INVESTIGATE OF INFLUENCE PERFORATED PLATE ON DETERMINATION OF TRANSVERSAL PERMEABILITY ON REINFORCED FIBER

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ABSTRACT

Polymeric composite materials can be build in different forms, resulting in different mechanical properties, with numerous industrial applications. Traditionally, they have been largely used in the automotive, naval and aerospace industries. A major concern in polymeric composites manufacture is related with the determination and control of the reinforcement and resin physical properties. They are responsible for the final composite mechanic properties and, if not correct defined, will result in defective composites. Reinforcement permeability is one of these physical properties that, in some cases, are difficult to be kept within the project specification. More specifically, for the case of the transverse permeability, its corrected determination is reported in literature as being considerably more difficult to experiment than the in-plane permeability. The most common experiment for transverse permeability determination is built with a cylindrical mold on which the reinforcement is positioned (and compressed) between two perforated plates. A fluid is forced transversely through the reinforcement, volumetric flow rate and pressure drop are measured, and the Darcy's Law is used to determine the permeability. In this experiment, flow is assumed rectilinear, and the holes of the perforated plates are ignored in the Darcy equation. It is known that size, number e position of these holes may influence the permeability determination, however this problem is not commonly discussed in literature. In this work it is presented a numerical study about the influence of the geometry of the perforated plates on the corrected determination of the reinforcement transverse permeability. The reinforcement region is molded as a porous medium and the two fluid flow (air + resin) is formulated with the Volume of Fluid (VoF) method. GMSH software was used to created and discretize the geometry and OpenFOAM software, more specifically using the interFoam solver, was used to solve the flow problem, determining pressure drop and flow rate inside the mold. Results have shown that correct determination of the transverse permeability is highly dependent on perforate plates geometry.

Keywords: transverse permeability experiment, numerical solution, polymeric composite materials

NOMENCLATURE

ρ	fluid density, kg/m³
$\vec{v}$	Velocity vector, m/s
t	time, s
p	pressure, Pa
$\bar{\tau}$	stress tensor, Pa
$\vec{F}$	field resistance, N/m³
α	volume fraction
μ	Viscosity, Pa s
K	Permeability, m²
Δh	the distance between the inlet and outlet sections , m
$\dot{V}$	volumetric flow, m³
A	Transversal mold area, m²

INTRODUCTION

The use of polymeric composite materials has been constantly increasing in the last few decades. Among many possible manufacturing applications, they are commonly used in the automotive, naval and aerospace industries. The interest of these industries for the composite materials mostly relies on their capacity of producing light pieces with good mechanical properties. However, process control requires a precise determination of the reinforcement and resin physical properties. This properties knowledge is very important to guarantee that defective composites will not be produced.

Liquid Composite Molding (LCM) constitutes an important set of technologies for manufacturing Polymer composites that include process such as Resin Transfer Molding (RTM) and Vacuum-Assisted Resin Transfer Molding (VARTM) (Rudd et al., (1997)). In the RTM process, a fluid (polymeric resin) is forced to fill a mold previously filled with a fibrous reinforcement. This reinforcement imposes a pressure drop to the flow which, if its permeability and resin viscosity were known, may be linearly correlated with the fluid velocity by the Darcy Law. Traditionally, the permeability determination takes place on experimental basis, which can be financially expensive. Thus, the use of computational techniques can be beneficial for the study of these processes.

Some numerical studies for the flow evaluation in reinforcements are already being carried out and obtaining results are very good predictions of the real situation. As discussed and compared in the work of Zarandi et al., (2019), there a number of theoretical and experimental methodologies to determine the reinforcement permeability. In their work it was tested four theoretical models for in-plane permeability and eight for the transverse permeability. These theoretical models were then compared with two numerical solutions: one using the Stokes flow and another using the Whitaker's closure formulation. In the work of Oliveira, (2019) it were conducted experimental and numerical analysis to evaluate transverse permeability in both single and hybrid (two different materials) reinforcements. Results have shown that the mold geometry, more specifically the perforated plates used to assemble the reinforcement inside the mold cavity, has great influence on permeability evaluation. If not well-designed, large errors in transverse permeability determination will occur, however these errors were not quantitatively evaluated. This perforated plate problem has already been reported by Chae et al., (2007), however its influence on permeability results where not sufficiently discussed.

