NUMERICAL TECHNIQUE FOR DETERMINATION OF TRANSVERSE PERMEABILITY IN RTM COMPOSITES

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Abstract. *With increasing demand for composite materials in different areas of application, manufacturing techniques are constantly being developed and improved. Liquid Composite Molding (LCM) processes comprise a number of injection techniques widely used in aerospace, automotive and naval industries. RTM (Resin Transfer Molding) process is an example of LCM on which a fibrous reinforcement is compressed and placed into a mold cavity. Resin is then injected into this cavity mold through one or more injection points. Through the RTM process it is possible to produce pieces with excellent control of their mechanical properties and with complex geometry. It is also possible to produce products of large dimensions presenting competitive low production costs. These advantages are only achieved when process parameters such as medium permeability and porosity, resin viscosity and density and injection pressure are known and controlled. Among these control parameters, transverse permeability in 3D pieces is an important property which is relatively difficult to be determined. There are a large number of consolidated techniques for in-plane permeability determination, however transverse permeability determination still is a challenge in many cases. Motivated by the determination of transverse permeability in 3D pieces, this work focuses on developing a numerical methodology for the determination of transverse permeability of reinforced media used in RTM processes. The method consists in using an inverse problem of parameter estimation to calculate the unknown transverse permeability. Inlet pressure and flow position as a function of time are measured experimentally and the mathematical model is solved for the permeability. Newton-Raphson method is combined with a CFD solution (obtained with PAM-RTM software) to solve the problem. Results showed that permeability can be precisely calculated with data measured in the final geometrical model, i.e., it is not necessary to build a specific mold for the permeability experiment determination.*

Keywords: *Transverse permeability, RTM, Numerical modeling*

1. INTRODUCTION

Composites materials are currently used in countless applications. For this reason many Liquid Composite Methods (LCM) are constantly under study and development. Resin Transfer Molding (RTM) is one of these methods widely used in automotive, naval and aerospace industries. According to Amorim Júnior (2007), in the RTM process a fibrous reinforced media is positioned inside a mold cavity and a polymeric resin is then forced into the media through one or more injection gates. Process is finished with the complete mold filling and resin cure. A successful molding is only possible when process parameters such as media permeability and porosity, resin density and viscosity and injection pressure are precisely determined and controlled. Among these, transverse permeability is an important parameter for injection into 3D geometries, which in many cases is difficult to determine.

According to Souza et al. (2012), numerical modeling is an important tool in developing pieces with the RTM process. With numerical modeling it is possible to determine resin flow advance inside the mold and predict void formation, thus avoiding many possible structural problems to the final peice. Moreover, in comparison to laboratory injection experiments, it is much less expensive to run numerical simulations to predict the behavior of the injection process.

Most of the numerical methods used to simulate resin injection in RTM molds are based in the Darcy's Law. To do so, firstly it is necessary to determine the fluid viscosity and medium permeability. Precision of the obtained results are directly associated with the precise determination of these parameters (Souza et al., 2012).

In this work, numerical modeling of the RTM process has been performed with PAM-RTM software (ESI Group, 2014). Geometry building and discretization was done with GMSH software (Geuzaine and Remacle, 2009).

There are a large number of works about experimental permeability determination applied to RTM problems (Sharma and Siginer, 2008). The great majority concentrates in determine in-plane permeability (K_{xx} and K_{yy}) while transverse permeability (K_{xx}) determination is usually much more difficult to be performed.

Kim and Daniel (2003) presented a method to determine transverse permeability by the inverse parameter estimation technique. The method is based on an optimization procedure that minimizes the difference between numerical and experimental injection times measured when the resin injection reaches several locations inside the mold. Numerical solution was obtained with the FE/CV method. According to authors, the proposed method can be easily implemented and is capable of producing reliable results.

Turner and Hjelmstad (2005) performed a study on the influence of experimental measurement errors to the determination of the permeability tensor. They used the Newton-Raphson method to solve the algebraic system of non-linear equations built to calculate the components of the permeability tensor. They reported several points about the importance of the correct initialization of the variables and also about the convergence of the method.

