IMPORTANCE OF THE INJECTION TIME IN MANUFACTURE OF COMPOSITES BY RTM PROCESS

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Abstract. *Composites manufactured by RTM (Resin Transfer Molding) process has been largely used in several industrial segments (naval, automotive, etc.). This process usually combines reduced production costs with good mechanical properties for the finished piece. Besides, RTM process produces small quantities of residues and is suitable to produce parts with complex geometry. The reinforced medium is actually a stack of a fibrous fabric, cut with the piece geometry and pressed inside the mold cavity. Mechanical properties are improved by increasing the number of layers in the stack which also increases the volume fraction of fibers and, depending on the application, the thickness of the piece. However, as larger is the volume fraction and as thick is the reinforced, more difficult is to the resin to flow (impregnates) through the preform. In order to investigate these flow patterns, this work presents a numerical simulation, using OpenFOAM software, of the resin advance inside the mold cavity. The influence of transverse permeability and cure time in mold filling were investigated. Viscosity was not considered constant and an equation that corelates its variation as a function of time is added to the model. Moreover, different values of transverse permeability are considered in these simulations. Results allowed to predict limiting injection times for different assembles (different transverse permeability) in order to guarantee that molding ends before resin curing.*

Keywords*: RTM process, numerical simulation, injection time.*

1. INTRODUCTION

Resin Transfer Molding (RTM) is a liquid molding process used to build polymeric composite parts of different sizes (from very small to very large and from very simple to very complex geometries) with good finishing in all surfaces. In RTM, a low viscosity polymeric resin is forced into a closed mold which was previously filled with a porous reinforced medium. After complete impregnation of the reinforced medium, resin curing process takes place completing the piece formation. Final step consist in open the mold and removing the finished piece. In order to predict flow advance and total filling time, some process parameters like reinforcement permeability, resin viscosity and injection pressure must determined. According to Saouab et al. (2001), the most important condition needed for a successful manufacturing are the perfect impregnation of the reinforced medium and complete filling of the mold, with the smallest possible cycle time.

As long as resin advances inside the mold, pressure gradient ($\Delta P_0/\Delta x_f$, being x_f the flow front position and P_0 the injection pressure) decreases and resin velocity diminishes, thus for large parts the injection time may be prohibitive and multiples injection points are used to accelerate the injection process. When thick parts are being manufacture, there is still the influence of the transverse flow, proportional to the transverse permeability which is usually 10 to 100 times smaller than the in-plane permeability. Smaller permeability leads to larger injection times, however in RTM process it is possible to increase the injection pressure to compensate flow resistance imposed by low values of permeability. As transverse permeability is usually more difficult to be experimental predicted, injection of thick parts by the RTM process may become challenging. Without the correct value for the transverse permeability it is not possible to precise determine flow advance and the position of injection and vent points (Poodts et al., 2014).

Injection time is a key parameter to be controled in the manufacturing of thick parts. Its prediction is important to guarantee that complete impregnation occurs before resin curing. Deléglise et al. (2005) presented an analytical model to predict filling time in isotropic reinforcements and with constant injection pressure.

Current work brings a finite volume solution, using Open FOAM software, for the resin infusion problem in a porous media with constant permeability and porosity, but with a time dependent resin viscosity model. Main goal is to predict injection times, and eventually resin cure, in molds used to manufacture thick parts by the RTM process.

2. PROBLEM DESCRIPTION

Current work consists on the numerical simulation of the resin infusion process in a thick porous medium part produced by the RTM process. In all simulation GMSH software (Geuzaine and Remacle, 2009) has been used for geometry creation and discretization while OpenFOAM (*OpenFOAM User Guide*, 2011), which is an open source application, was used for the mathematical model solution. Multiphase fluid problem was formulated with the Volume Of Fluid (VOF) (Hirt and Nichols, 1981) method which is implemented in the *porousInterFOAM* solver, solver from the OpenFOAM package.

VOF method solves a single set of continuity and momentum equations for all fluid (in this case resin and air) and creates and additional transport equation for the volume fraction of each phase. This method is only applied to inviscid fluids. Formulation for an incompressible flow is given by continuity equation (Eq. (1)), resin volume fraction equation (Eq. (2)) and momentum equation (Eq. (3)) given by:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho\vec{V})=0 \tag{1}$$

where ρ is the density (kg/m^3), $\vec{V}$ the velocity vector (m/s) and t the time (s).