Present work continues the investigation of the perforated plate influence on permeability determination. To do so, a transverse permeability determination experiment is numerically reproduced. It was modeled a cylindrical mold on which the reinforcement is positioned (and compressed) between two perforated plates. Main objective is to evaluate the perforated plate hole distribution influence on the determination of the reinforcement transverse permeability. The reinforcement region is molded as a porous medium and the multiphase flow (air + resin) if formulated with the Volume of Fluid (VoF) method. GMSH software was used to created and discretize the geometry and OpenFOAM software was used to solve the flow problem, determining pressure drop and flow rate inside the mold. The Darcy's law is then used to calculate the permeability. Results have shown that correct determination of the transverse permeability is highly dependent of perforate plates geometry.

PROBLEM DESCRIPTION

Experimental setup and computational domain are described in Fig. 1. Figure 1a shows an internal view of the mold cavity where can be visualized the region between the perforated plates. The reinforcement is placed between these two plates and resin is forced to flow through it in fibers transverse direction. Computational domain shown in Fig. 1b is a simplification of the mold geometry where only the region with the reinforcement is considered.

Reinforcement permeability is obtained with a saturated experiment on which flow velocity and pressure drop are measured. Actually, in the numerical experiment, flow velocity is imposed and pressure drop calculated. According to the Darcy's Law, pressure drop and flow velocity can be linearly correlated as

$$\vec{v} = \frac{K}{\mu} \nabla p \qquad (1)$$

where $\vec{v}$ is the average flow velocity [m/s], K the reinforcement permeability [m²], μ the fluid viscosity [Pa s] and p the pressure [Pa].

Equation (1) can be rewritten as

$$K = \frac{\dot{\forall} \mu \Delta h}{A \Delta p} \qquad (2)$$

where Δh is the reinforced medium height [m] and Δp is the pressure drop [Pa].

A set of experiments are run for different flow rates and permeability can be obtained from Eq. (2) with a regression analysis.

At the begging of the experiment the mold is filled only with air. Resin enters the mold from the inlet vents (Fig. 1), passes through the reinforcement and leaves the mold through the outlet vents (Fig. 1). The two fluid flow problem is molded with the Volume of Fluid (VOF) method proposed by Hirt and Nichols, (1981). This model assumes a multi-phase flow with two or more immiscible fluids. Flow is also assumed incompressible with constant physical properties. Mathematically, three conservation equations as simultaneous solved. They are the continuity equation

$$\nabla \cdot \vec{v} = 0 \qquad (3)$$

a single momentum equation used to describe fluid velocity of both fluids

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \vec{F} \qquad (4)$$

and an adjective transport equation for the resin volume fraction

$$\frac{\partial(\rho\alpha)}{\partial t} + \nabla \cdot (\rho\alpha\vec{v}) = 0 \qquad (5)$$

In Eqs. (3-5), $\vec{v}$ is the velocity vector [m/s], p is the pressure [Pa], $\bar{\bar{\tau}}$ the stress tensor [Pa], t the time [s], ρ the mixture density [kg/m³] and $\vec{F}$ a field resistance [N/m³].