This work concentrates in developing a methodology to calculate the transverse permeability in reinforced media used with the RTM process. Inverse parameter estimation method is used to calculate the unknown transverse permeability. Pressure and flow position are considered known and the mathematical model is solved for the permeability. Newton-Raphson method for the solution of algebraic equations is combined with a CFD (Computational Fluid Dynamics) solution in order to calculate the desired permeability.

2. PROBLEM DESCRIPTION

Resin flow inside mold cavity can be modeled as a porous media fluid flow problem. Usually, Darcy's law is used to formulate the problem. Darcy's law states that flow velocity is said to be proportional to the pressure gradient as

$$\boldsymbol{V}=-\frac{1}{\mu}\boldsymbol{K}\cdot\nabla P \tag{1}$$

where $\boldsymbol{V}$ is the average flow velocity [m/s], $\boldsymbol{K}$ is the medium permeability tensor [m²], μ is the resin viscosity [Pa.s] and P the pressure [Pa].

Combining Eq. (1) with the mass conservation equation for an incompressible flow results in an equation for the pressure as

$$\frac{1}{\mu}\nabla\cdot\left(\boldsymbol{K}\cdot\nabla P\right)=0 \tag{2}$$

There are two common formulations used to simulate resin advance in RTM problems: VOF and FE-CV. In the VOF (Volume of Fluid) formulation, air and resin are considered in the model. Fluids are said immiscible and a unique set of momentum and continuity equations are written for both fluids. An additional equation is then added to the model in order to compute the amount of each phase inside every control volume (Hirt and Nichols, 1981), (Srinivasan et al., 2011), (Oliveira et al., 2009). Darcy's law is then used as a source term in the momentum equation to include media resistance to the flow (Silva et al., 2008).

The FE-CV (Finite Element-Control Volume) method is simpler in terms of formulation (Phelan, 1997). In this case, only the resin is considered in the formulation and Eq. (2) is the unique differential equation needed to be solved with a CFD (Finite Element usually). Transient problem is addressed by solving Eq. (2) successively until the whole mold cavity is filled with resin. This technique can be described in terms of 6 steps: 1) boundary conditions are set to the inlet gates and the whole domain is considered empty (with air) at atmospheric pressure, 2) Eq. (2) is solved to determine a new pressure field inside the computational domain, 3) Eq. (1) is used to calculate the velocity field and mass flow rate of resin entering the control volumes next to the inlet gates, 4) a minimum injection time, necessary to fill at least one control volume is calculated, 5) volume fraction (amount of resin) of all volumes are updated, 6) the new flow front is defined. This algorithm is repeated until mold is completely filled. A schematic description of these 6 steps is presented in Fig. 1.

In present work, PAM-RTM software was used to the fluid flow problem. Even though it is not clear from the manuals (ESI Group, 2014), it is possible to infer that the FE-CV method is used in this software.