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

where α is the resin volume fraction.

$$\frac{\partial(\rho\vec{V})}{\partial t}+\nabla\cdot(\rho\vec{V}\vec{V})=-\nabla P+\nabla\cdot(\mu\bar{\bar{\tau}})+\rho\vec{g}+\vec{F} \tag{3}$$

where p is the pressure (Pa), $\vec{g}$ the gravity acceleration (m/s^2), $\bar{\bar{\tau}}$ the stress tensor (N/m³) and $\vec{F}$ a force term used to include porous media resistance to the fluid flow (N/m³).

According to Srinivasan et al. (2011), from the definition of volume fraction, density and viscosity can be approximated by

$$\rho=\alpha\rho_{resin}+(1-\alpha)\rho_{air} \tag{4}$$

$$\mu=\alpha\mu_{resin}+(1-\alpha)\mu_{air} \tag{5}$$

Moreover, in current solution, resin viscosity is a function of the injection time. Thus viscosity time dependence was experimentally obtained in LaPol/UFRGS and results were compiled in a regression function given by

$$\mu_{resin}=0.0355398377\,t^2-2.0391785789\,t+326.2930547713 \tag{6}$$

Mold geometry and boundary conditions are presented in Fig. 1. Inlet and outlet section have diameters of 0.0166 m. Mold is squared with edges of 0.3 m and height of 0.024 m.

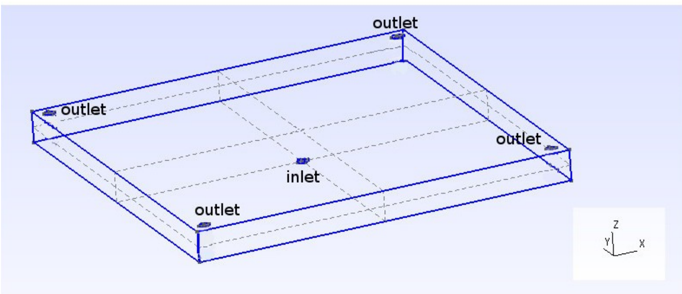

Figure 1. Mold geometry and boundary conditions

Resin enters the mold through an inlet port positioned at the center of the lower section of the mold as show in Fig. 1. Four outlet ports are located at the corners of the top (upper) mold section. All other surfaces are considered walls. Boundary conditions are prescribe pressure, P_0, and resin volume fraction equal to 1 at the inlet section, prescribed pressure equal to zero (gauge) and zero gradient for the resin volume fraction at the outlet sections and zero gradient for resin volume fraction and no slip condition for velocities are prescribed at the walls.

Domain discretization is shown in Fig. 2. Independent grid has 226.839 elements being all of them, except at inlet and outlet sections, hexahedra.

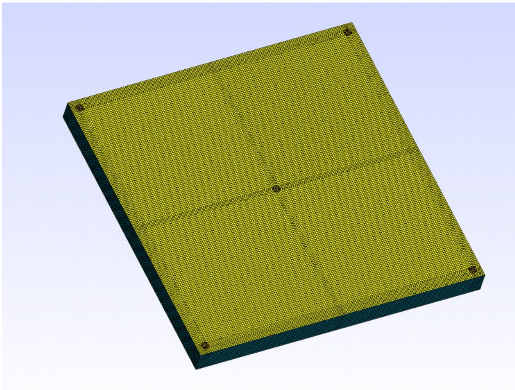

Figure 2. Discretize computational domain

Grid refinement test was performed for a 2D geometry and solution obtained with the independent grid was validated by direct comparison to the algebraic solution for the radial problem (Rudd et al., 1997). 2D independent grid was extruded in the third (z) direction. Final grid was than analyzed with GMSH software by the evaluation of the γ parameter which is defined as the ratio between the smallest and the largest edge of each element. For all elements in the grid $\gamma > 0.55$. Table 1 summarizes parameters used in all simulations.

Table 1: Simulation parameters

Parameters	**Values**
Fiber volume fraction [%]	50
Resin viscosity [Pa s]	0.3
Injection pressure [bar]	3, 4 e 5
In-plane $K_x = K_y$ [m²]	$3x10^{-10}$
Transverse permeability K_z [m²]	$3x10^{-11}$ and $3x10^{-12}$

3. RESULTS

The following results show that infiltration in thick composites by RTM process stills being a difficult task. The low values of the transverse permeability increases medium resistance to fluid flow resulting in larger injection times. As resin viscosity is time dependent, as long as injection time increases, resin viscosity also increases, and if injection process takes too long, curing process may initiates before complete impregnation of the reinforced medium. According to Kiuna et al. (2002), resin time dependence has an exponential like behavior.

Figure 3 show result for the implantation of Eq. (6) as a viscosity model in OpenFOAM software.

