COMPARISON BETWEEN TWO WAYS OF MODELING THE FLOW RESISTANCE IN A POROUS MEDIUM

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ABSTRACT

Pieces manufactured from polymeric composites are known for their good mechanical properties and low specific weight. However, controlling their fabrication process requires precise knowledge of the reinforcement and resin physical properties. This is needed to ensure that defective composites are not manufactured. Investigations into these materials physical properties are generally carried out experimentally, which makes it difficult to observe what happens on microscale level. Present work aims to analyze, and compare, flow behavior in a porous medium using two approaches: a) flow resistance is modeled with Darcy's Law, and b) fluid flow is solved through the reinforcement fibers in a micro-sample level. Medium permeability determination was used in results comparison. A good quantitative agreement in predictions obtained with both methods was observed.

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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

INTRODUCTION

The use of polymeric composites has been steadily increasing in recent decades. Among the possible applications, we can mention the use of these materials in the naval, automotive and aerospace industries. The great advantage offered by the use of these materials is mainly due to their ability to produce light parts with good mechanical properties. However, controlling the manufacturing process requires accurate determination of the physical properties of the reinforcement and resin to ensure that defective composites are not produced.

Among the production technologies for these materials, it is possible to highlight the Liquid Composite Molding (LCM), which comprises a wide range of manufacturing processes including the Resin Transfer Molding (RTM) and the Vacuum-Assisted Resin Transfer Molving (VARTM) processes. In the RTM process, a fluid (polymeric resin) under pressure is injected into a mold previously filled with a fibrous reinforcement. This reinforcement imposes a pressure drop on the flow, which, if permeability and viscosity are known, can be linearly correlated with the Darcy's law. Since the viscosity is, usually, easy to determine, the permeability is the parameter to be estimated. It depends on the fibers distribution and volume fraction inside the mold cavity. Generally, LCM processes permeability is evaluated experimentally, which can be costly (financially) making the use of numerical simulation an advantageous option (Rudd et al., 1997; Advani and Sozer, 2010).

Porous medium flows can usually be molded with the Darcy’s Law which correlates the pressure drop with the flow velocity. Two constants are used in the model: a fluid property (viscosity) and a medium property (permeability). This model simplifies the flow behavior and assumes an average value for the flow velocity.

The problem with this approach is that it is not possible to evaluate the flow details inside the mold cavity, making it impossible to estimate how the fiber distribution influences the medium permeability, as well as other factors.

As discussed and compared in the work of Zarandi et al. (2018), there are numerous theoretical and experimental methodologies to determine the permeability of the fibrous reinforcement. In theirs work, some models were tested for in-plane and transverse permeability. These theoretical models are then compared with two numerical solutions: one using the Stokes flow and another using the Whitaker flow for the closure formulation, concluding that both techniques reach similar results.

Most of the experimental investigations carried out in literature have basically been conducted at the macroscopic level where the details of the micro-sample flow pattern in the porous medium cannot be captured. Furthermore, the investigation of the effect of micro structure on general properties mainly involves a large dataset that is time-consuming and expensive to be generated (Chen & Papathanasiou, 2007; Papathanasiou & Chen, 2009; Soltani and Zarrebini, 2013).

Present work numerically evaluates the pressure drop inside a cavity using two approaches: the first is simulating the resin flow through a volume of fibers and the second is simulating the same problem but simplifying the fibers by modeling the flow resistance with the Darcy’s Law.

The multiphase flow (air + resin) is simulated with the Volume of Fluid (VoF) method. The Gmsh software is used to design and discretize the geometry and the OpenFoam software is used to solve the flow problem, determining the pressure drop and flow rate inside the geometry. Darcy's law is then used to calculate the reinforcment permeability.

PROBLEM DESCRIPTION

Figure 1 presents the two ways of approaching the flow problem used in this work: making use of the fibers (approximated by 73 circle) in the numerical simulation or replacing them with an estimated permeability and imposing a linear pressure drop.

The problem with the approach of using a estimated permeability is that it simplifies the problem and flow patterns can only be averaged evaluated inside the mold cavity.

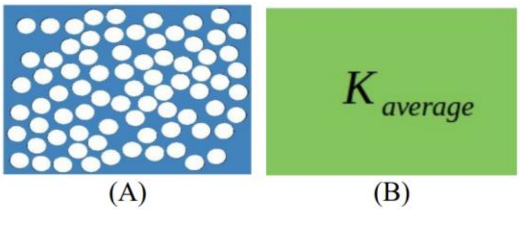

Figura 1: Flow approaches in porous media: (A) microscale fluid flow, (B) Darcy’s Law approximation.

For the construction of the computational domain with the fibers, an image mapping of a sample of composite material taken from Zarandi, Arroyo and Pillari (2018) was carried out. In the computational modeling, all the fibers had the approximate diameter of 5.7 micrometers. Around the fibers, a rectangle with dimensions of approximately 0.6 x 0.7 mm was generated.

After mapping the fibers, the 2D computational domain was generated. The boundary conditions are shown in Fig. 2, where a velocity is prescribed at the inlet that is low enough to use Darcy's law to assess flow in porous media. In this experiment, the fibers are assumed impermeable, so the non-slip condition is considered for the fiber approach (circles on Fig 2), the null pressure are prescribed on the outlet (yellow line) and at the extremes (red lines) are prescribed the slip condition.