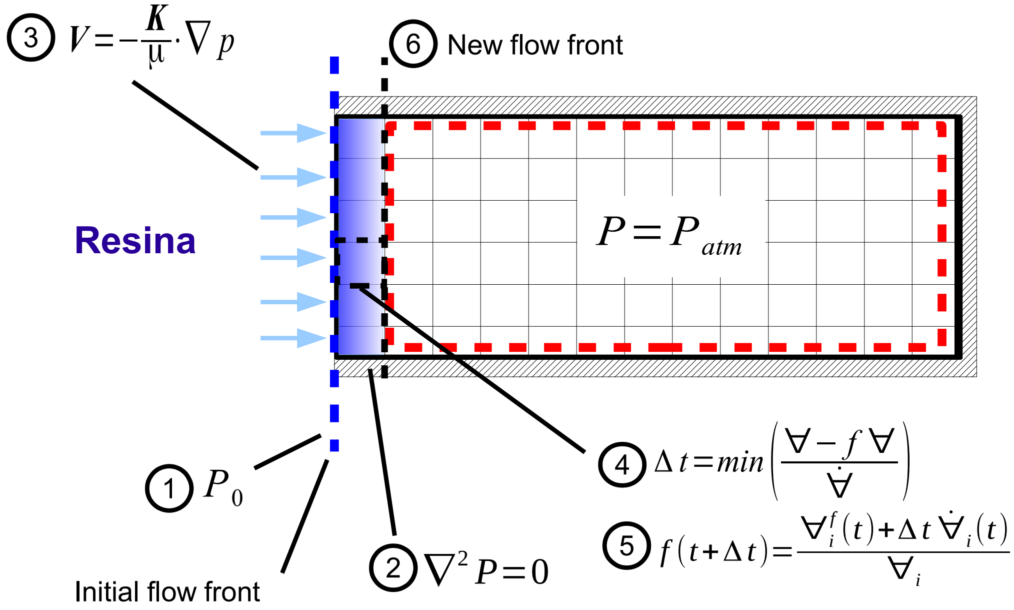


Figure 1. Schematic representation of the FE-CV method

2.1 Geometry and solution procedure

Computational domain is shown schematically in Fig. 2. It was built in the form of a regular hexahedron with (base edge 0.25 m; height 0.05 m). The injection gate (radius $r = 0.005$ m) was placed at the top center of the domain.

The independent grid used in all simulations summed up 248,186 tetrahedra. This type of element was chosen because the current version of PAM-RTM software does not support hexahedra elements.

At the inlet gate, a prescribed pressure [$P_0 = 0.5$ bar] was imposed. For all other boundaries, normal to the surface pressure derivative (dp/dn) was set to zero. In this formulation there is no need to specify any outlet gate.

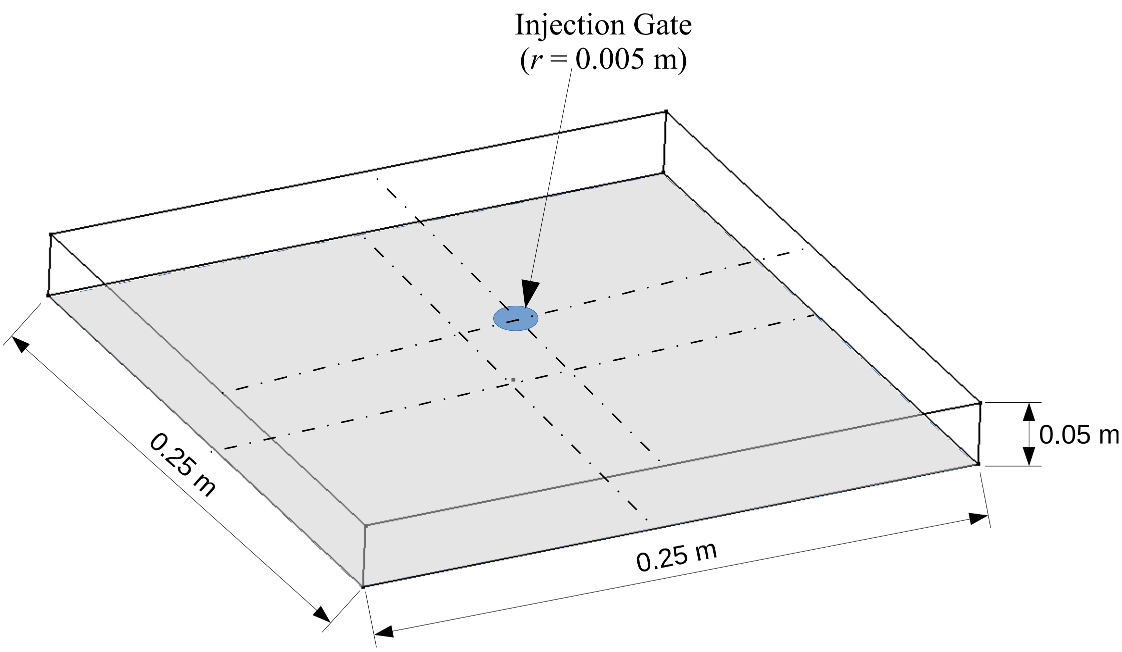


Figure 2. Computational domain (not to scale)

Physical properties and operating parameters set to the current problem are presented in Tab. 1.

