the fibers, resulting in a saturated preform. In the second step, the fiber-resin mixture is subject to high temperatures that harden the catalyzed resin around the fibers, and form the composite part, via a cross-linking chemical reaction, called cure (Nielsen and Pitchumani, 2002).

This manufacturing process has some advantages, as the good finish in both side of parts, higher production rate, flexibility, relative ease to produce geometrically complex parts and a low loss of raw materials. Therefore, it is possible to affirm that the RTM process can be very efficient to produce parts used in marine and naval engineering.

However, there is a great difficulty in the mold design to produce parts with complex geometries using the RTM process: the adequate localization of the air/resin outlet nozzles. If the part has a simple geometry the definition about the adequate outlet nozzles positions is obvious, but this is not possible when the part has a complex shape. A wrong positioning of these nozzles may result in final part with defects, or else an excessive time for the complete mold filling, or even the waste of resin.

In this sense, the computational modeling can be used as an auxiliary step for evaluation of the RTM process, because the resin flow behavior will be predicted, allowing the adequate identification of the mold regions where the outlet nozzles must be positioned. Shojaei (2006) stated that the main objectives of the numerical simulation in the RTM process are to predict the flow behavior into the mold, to define the flow front position and to identify regions with void formations (regions of the part without resin), allowing the design of an efficient mold and hence the manufacturing of quality parts. Besides, the prior knowledge of the resin flow is very useful to estimate the injection time and to improve the properties of the final parts (Shin et al., 2006). Thus, the numerical simulation can be considered as an important tool for the manufacturing of parts by the RTM process, mainly those ones with complex geometries.

Based on the foregoing, in this work a numerical simulation of the RTM process was performed. The aim was to show the relevance of the Computational Fluid Dynamics (CFD) in the development of an adequate mold design. For this, a case study applied to the naval engineering was chosen, combining the geometric complexity of a marine propeller with the advantage to employ a polymeric composite material for its manufacture.

2. PROPELLERS FOR NAVAL PROPULSION

Among the existing methods for the propulsion of boats, the use of propellers is the most widespread (Villas, 2006). Basically, the propeller is a propulsion device based on the rotational movement of surfaces (blades) radially arranged on a shaft. This shaft must be aligned with the movement direction and as a consequence the blades of the propeller are subjected to axial and radial velocity components (Wald, 2006). The propeller function is to transfer the engine power to the water, causing the boat displacement (Geer, 1989).

Currently, a great effort has been made for the development of composite propellers and propulsion shafts. The composite are expected to offer a number of important benefits over metal when used in propulsion systems, including lower cost, reduced weight, lower magnetic signature, better noise damping properties and superior corrosion resistance. For instance, it is anticipated that propulsion shafts made of composites will be 18 to 25% lighter than steel shafts of the same size and will reduce life cycle cost by at least 25% because of fewer problems associated with corrosion and fatigue (Selvaraju e Ilaiyavel, 2011). An example of a marine propeller manufactured with polymeric composite material can be observed in Fig. 1.

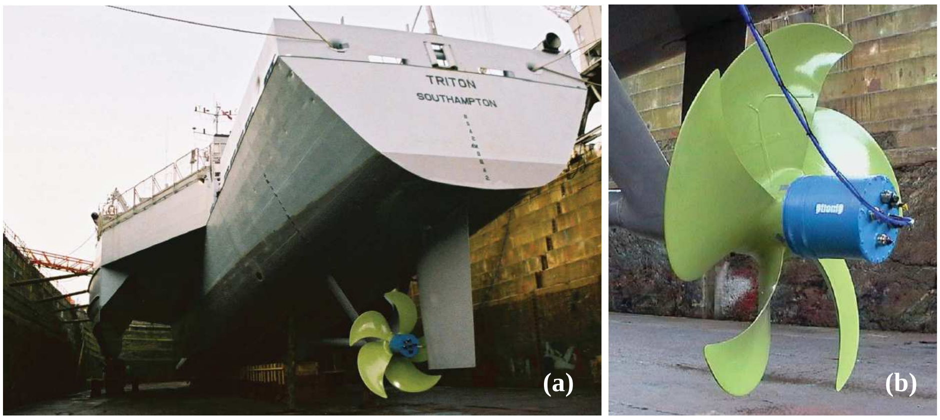


Figure 1. Polymeric composite marine propeller (Marsh, 2004): (a) overview and (b) detail.

