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DEVELOPMENT OF A NEW TRANSVERSE PERMEABILITY EXPERIMENT

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Abstract. *This work proposes a new methodology to determine transverse permeability of reinforcements used in resin infusion processes. A new design for the experimental mold is developed not based on a rectilinear flow, as seen in literature, but on a two-dimensional flow. Coupled with the laboratory experiment, a numerical simulation is used to calculate the transverse permeability. In the numerical simulation, resin advance is tracked over the transverse direction and time needed to reach a specific location is compared with laboratory measurements. This work actually reports the first studies about this new method and laboratory experiments have not yet been performed. The needed laboratory data is emulated, however this simplification does not compromise the study presented in the article. Main goal is to develop a simple and easier to assemble experiment for the transverse permeability determination. Preliminary results have shown that proposed method is a viable alternative for the traditional transverse permeability methods. Direct comparison between numerical and experimental result presented an difference (error) smaller than 5%.*

Keywords: *RTM, transverse permeability, numerical modeling*

1 INTRODUCTION

Resin Transfer Molding (RTM) is a manufacture process used to produce polymeric composite pieces. In this process, a polymeric resin is forced into a metallic mold previously filled with a reinforced medium. As a tendency for the last three or four decades, due to good properties like low density, thermal stability, corrosion and mechanical resistance, composite materials are become more and more used to produce pieces of different sizes and geometric complexities. Typical applications are found in the aeronautic, automotive and naval industries (Gutiérrez et al., 2014).

Numerical modeling is a powerful tool used in many engineering applications. More specifically, Computational Fluid Dynamic (CFD) deals with fluid flow calculations and in this work it is used to predict resin advance inside the mold cavity. With CFD simulation it is possible, among other things, to determine the injection/vent positions, predict void (bubbles) formation and estimate mold filling time.

Traditional methods used to determine transverse permeability are based on a rectilinear flow and the application of the Darcy's Law to correlated pressure drop and fluid velocity (or flow rate), which are experimentally measured. If Resin viscosity and reinforcement volume fraction are also known (from separated measurements), permeability is easily calculated (Rudd et al., 1997; Sharma and Siginer, 2008). These rectilinear techniques are very suitable for determination of the in-plane permeability, however for the transverse permeability determination, resin must flow not in fibers direction, but thought (normal to) it. Usual experimental setup assembles a stack of several fabric layers over a perforated plate, and resin flow is assumed to be rectilinear in the transverse direction (Chae et al., 2007; Ouagne and Bréard, 2010; Scholz et al., 2007; Trindade et al., 2019). The problem with this construction is that in many situations, this perforated plate has an important influence in resin flow and the rectilinear conditions is not really achieved. Aiming to avoid the use of this perforate plate, a new assembly is proposed in this work.

The new experiment setup uses a two-dimensional resin flow to determine transverse permeability. In this case, rectilinear analytic solution can not be used to predict flow advance. Permeability determination is now based on a CFD solution performed with OpenFOAM software (Weller et al., n.d.) combined with the method proposed by (Härter et al., 2017).

2 PROBLEM DESCRIPTION

The new mold geometry, designed to produce a two-dimensional flow, is presented in Fig. 1. Resin is forced to enter the mold through the left wall lower section (inlet) and leave the mold through two vents (outlets): one at the upper section of the right wall and the other at the middle section of the top wall. As can be seen in Fig. 1, these two outlets sections are considerably long in comparison to the mold size. This design was imposed to facilitate resin detection at probe location.

In Figure 1, reinforcement occupies only the mold cavity (gray area) while both outlet sections are empty. At the superior wall there are two additional channels used to reduce air bubbles propagation inside mold cavity. They are essential in run cases where transverse permeability is much smaller than in-plane permeability.