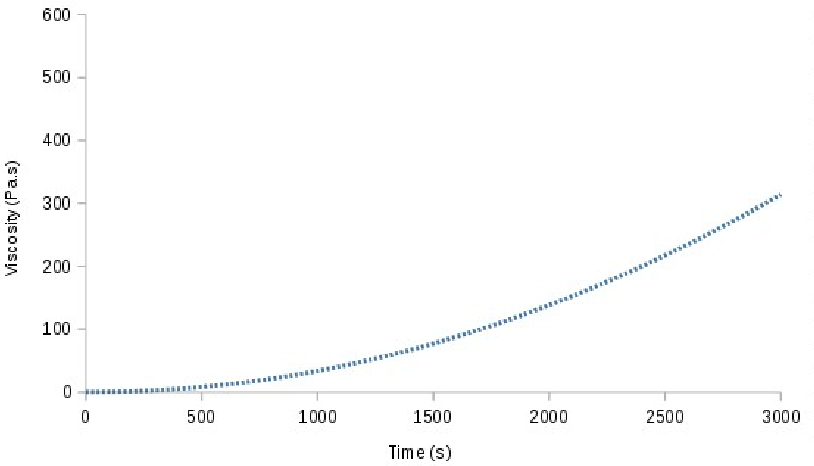

Figure 3. Time versus viscosity curve fitting (LaPol/UFRGS)

Resin used in all simulations is the epoxy has initial viscosity of approximated 0.3 Pa s. With the addition of the initiator, resin viscosity will remain almost unchanged up to 500 s. After that, curing process starts and resin will start to gel at approximated 1000 s. Then, resin viscosity quickly increases and flow advance stops.

Influence of medium transverse permeability as a function of injection pressure and filling time is investigates in Figs. 4 to 6. Flow position in z direction is measured at the geometric center (in x and y directions) of the mold. As can be seen in Figs. 4, to decrease one order of magnitude in transverse permeability is enough to prevent resin from reaching the top of the mold.

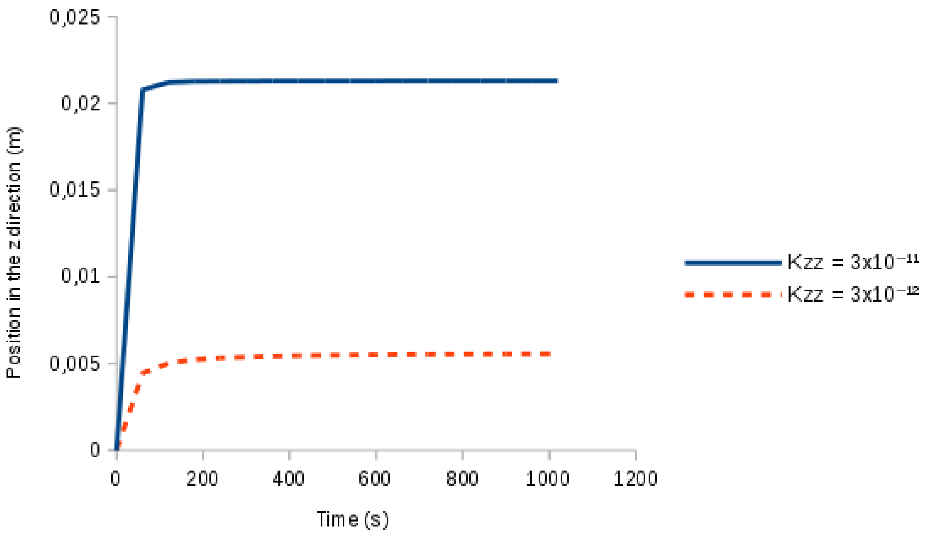

Figure 4. Flow position in z direction (transverse) obtained for different values of K_{zz} for $P_0 = 3$ bar

In Fig. 4 injection pressure is relatively low ($P_0 = 3$ bar) and injection with $K_{zz} = 3x10^{-12}$ m² did not reached the upper section of the mold before resin curing. As an attempt to solve this problem, same simulation was performed three more times with injection pressures of 3, 4 and 5 bars. This study is presented in Figs. 5 and 6.

Figure 5 shows results for $K_{zz} = 3x10^{-11}$ m² and, as expect, in all cases resin reached the upper section of the mold.