Searle (1998) has manufactured marine propellers with three blades using the RTM process. The experimental results indicated that the polymeric composite propellers presented a similar performance when compared with propellers fabricated with conventional materials (nickel, aluminum and bronze).

Fontoura et al. (2009) has studied a polymeric composite propeller with two blades obtained by the RTM process. For the characterization of the composite, short-term mechanical tests such as tensile, flexural, impact and Barcol hardness were used. For the physical evaluation of the composite, density and void content were tested. Differential scanning calorimetry was used to determine gel and curing time and temperature. Thermogravimetric analysis was used to determine fiber content. The dynamic mechanical properties of the composite under a range of temperature and frequency were also evaluated. To evaluate the susceptibility of the material to the environment, water absorption test was carried out. The results showed that the composite materials can be considered a good alternative for the replacement of metallic materials in propulsion systems.

3. RESIN TRANSFER MOLDING

The Resin Transfer Molding (RTM) is a manufacturing process in which a liquid resin is injected into a closed mold pre-loaded with a porous fibrous preform, producing complex composite parts with good surface finishing after the resin cure (Isoldi et al., 2012). Figure 2 shows a schematic representation of the RTM process.

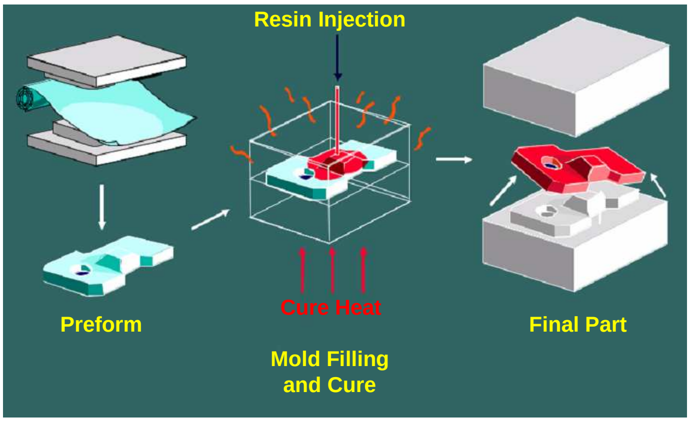


Figure 2. RTM process.

This process also is characterized by the facility for obtaining parts with complex geometries and with high structural performance. However, the behavior of the polymeric resin flow through the fibrous reinforcement is a key point in this process. It is necessary a complete impregnation of the fibrous reinforcement and a total filling of the mold by the resin to ensure the quality of the produced part. In this context the mold design has a fundamental importance, particularly in preventing the voids formation. The existence of these voids causes structural problems and changes in the mechanical properties of the components manufactured by the RTM process. So, to avoid these manufacturing defects, the positioning of the resin injection nozzle and mainly the outlet nozzles of the air and resin in the mold must be adequately defined, being the computational modeling an efficient methodology to predict the resin flow behavior. Besides, the definition of the inlet and outlet nozzles locations by numerical simulation eliminates additional costs related with mold redesign and with waste resin.

Dimitrovová and Faria (2000) has performed numerical simulations of the mold filling in a RTM process employing the Finite Element Method (FEM) and the homogenization technique. The obtained results were compared with the literature ones and a good agreement was observed.

Shen and Zhai (2005) developed an algorithm to simulate the mold filling during the RTM process. This algorithm is solved in an iterative way without constraints related with the time step (Courant number). The numerical results showed the effectiveness of the model.

Ribeiro et al. (2007) used the FLUENT software to develop a computational model for the RTM process. Two 2D cases were analyzed: rectilinear and radial flows. The numerical results were compared with analytical solutions, verifying the model.

Souza et al. (2008), using the FEM and the Flow Analysis Network (FAN) technique, developed an algorithm to define the resin flow front position. The results presented a good agreement with the analytical ones.

Oliveira (2010) performed a numerical study of the RTM process applied to manufacture multilayer polymeric composite materials. The FLUENT and the PAM-RTM software were employed. The obtained results with these computational packages presented a good concordance.