Table 1. Physical properties operating parameters

Variable	Symbol	Value
Injection pressure	P	0.5 bar
Injection radius	r	0.005 m
Resin viscosity	μ	0.06 Pa s
Resin density	ρ	920 kg/m³
Medium porosity	ε	0.7
Medium in-plane permeability	$K_{xx} = K_{yy}$	3 x 10^{-10} m²

After the mold is completely filled with resin, by assuming that t_{exp} is the injection time experimentally measured and that t_{num} is the flow time calculated numerically with PAM-RTM software, it is possible to write an equation for the residue as

$$f(K_{zz}, t) = t_{\exp} - t_{num} = 0 \tag{3}$$

In Eq. (3), K_{zz} is the unknown.

Using the Newton-Raphson method (Kincaid and Cheney, 2001), Eq. (3) can be solved for Kzz by

$$K_{zz}^{n+1} = K_{zz}^{n} - \frac{f(K_{zz}, t)}{f'(K_{zz}, t)} \tag{4}$$

where n is the iteration and f' the derivative of f.

In Eq. (4), the derivative is numerically approximated by

$$f'(K_{zz}, t) = \frac{\partial f(K_{zz}, t)}{\partial K_{zz}} = \frac{f(K_{zz}+h, t) - f(K_{zz}, t)}{h} \tag{5}$$

where h is a constant with value equal to 1 x 10^{-15}.

3. RESULTS

Proposed methodology uses experimental data in order to solve Eq. (3), however in this work t_{exp} has been calculated with PAM-RTM software. The theoretical experiment starts by defining a transverse permeability to the medium and then running a simulation to determine t_{exp}. This procedure does not invalidate the proposed methodology because t_{exp} is only a reference value to which solution of Eq. (3) must converge.

It was defined K_{zz} = 3 x 10^{-10} m² and resin injection was simulated up to the time that the mold is completely filled with resin. Calculated time for this condition was t_{exp} = 512.991s.

Equation (3) is then solved for K_{zz} with the Newton-Raphson method. It is important to highlight that each time that t_{num} is called by the Newton algorithm, it is necessary to solve Eq. (2), what is done with the Finite Element Method using the software PAM-RTM.

Convergence log is shown in Tab. 2. It is recommended to have an initial guess as close as possible to the real permeability however this is not a constraint to the proposed method. In the current experiment, K_{zz} was initially set to 1 x 10^{-9} m² which is one order of magnitude larger than the aimed value of K_{zz} (1 x 10^{-10} m²) and it was necessary 21 iterations to reach a relative error smaller than 1 %.

The calculated K_{zz} value is 2.99 x 10^{-10} m² while the aimed value was 3 x 10^{-10} m² leading to an absolute error in determine Kzz of approximated 0.5 %.

In Fig. 3 resin injection simulated with PAM-RTM software is shown at three different times. In this figure blue indicate regions with air and red regions completely filled with resing. Due to symmetry of the chosen geometry, the top view of the mold shows a circular advance of the resin while the mid section cut shows that resin advance is also symmetric in z direction. This behavior is physically expected once in this example, $K_{xx} = K_{yy} = K_{zz}$ = 3 x 10^{-10} m².

The proposed algorithm was applied to a simple geometry, however it can predict final piece permeability for any complex geometry.