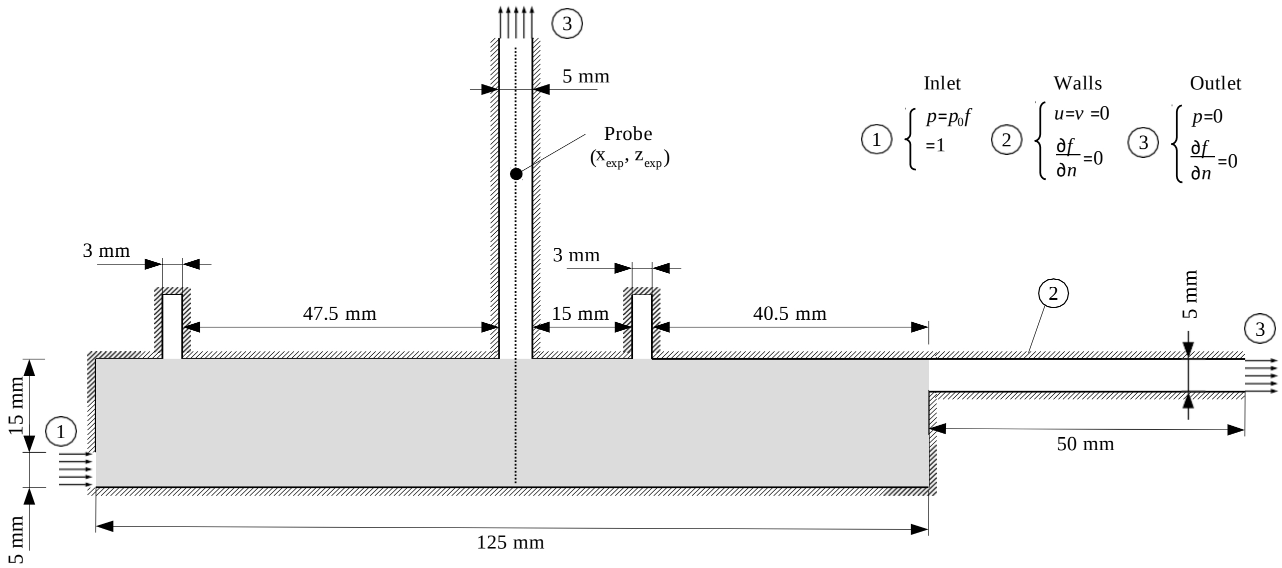

Figure 1. Mold dimensions and boundary conditions.

2.1 Numerical formulation

Fluid flow is modeled as incompressible with constant physical properties. Resin and air are modeled as immiscible fluids and the Volume of Fluid (VOF) method (Hirt and Nichols, 1981) has been used to solve the multiphase flow. In VOF method, a single velocity field is applied for both fluids and an additional transport equation is written for the resin volume fraction. The mathematical model includes the continuity equation

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

where ρ is density [kg/m³], t is time [s], and $\boldsymbol{V}$ is the velocity field [m/s], the momentum equation

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t}+\nabla\cdot(\rho \boldsymbol{V}\boldsymbol{V})=-\nabla p+\nabla\cdot\boldsymbol{\tau}+\rho \boldsymbol{g}+\boldsymbol{F} \tag{2}$$

where p is pressure [Pa], $\boldsymbol{g}$ the gravity vector [m/s], $\boldsymbol{F}$ the force term [N/m³] and $\boldsymbol{\tau}$ the stress tensor [Pa] and the volume fraction

$$\frac{\partial (\rho \alpha)}{\partial t}+\nabla\cdot(\rho f \boldsymbol{V})=0 \tag{3}$$

where f is the resin volume fraction equation.

The region filled with the reinforcement is molded as a porous medium and Darcy's Law is used to include medium resistance to the fluid flow. Thus, force term in Eq. (2) is written as

$$\boldsymbol{F}=\nabla p=-\frac{\mu}{\boldsymbol{K}}\boldsymbol{V} \tag{4}$$

being $\boldsymbol{K}$ the permeability tensor [m²].