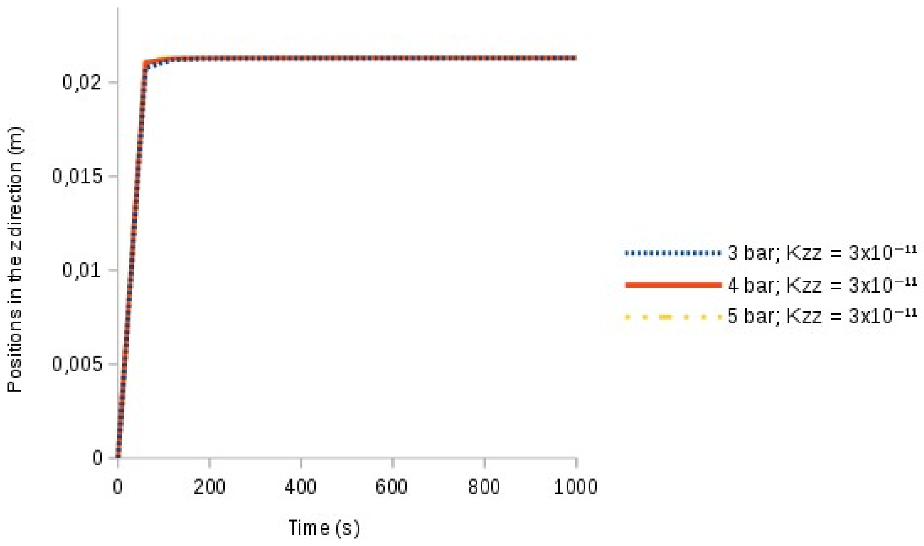

Figure 5. Flow position in z direction (transverse) obtained for different injection pressures and $K_{zz} = 3x10^{-11}$ m²

In Fig. 6 flow position in transverse direction for $K_{zz} = 3x10^{-12}$ m² is plotted for different injection pressures. Increasing injection pressure results in a faster flow advance, however for all tested cases, resin cure started before mold is fully filled, i. e., resin did no reached the upper section of the mold.

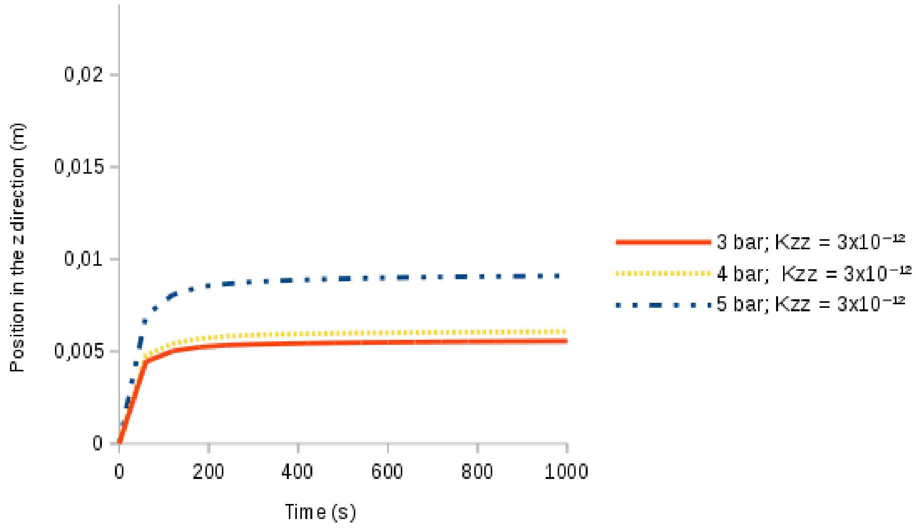

Figure 6. Flow position in *z* direction (transverse) obtained for different injection pressures and $K_{zz} = 3\text{x}10^{-12}$ m²

One of the major problems in forming thick parts by RTM is to guarantee that injection process is finished before resin curing. Results presented in this work showed that used resin enters the vitreous phase at about 1000 s, thus its viscosity quickly increases and flow advance stops. According to these results, mold must be completely filled before 1000 s.

Figure 7 shows a top view of the injection process on which $K_{zz} = 3\text{x}10^{-11}$ m² and injection pressure is 5 bar (all other parameters are described in Tab. 1). Even though resin has reached the upper section of the mold, it did not reached the outlet vents and cured before completing the injection process. Injection radius in this figure is 0.13 m.

In Fig. 7 red regions are completely impregnated with resin ($\alpha = 1$) and blue regions are completely impregnated with air ($\alpha = 0$). In green to yellow regions ($0 < \alpha < 1$) resin and air coexists inside the same grid element. They represent positions where air is trapped inside the reinforcement. These regions are not completely impregnated with resin and must be avoid in order to prevent structural problems to the finished part.