Table 2. Convergence log for the inverse problem solution

Iteration	K_{zz} **(m²)**	**Error (%)***
1	1.00E-009	-
2	1.07E-009	6.66
3	1.00E-009	-6.96
4	9.59E-010	-4.41
5	1.01E-009	5.01
6	2.45E-010	-313.01
7	3.89E-010	37.12
8	3.75E-010	-3.61
9	3.66E-010	-2.67
10	3.61E-010	-1.21
11	4.19E-010	13.89
12	3.46E-010	-21.15
13	3.37E-010	-2.77
14	3.34E-010	-0.92
15	3.09E-010	-8.08
16	3.16E-010	2.22
17	3.21E-010	1.56
18	2.96E-010	-8.47
19	3.00E-010	1.23
20	2.99E-010	-0.23
21	2.99E-010	0.07

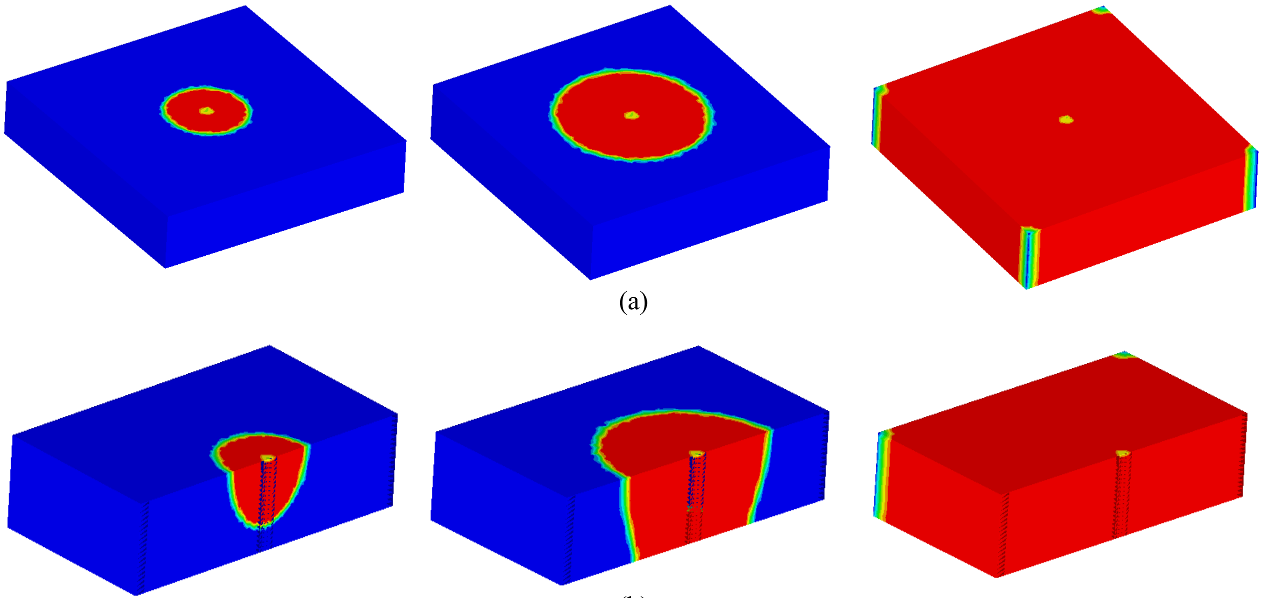
* error = 100 x $(K^{n+1} - K^{n})/K^{n+1}$ where n is the iteration

4. CONCLUSIONS

In this work a simple methodology has been proposed for the transverse permeability determination of porous reinforcements used in the RTM process. The method combines a numerical simulation for resin infiltration inside the porous media with the solution of a non-linear algebraic equation. This algebraic equation was built such as it minimizes the residue between numerical and experimental (in this case a reference value numerically calculated) results for mold filling time.

Results have shown that knowing in-plane permeabilities (K_{xx} and K_{yy}), the other physical constants (ρ, μ and ε) and the total filling time it is possible to predict the transverse permeability in a 3D piece. Proposed method does not requires any experimental apparatus, however it is imperative to know all physical properties and the injection pressure dependence with time (if exists).

The next step will be to employ the same formulation for the solution of a multi-variable inverse problem. In this case, all three components of the permeability tensor should be estimated simultaneous.



(a)

(b)

t = 16 s t = 101 s t = 512 s

Figure 3. Simulation using PAM-RTM for different injection times: (a) top view, (b) mid section cut.

5. ACKNOWLEDGMENTS

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7. RESPONSIBILITY NOTICE

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