In VOF method, computational control volumes may contain both air and resin. Quantities of each phase are computed based on the volume fraction f. If α = 1, there is only resin in the control volume; If α = 0 there is only air in the control volume; if $0 < \alpha < 1$, air and resin coexists in the control volume. Physical properties must be averaged as a function of α such as

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

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

Boundary conditions are also shown in Fig. 1. Fluid flow boundary conditions are prescribed pressure at inlet and outlet sections and no slip condition at the walls. For the volume fraction, $\alpha = 1$ is prescribed at inlet section and null derivative, normal to the boundary, is specified in all other faces and outlets.

Computational domain creation and discretization was obtained with GMSH software (Geuzaine and Remacle, 2009) while numerical solution was performed with OpenFOAM application (Weller et al., n.d.). Main control solution parameters are presented in Tab. 1.

Table 1 - OpenFOAM control parameters.

Variable		Parameter
Software version		7.0
Algorithm		PIMPLE
Solver		interFoam
Linear solvers		
Velocity		Smooth solver
Pressure		PCG
Volume fraction		Smooth solver
Interpolation Schemes		
Transient		Euler
Gradients		Gauss linear
Divergent		
	div(phirb,alpha)	Gauss interfaceCompression
	div(rho*phi,U)	Gauss limitedLinearV 1
	div(phi,alpha)	Gauss vanLeer

2.2 Transverse permeability determination

Similar to what was done in (Härter et al., 2017), an iterative solution is used to calculate transverse permeability inside the mold cavity. The experimental setup presented in Fig. 1 is used to determine the filling time (t_{exp}) when resin reaches the probe location (x_{exp}, z_{exp}). These experimental data should be numerical reproduced with the CFD simulation, however to do so it is necessary to know correct values for transverse (K_{zz}) and in-plane (K_{xx}) permeabilities. Here, resin density and viscosity, reinforcement porosity and in-plane permeability are assumed to be known and the only variable to be calculated is the transverse permeability K_{zz}.

Resin position (z_{num}) along the dashed line in Fig. 1 is tracked in the CFD simulation and at time t_{exp}, numerical and experimental measurements should be equal ($z_{\text{exp}} = z_{\text{num}}$). This condition will only be verified if correct value of transverse permeability is known, thus a residue equation can be written such as

$$f(K_{zz}, t) = z_{num} - z_{\text{exp}} \tag{7}$$

It is important to highlight that z_{exp} was obtained from laboratory experimentation and z_{num} is numerically calculated with the CFD solution described in section 2.1.

Equation 7 can be solved with the Newton Raphson method on which current value for K_{zz}^{n+1} is obtained from a previous approximation K_{zz}^{n+1} by solving the equation

$$K_{zz}^{n+1} = K_{zz}^{n} - \frac{f(K_{zz}, t)}{f'(K_{zz}, t)} \tag{8}$$

where, n it the iteration and f' the numerical derivative of f given by

$$f' = \frac{f(K_{zz}+h, t) - f(K_{zz}, t)}{h} \tag{9}$$

being h a small constant (1×10^{-15} in this work).

Main goal is to determine transverse permeability by solving Eq. (8) iteratively. For every time that $f(K_{xx}, t)$ is evaluated, z_{num} must be calculated by solving the CFD problem. Solution runs from t = 0 to $t = t_{exp}$ and z_{num} is integrated along the dashed line shown in Fig. 1.

This paper reports a preliminary step on which the method is under development. Mold presented in Fig. 1 has not yet been constructed, however experimental data t_{exp} and z_{exp} can be numerical emulated without any loss in the proposed permeability determination method.

Experimental data for porosity, K_{xx} and K_{zz} were taken from literature for six different reinforcements (Trindade et al., 2019) and are compiled in Tab. 2. In all simulations, resin density and viscosity where assume constant and equal to 0.06 Pa s and 920 kg/m³, respectively. Used air properties were density equal to 1.23 kg/m³ and viscosity equal to 1.82 x 10 $^{-5}$ Pa s.

Table 2 - Properties of the reinforcements (Trindade et al., 2019).