Isoldi et al. (2012) discussed the 2D and 3D numerical simulation of the RTM and the Light Resin Transfer Molding (LRTM) processes. The FLUENT software was used and the computational modeling was adequately validated and verified.

4. COMPUTATIONAL MODELING

In the RTM process modeling, Darcy's Law is usually used to correlate velocity and pressure fields of the resin flow inside the mold cavity. This Law can be mathematically expressed by:

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

where $\vec{v}$ is the resin velocity (m/s), K the reinforced media permeability (m²), μ the resin viscosity (Pa s) and P the pressure (Pa).

The Volume of Fluid (VOF) method (Hirt and Nichols, 1981) has been used within FLUENT software to solve the resin flow in the RTM problems. Besides FLUENT software that has been used to solve the numerical problem and post process the results, GAMBIT software has been used to create and discretize the mold geometry.

According to Maliska and Vasconcelos (1998), Luoma and Voller (2000) e Minussi (2007), the VOF method is used to solve multiphase problems of inviscid fluids. In this method, all phases in the mixture are well defined and the volume occupied by one phase can not be occupied by any other phase. To represent the different phases inside a domain cell (element), the volume fraction concept is used.

In the particular case of the RTM problem only two phases are defined: resin and air. Thus, defining f as the volume fraction of the resin, one cell will be considered filled with resin when f = 1. If f = 0 the cell will be completely filled with air. When f assumes a value between zero and one both phases will coexist inside the cell.

In the VOF method, the fluid flow problem is modeled with a single set of differential equations for the momentum and continuity. The volume fraction is modeled by adding to the system a transport equation for f.

For a Newtonian fluid, the continuity, momentum and volume fraction equations can be written as (Isoldi et al., 2012):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v} \right) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v} \right) + \nabla \cdot \left(\rho \vec{v}\vec{v} \right) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}} \right) + \rho \vec{g} + \vec{F} \tag{3}$$

$$\frac{\partial (f)}{\partial t} + \nabla . \left(f \vec{v} \right) = 0 \tag{4}$$

where ρ is the density (kg/m³), t the time (s), $\vec{g}$ the gravity acceleration vector (m/s²), $\bar{\bar{\tau}}$ the stress tensor (Pa), $\vec{F}$ the external resistance (force) to the fluid flow (N) and f the volume fraction. The physical properties ρ and μ are assumed to be average values calculated by:

$$\rho = f \rho_{resin} - (1 - f) \rho_{air} \tag{5}$$

$$\mu = f \mu_{resin} - (1 - f) \mu_{air} \tag{6}$$

In the RTM process solution, $\vec{F}$ is used to model the resistance imposed by the fibrous reinforcement (porous media) to the flow such as:

$$\vec{F} = -\frac{\mu}{K} \vec{v} \tag{7}$$

Several authors has successfully used the numerical methodology employed in the present study (FVM with FLUENT) for estimative of the RTM process. For example, Ribeiro et al. (2007) verified the methodology for solution of 2D problems by direct comparison with analytical solutions. Studies by the research group of the present work are also performed, e.g., Oliveira (2010) employed FLUENT to model resin injection in multilayered reinforcements. Porto et al. (2011) evaluated the resin injection process in complex 2D and 3D geometries and Isoldi et al. (2012) presented a validation for this numerical model for RTM and LRTM processes. For the sake of brevity the verification and validation of the numerical model will not be re-exhibited here.

5. RESULTS

The proposed case study consists in apply the above described computational modeling of RTM in a marine propeller used in naval vessels. The numerical simulation of the resin advance inside the mold was used to determine the flow front position as a function of the injection time and hence to define the correct locations of the resin/air outlets.

In this simulation, the injection pressure was set to 35 kPa and the used resin had density equal to 920 kg/m^3 and viscosity equal to 0.06 Pa s. The reinforced media properties were: porosity equal to 0.7 and permeability equal to

$3x10^{-10}$ m^2. Propeller's geometry (3D) and main dimensions are shown in Fig. 3. More details about this geometry can be found in Speluzzi e Tessarotto (1961). The geometry was discretized with 938.606 tetrahedral elements.

The resin is inject through the core section of the propeller and forced to flow to its extremities, as can be observed in Fig. 4. During the flow advance, a similar behavior to the radial injection can be qualitatively observed (Porto et al., 2011). Three outlet sections (nozzles) were placed at the propeller's extremity. In the first simulation presented in Fig. 4 the outlet nozzles were placed exactly at the symmetry section of each propeller blade (see Fig. 4).