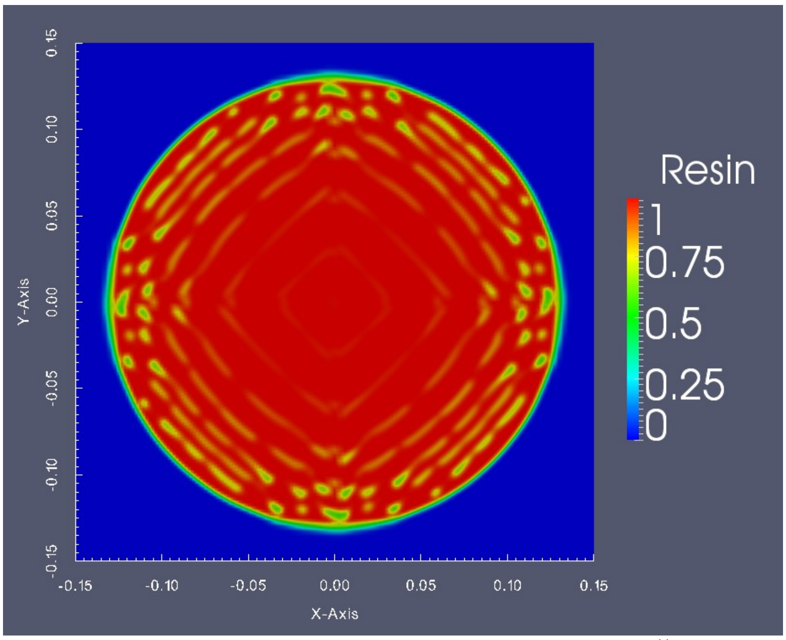

Figure 7. Top view of resin injection at $t = 1000$ s for $K_{zz} = 3\text{x}10^{-11}$ m² $P_0 = 5$ bar

The following simulation, shown in Fig. 8, repeats simulation shown in Fig. 7 with a different mold geometry. In this case, mold height (in *z* direction) was reduced to 0.0127 m (0.5 in) and mold was completely filled in 1000 s. Void regions (green to yellow in Fig. 8) can be observed at the top boundaries edges of the mold. This is an undesired behavior that can be experimentally observed and was correctly predicted by current simulation. If simulation took longer and resin did not cured, most of these air bobbles would be pooled out of the mold, however complete removing of these bobbles is not possible and the amount of resin loss is prohibitive.

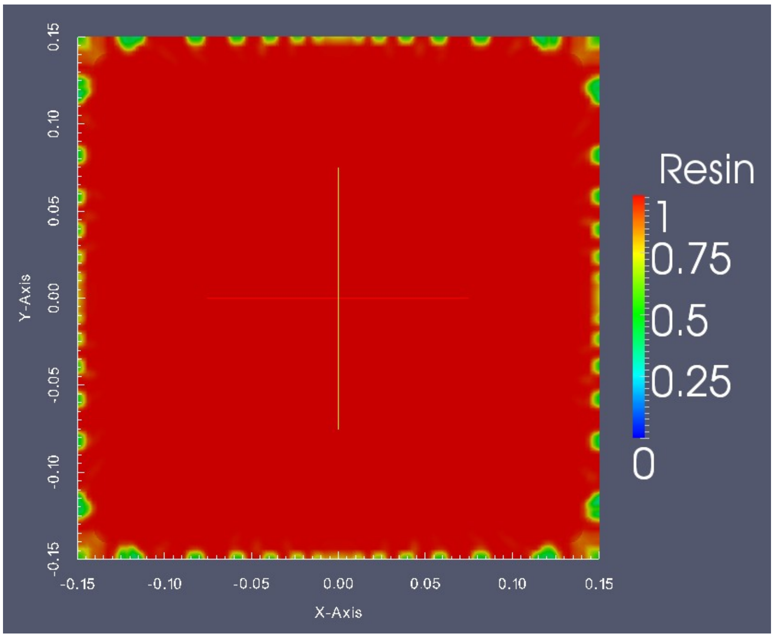

Figure 8. Top view of the injection process at 1000 s (mold height equal to 0.0127).

4. CONCLUSIONS

In this paper a numerical simulation of resin injection in thick parts produced by RTM has been performed. The work concentrated in evaluate transverse permeability influence to the injection process. Proposed solution used the VOF method to solve the multiphase (resin-air) fluid flow inside mold cavity and considered viscosity variation with time in a full 3D simulation.

Results have shown that transverse permeability is an important medium property for the injection process. As injection time is limited by the resin curing time, if mold is not completely filled in time, resin viscosity will quickly increase and flow advance will stops, resulting in a not fully impregnated composite. With the performed simulations it was possible to observe that reducing transverse permeability by one order of magnitude, flow advance velocity is significantly reduced and resin may starts to cure during the injection process.

5. ACKNOWLEDGEMENTS

The author acknowledges the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support.

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