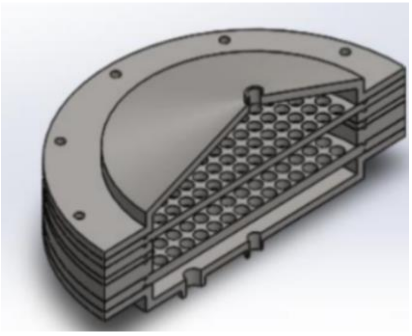
The reinforcement region is formulated as as porous medium and its resistance to flow movement is accounted in momentum equation by defining

$$\vec{F} = \frac{\mu}{K}\vec{v} \tag{6}$$

The mixture physical properties (density and viscosity) are calculated as a function of the resin volume fraction such as

$$\rho = \alpha\rho_{resin} + (1-\alpha)\rho_{air} \tag{7}$$

$$\mu = \alpha\mu_{resin} + (1-\alpha)\mu_{air} \tag{8}$$



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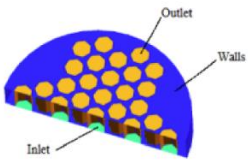


(b)

Figure 1 - Mold geometry: a) CAD drawing cut (Escher and Santos, (2016)), b) Computational domain and boundary conditions.

The boundary conditions are:

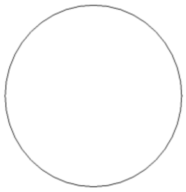
- *inlet:* prescribed velocity and resin volume fraction equal to 1;
- *outlet*: total pressure (gauge) equal to zero and zero gradient (normal to the surface) equal to zero for the resin volume fraction;
- walls: no slip and zero gradient for the resin volume fraction.

To guarantee that numerical solution does not depend on the computational domain discretization, a grid independent test has been performed. Five grids have been testes and the independent grid has approximated 150,000 volumes.

Numerical solution was obtained with a finite volume discretization using the OpenFOAM software (Weller et al., 2022), more specifically using the *interFoam* solver. Solution is transient and convergence stability is controlled by limiting the maximum Courant number to 1.

Evaluation of the transverse permeability experiment

The perforated plate geometry has a great influence on the transverse permeability evaluation. Darcy's Law (Eq. (1)) considers a plug-flow through a porous medium without any interference. The geometry of these perforated plates changes the flow behavior and, depending on the experimental conditions, may result in large errors in permeability values. Aiming to quantify these errors, the permeability determination is numerically modeled using three perforated plates geometries (Fig. 2).



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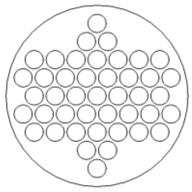

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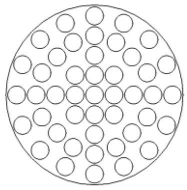


(c)

Figure 2 - Perforated plates geometry.

RESULTS

The transverse permeability determination experiment is here numerically reproduced for the three perforated plates shown in Fig. 2. For all simulation, used flow conditions, mold geometry and physical parameters are summarized in Tab. 1. The experimental setup and reinforcement properties shown in Tab. 1 were taken from previous laboratory experiments (Escher and Santos, (2016); Oliveira, (2019); Trindade et al., (2019)).

The reinforcement transverse permeability was defined as the numerical permeability such as $K_{zz}^{num.} = 2.519 \times 10^{-12}$ m². With this value, the simulations were run and the pressure drop for every case was calculated as shown in column 2 of Tab. 2. With the properties given in Tab. 1 and the pressure drop of Tab. 2, a theoretical permeability, $K^{Theo.}$, can be calculated using Eq. (2). The theoretical permeabilities are shown in column 4 of Tab. 2 and compared with the given numerical permeability of column 2. The difference, defined as the *Error*, is shown in the last column of Tab. 2.

Table 1 - Main simulation parameters.