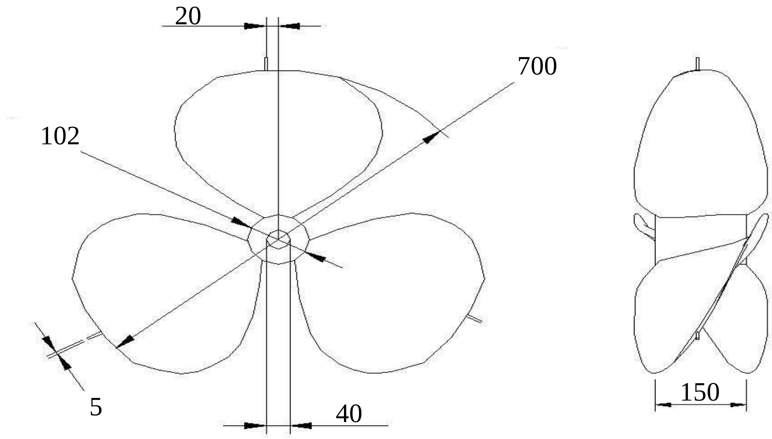
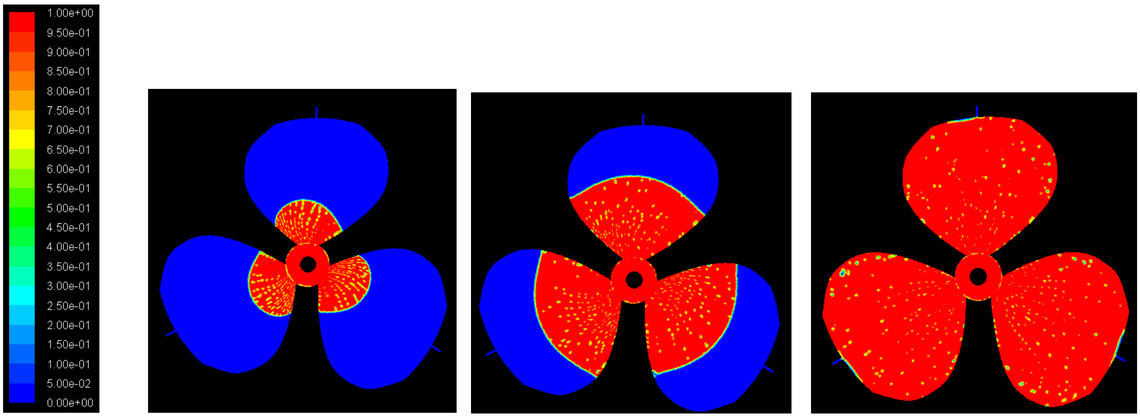


Figure 3. Marine propeller geometry and its main dimensions (in mm).



t = 50.53 s　　*t* = 107.60 s　　*t* = 190.50 s

Figure 4. Resin flow behavior.

In Fig. 5 it is possible to observe that the outlet section (detail) is not correctly positioned. The resin (red) has already reached the nozzle from one side (below in the figure), but stills far from the nozzle in the other side (above). This inadequate position of the outlet nozzle causes the air (blue) remains inside the mold. However, even with the outlet nozzle in the wrong position was still possible to finish the mold filling. The process was interrupted when all remaining air has left the mold and the resin has reached the outlet section from both sides. The calculated filling time was 215 s.

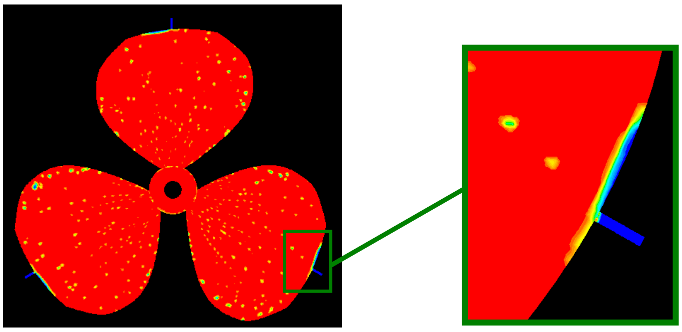


Figure 5. Resin filling at the outlet nozzles (detail).