Name	**Fiber type**	**Architecture**	**Areal density [g/m²]**	***e***	K_{xx} **[m²]**	K_{zz} **[m²]**
E	E-glass	Plain weave	826	0.65	7.00 x 10 $^{-11}$	7.78 x 10 $^{-12}$
R	R-glass	Plain weave	303	0.59	3.50 x 10 $^{-11}$	1.52 x 10 $^{-12}$
K1	Kevlar®129	Plain weave	148	0.60	3.00 x 10 $^{-11}$	3.75 x 10 $^{-12}$
K2	Kevlar®29	Basket 2x2	532	0.62	7.50 x 10 $^{-11}$	1.97 x 10 $^{-12}$
M1	E-glass	Random Mat	309	0.66	4.50 x 10 $^{-11}$	2.25 x 10 $^{-11}$
M2	E-glass	Random Mat	462	0.64	4.00 x 10 $^{-11}$	1.33 x 10 $^{-11}$

Data from Tab. 2 are used to run reference cases for every reinforcement and emulate the necessary t_{exp} and z_{exp} values. Resin position is tracked inside the mold cavity up to a position, free of voids, inside the superior vent. These values are presented in Tab. 3.

Table 3 - Emulated experimental time and resin position.

Material	t_{exp} **(s)**	z_{exp} **(mm)**
E	90	0.046264
R	190	0.034511
K1	90	0.047825
K2	150	0.038694
M1	100	0.062929
M2	130	0.063569

3 RESULTS

Figure 2 shows resin injection inside mold cavity for the E-glass case. In-plane permeability is about one order of magnitude larger than transverse permeability (see Tab. 2), thus resin advances faster in x direction than z direction. In Fig. 2, red color represents the resin (α = 1) and blue color the air (α = 0). At the interface between the fluids, color varies from yellow to green.

Solution is performed up to time $t = t_{exp}$, which in this case is shown at t = 90 s in Fig. 2. There is no need to fulfill the mold, however if resin flow front does not reach the dashed line (see Fig. 2), convergence problems occurs and the method fails. The method has presented itself dependent on the initial guess for K_{zz} and a “bad” initial guess may lead solution procedure to fail. It was observed that the initial guess must be smaller than the correct value of K_{zz}, however this imposition does note guarantee the convergence.