Property	Symbol	Value
Flow rate [m³/s]	$\dot{\forall}$	1.39×10^{-07}
Mold height (reinforcement) [m]	Δh	0.02223
Mold diameter [m]	D	0.15
Resin density [kg/m³]	ρ	920
Resin viscosity [Pa s]	μ	0.993
Reinforcement in-plane permeability [m²]	K_{xx}	2.519×10^{-11}
Reinforcement transverse permeability [m²]	K_{zz}	2.519×10^{-12}

For the perforated plate case a, which is the exact representation of the physical problem modeled by Eq. (1), the calculated Error was very small, just -1.88 %. This is a verification that the CFD simulation is solving correctly the proposed physical problem. With this result, it was assumed that the physical experiment for the other two cases can be correctly reproduced numerically and the calculated pressure drop could be used to evaluate the transverse permeability with Eq. (2). Results for cases b and c shown in Tab. 2 gives a clear indication of the influence of the perforated plates to the permeability calculation. Geometry of case b is clear a "bad" choice, and the calculated Error is about 15 %. For the geometry of case c, which has a much more homogeneous distribution of the inlet holes, the Error in the permeability calculation is about half of the obtained with geometry b, about 8 %.

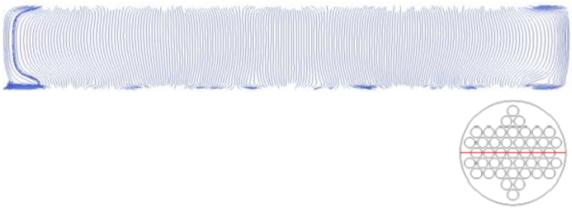
Table 2 - Results for pressure drop and calculated permeability

Perforated plate	Δp [kPa]	$K_{zz}^{num.}$ [m²]	$K_{zz}^{Theo.}$ [m²]	Error [%]*
a	67.9	2.519×10^{-12}	2.566×10^{-12}	-1.88
b	80.7	2.519×10^{-12}	2.152×10^{-12}	14.61
c	75.1	2.519×10^{-12}	2.313×10^{-12}	8.18

$$\text{*Error} = |(K_{zz}^{num.} - K_{zz}^{Theo.})/K_{zz}^{num.} \times 100|$$

The error associated with the perforated plate geometry discussed with results presented in Tab. 2 can be explained by taking a look at the flow behavior inside the mold cavity. To help with this analysis, flow streamlines for the three studied cases are shown in Fig. 3. Top view is represented on the right with a red line indicating the cutting plane show on the left.

(a)



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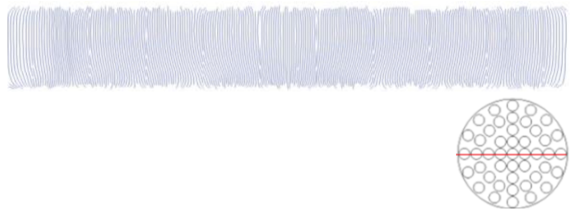

(c)

Figure 3 - Perforated plates geometry.

For case (a), streamlines are straight lines, reporting a rectilinear (plug-flow) advance of the resin inside the mold cavity. This is exactly the solution given by Eq. (2), which is used to calculate (from the laboratory experiments) the permeability. For cases *b* and *c*, streamlines are no longer straight lines. This is an indication that the rectilinear flow assumption that does not exactly represent the theoretical solution given by Eq. (2). The differences seems to be small, but as reported in Tab. 2, they may result in permeability calculation errors as large as 15 %.

From results presented in Tab. 2 and Fig. 3, it can be assumed that the perforated plate holes distribution should be as homogeneous as possible. Moreover, the total holes area should be as close as possible to the mold cross section area.

CONCLUSIONS

In present work it was developed a numerical experiment aiming to verify the influence of the perforated plates on the transversal permeability determination. Their influence to the flow behavior inside the mold cavity, as well as, to the permeability evaluation has been already reported in technical literature, however no quantitative study has been reported. In order to perform this task, three geometries for the perforated plates were built (drawn) and tested. The first geometry reproduces the exactly theoretical solution (Darcy's Law) and was used as a verification of the numerical solution. The other two geometries described possible holes distributions in the perforated plate and were used to calculate its influence to the permeability determination. In both test cases, the same inlet area (sum of the area of all holes) was used and results have shown that errors in permeability determination my reach values as high as 15 %. Results have also shown that changing only the holes position, this error can be reduced to half of this value (about 8 %).

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