Based in the resin flow behavior observed in this numerical simulation it was possible to determine the correct position for the outlet nozzles. Therefore, the outlet nozzles were displaced 20 mm from the location adopted in the preliminary simulation (as noticed in Fig. 3). The new behavior for the numerical simulation of the resin flow in the RTM process is indicated in Fig. 6, where it is possible to note that the total filling of the mold occurs before to reach the outlet nozzles.

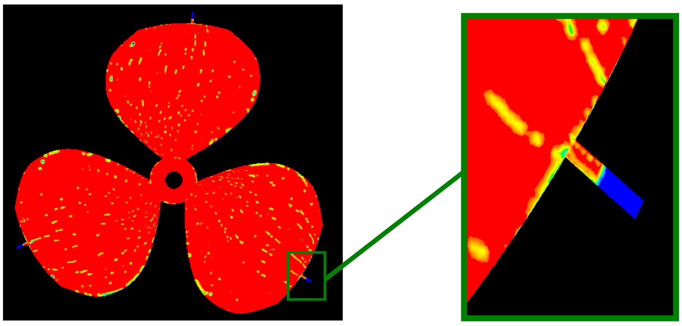


Figure 6. Correct position for the outlet nozzles.

In this simulation, with the outlet nozzles adequately positioned, the time necessary to fill the mold was 193 s. A comparison between the two solutions showed that the inadequate position for the outlets led to a filling time 10.23 % higher than that found when the correct outlets location were employed. During the extra time needed to fill the mold a resin waste around 0.04 kg was observed, representing a resin loss of 1.50% (considering the total amount of resin to manufacture the propeller). This increase of manufacturing time, as well as, the resin consumption caused by the erroneous definition of the outlets nozzles placement can represent an enormous additional cost for the serial production of this marine propeller using the RTM process.

Therefore, it is possible to affirm that the computational modeling can be used as an auxiliary tool in the RTM process. The correct definition of the inlet and outlet nozzles during the mold design is fundamental information to avoid unnecessary extra costs related with the mold redesign and with the prevention of inadequately manufactured parts. These capabilities are even more evident when the part has a complex geometry because in this situation there is no preliminary reference about the ideal positions of the nozzles, being the numerical simulation an efficient procedure to define them.

6. CONCLUSIONS

In current work, computational modeling was used to determine the correct positioning of resin/air outlets in a RTM mold cavity. The conservation equations of mass and momentum, as well as, the equation for transport of species were solved with the finite volume method (FVM). To tackle with the mixture of resin-air it is employed the volume of fluid (VOF) method.

It was highlighted the importance of such modeling in mold design and process control. The complex 3D geometry of a marine propeller used in naval boats was used as a case study example. For the specific study, the numerical approach allowed the reduction of filling time in nearly 10 % and the reduction of 1.5 % in costs with waste of resin. Considering the series production of the analyzed propeller, the extra filling time and the associated resin waste will lead to a considerable additional cost to the manufacture process. Therefore, the use of the numerical modeling as an auxiliary tool to determine the resin flow behavior inside the mold cavity allow an efficient mold design, especially in the case of pieces with complex geometries.

7. ACKNOWLEDGEMENTS

The authors thank to CNPq and FAPERGS for the support.

8. REFERENCES

Dimitrovová, Z. e Faria, L., 2000, Finite element modeling of the resin transfer molding process based on homogenization techniques, Computers e Structures, v. 76, p. 379-397.

Fontoura, C. M., Rocha, I. C., Ferreira, C. A., Amico, S. C., Costa, C. A., 2008, Desenvolvimento e caracterização de materiais compósitos para sistemas propulsores, CBECiMAT – Congresso Brasileiro de Engenharia e Ciência dos Materiais.

Fortuna, A. O., 2000. “Técnicas Computacionais para Dinâmica dos Fluidos - Conceitos Básicos e Aplicações”, São Paulo, Edusp, 426p.

Geer, D., 1989. Propeller Handbook: The Complete Reference for Choosing, Installing and Understanding Boat Propellers. New York: Mc Graw- Hill – International Marine.