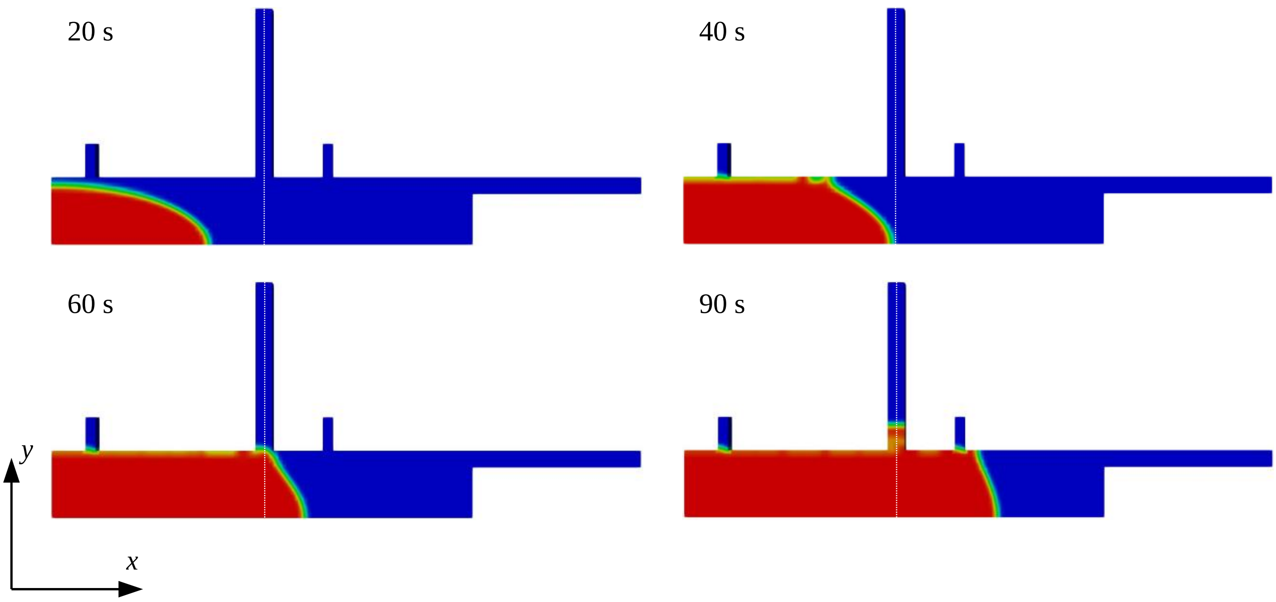

Figure 2. Flow position inside mold cavity.

Results for the six studied cases are presented in Tab. 4. Only best results for each case are shown, however several initial guesses were tried. As an example, for the E material, besides the value case in Tab. 4, it was used as initial guess the values 7.78 x 10 $^{-13}$, 1.28 x 10 $^{-12}$, 1.00 x 10 $^{-13}$, 9.78 x 10 $^{-12}$ and 2.78 x 10 $^{-13}$ resulting in a difference *D* (see footnote in Tab. 4) of *diverged*, 4.01%, *diverged*, 3.89%, respectively. It is important to highlight that when convergence is obtained, same magnitude of *D* is observed, i.e, it always converges for the same solution.

Difference *D* between the reference value K_{zz}^{exp} and the calculated value K_{zz}^{num}, when converged, is always below 5%. This may be considered an excellent result taking into account the complexity of the problem and the difficulties associated with transverse permeability determination. This error (*D*), is associated only with the numerical approximations of the proposed method. Transverse permeability K_{zz}^{exp} comes from laboratory experimental data (Trindade et al., 2019), however time to reach probe location (see Fig. 1) is numerically calculated and used as a reference value for the iterative methodology proposed in this work. It is expected that when K_{zz}^{exp} and t_{exp} were both obtained from laboratory experimentation, due to the associated experimental errors which were not considered in current solution, *D* will be higher.

Table 4 - Calculated transverse permeabilities.

Material	K_{zz}^{exp}	Initial K_{zz} guess	K_{zz}^{num}	*D (%)
E	7.78 x 10 $^{-12}$	9.78 x 10 $^{-12}$	8.00 x 10 $^{-12}$	2.82
R	1.52 x 10 $^{-12}$	6.52 x 10 $^{-13}$	1.59 x 10 $^{-11}$	4.61
K1	3.75 x 10 $^{-12}$	8.75 x 10 $^{-13}$	*diverged*	-
K2	1.97 x 10 $^{-12}$	6.97 x 10 $^{-13}$	2.06 x 10 $^{-12}$	4.57
M1	2.25 x 10 $^{-11}$	2.25 x 10 $^{-12}$	2.32 x 10 $^{-11}$	3.11
M2	1.33 x 10 $^{-11}$	1.33 x 10 $^{-12}$	1.27 x 10 $^{-11}$	4.51

$$* D=\frac{\left|\left(K_{zz}^{exp}-K_{zz}^{num}\right)\right|}{K_{zz}^{exp}}\times 100$$

4 CONCLUSIONS

An original methodology for transverse permeability determination was proposed in this work. The method differs from other procedures found in literature mainly by the new mold design on which a two-dimensional flow, unlikely the usually one-dimensional, is used. Once resin advance inside mold cavity is bi-dimensional, association of laboratory experiments with an analytic solution is not an alternative for permeability determination. This is due because there is no analytic solution for the needed mold geometry. As a replacement for the analytic solution, it is proposed the use of a CFD solution, which combined with laboratory experimentation, allows the transverse permeability determination of reinforcements used in RTM like processes. Results presented in this work are preliminary, once the injection experimental time was numerically emulated, however since differences between experimental and numerically calculated permeabilities remain below 5% for all converged cases, proposed methodology presented itself very promissing.

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