Hirt, C.W. and Nichols, B.D., 1981. "Volume of Fluid (VOF) method for dynamics of free boundaries", J. Comput. Phys. Vol. 39, pp. 201-225.

Isoldi, L.A., 2008. Análise estática e dinâmica de estruturas delgadas de materiais compostos laminados incluindo materiais piezelétricos. Ph.D. thesis, Universidade Federal do Rio Grande do Sul, Brazil.

Isoldi, L.A., Oliveira, C.P., Rocha, L.A.O., Souza, J.A. and Amico, S.C., 2012. "Three-dimensional numerical modeling of RTM and LRTM processes". Journal of the Brazilian Society of Mechanical Sciences and Engineering. Vol.34, No. 2, pp. 105-111.

Lin; C.C., Lee, Y.Y. and Hung, C.S., 2008. "Optimization and Experiment of Composite Marine Propellers", Journal Composite Strutures.

Luoma, J.A. and Voller, V.R., 2000. "An explicit scheme for tracking the filling front during polymer mold filling", Applied Mathematical Modelling, Vol. 24, pp. 575-590.

Maliska, C.R. and 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.

Marsh, G., 2004. "A new start for marine propellers?" Reinforced Plastics, Vol. 48, No.11, p. 34-38.

Minussi, R.B., 2007. "Rompimento de Barreiras – Analise Experimental e Numérica na Previsão de Velocidades de Propagação de Frentes de Material Hiperconcentrado". Ms.C. thesis, Universidade Estadual Paulista, Brazil.

Nielsen, D.R. and Pitchumani R., 2002. "Closed-Loop Flow Control in Resin Transfer Molding using Real-Time Numerical Process Simulations". Composites Science and Technology, Vol. 62, pp. 283-298.

Oliveira, C.P., 2010. "Modelagem Numérica do Transporte de Resinas em Meio Poroso Aplicado ao Processo de RTM" Máster thesis, Universidade Federal do Rio Grande, Brazil.

Porto, J. Da S., Teixeira, F.P., Letzow, M., Amico, S.C., Dos Santos, E.D., Souza, J.A. and Isoldi, L.A., 2011. "Modelagem Computacional do Processo de Light Resin Transfer Molding (LRTM)" In Proceedings of CILAMCE 2011 32th Iberian Latin American Congress on Computational Methods in Engineering, Ouro Preto, Brazil.

Ribeiro, G.G., Souza, J.A., Rocha, L.A.O.and Amico, S.C., 2007. "Utilização do aplicativo FLUENT na modelagem numérica do processo RTM". In Proceedings of CBC 2007 Congresso Brasileiro de Carbono.

Searle, T. ,1998, Composites Final Frontier. Desing Engineering. April, p.51-52.

Selvaraju, S. and Ilaiyavel, S., 2011. "Application of Composites in Marine Industry". Journal of Engineering Research an Studies, Vol II, pp. 89-91.

Shen C.; Zhai M., 2005, An Improved Algorithm for the Simulation of Injection-molding Filling Process. National Engineering and Research Center for Mold and Die Zhengzhou University, Zhengshou 450002, China.

Shin, K.S. Song, Y.S. and Youn, J.R., 2006. "Radial flow advancement in multi-layered preform for resin transfer molding". Rheology Journal, Vol. 18, No. 4, pp. 217-224.

Shojaei, A., 2006. "A numerical study of filling process through multilayer performs in resin injection/compression molding". Composites Science and Technology, Vol. 66, pp. 1546–1557.

Souza, J. A.; Nava, M. J. A.; Rocha, L. A. O.; Amico, S. C., 2008, Two- Dimensional Control Volume Modelling of the Resin Infiltration of a Porous Medium with a Heterogeneous Permeability Tensor, Materials Research, Vol. 11,No. 3, 261-268.

Speluzzi, M. and Tessarotto, M., 1961. "Disegno di Macchine". 3. Ed., Editore Ulrico Hoepli Milano, Ristampa.

Villas, F.B., 2006. Desenvolvimento de uma Ferramenta de CAD Aplicada ao Projeto de Hélices para Veículos Aquaticos Não Tripulados. Ms.C. thesis. Escola Politécnica da Universidade de São Paulo.

Wald, Q.R., 2006. "The Aerodynamics of Propellers". Proces in Aerospace Sciences. V. 42, p. 85-128.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.