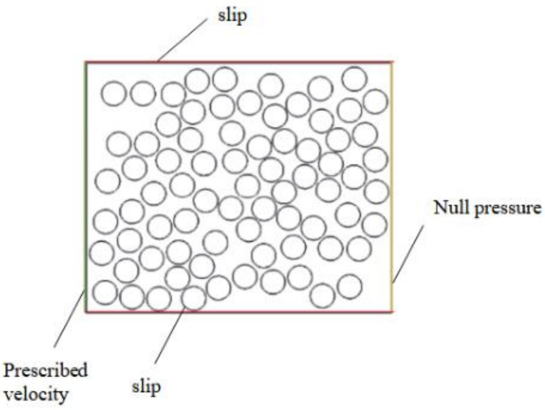

Figure 2: Construction of the computational domain: A) fiber mapping, B) computational domain.

Mathematical Modeling

The simulation is performed with a multiphase solver that takes into account both resin and air. With this model, it is possible to reproduce the unsaturated experiment in which flow front inside the cavity is tracked as a function of time. The Volume of Fluid (VoF) method (Hirt and Nichols, 1981) is used, which is based on the solution of the continuity, momentum and resin volume fraction equations, as follows:

$$\nabla \cdot \left(\rho\vec{V}\right) = 0 \tag{1}$$

$$\frac{\partial\rho\left(\vec{V}\right)}{\partial t} + \nabla \cdot \left(\rho\vec{V}\vec{V}\right) = -\nabla \cdot P + \nabla \cdot \bar{\tau} + \vec{F} \tag{2}$$

$$\frac{\partial(\rho\alpha)}{\partial t} + \nabla \cdot \left(\rho\vec{V}\alpha\right) = 0 \tag{3}$$

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where ρ is the fluid density [kg/m³], $\vec{V}$ is the velocity vector [m/s], t is the time [s], α the resin volume fraction, p the pressure [Pa], $\bar{\tau}$ the stress tensor [Pa] and $\vec{F}$ is the source term [N/m³].

The last term of Eq. 2 represents the medium flow resistance. Here, aiming to compare both results, the gravity effects (not accounted in Darcy's Law) is not considered. Thus,

$$\vec{F} = \frac{\mu}{K}\bar{V} \tag{4}$$

where K is the permeability [m²] and μ the fluid viscotity [Pa.s].

The experiment is reproduced numerically assuming that at the beginning of the simulation the cavity is filled with air (α = 0) and the resin is moving at the inlet velocity (calculated from the prescribed flow rate), so it is possible to trace the air-resin interface between the input and output of the model.

The boundary conditions of the problem are: prescribed resin flow rate and volume fraction (α = 1) at the inlet, zero (gauge) pressure and zero gradient (normal to surface) for volume fraction at the outlet section, no slip and zero gradient for the volume fraction on all walls and on the fiber's perimeter.

The numerical solution was obtained using the interFoam solver, which solves multiphase flows for two immiscible fluids and is available in the OpenFoam software (Weller, Greenshields and Rouvray, 2022).

PERMEABILITY EVALUATION

In present work, ten simulations were carried out. Five of them where the presence of fibers in the rectangular cavity was considered and five where an average permeability is considered.

For each simulation, a different flow rate was specified as boundary condition and the pressure drop was measured between the inlet and outlet sections. Permeability is then calculated from Darcy's law rewritten as a function of the flow rate such as

$$K = \frac{\dot{\forall}\mu\Delta h}{A\Delta p} \tag{5}$$

where $\dot{\forall}$ is the flow rate [m³/s], Δh the distance between the inlet and outlet sections [m], A the cross section area (m²) and Δp the pressure drop [Pa].

Since the reinforcement medium geometry does not change, all run cases should return the same permeability within a numerical error. In order to obtain the permeability to be used in the Darcy's Law based simulations, for all five runs, pressure drop versus flow rate was plotted and a linear regression was performed to determine the average permeability ($K_{average}$). This permeability is then used as an input data for the next five simulations. From these simulations, pressure drop inside mold cavity is obtained again. After that, the results are evaluated in order to verify if there is no disagreement between the two approaches.

RESULTS AND DISCUSSION

The flow experiment in a porous medium is reproduced here in order to evaluate the approach techniques considering the fibrous reinforcement physically inside the rectangular cavity and the approach reducing the fibrous reinforcement to a flow resistance coefficient, i.e. using Darcy's Law.

Figures 4show the pressure gradient of the rectangular cavity. When they are compared, it can be observed that the presence of fibers causes a distortion in the pressure gradient what can not be observed (modeled) with the Darcy's Law approach and may affect the permeability determination results.

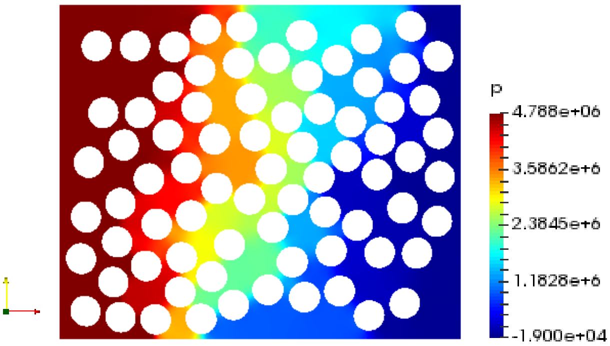

Figure 4: Pressure gradient [Pa] through the fibers

Table 1 presents the results for the pressure drop obtained through numerical simulation as well as the permeability calculated through Darcy's law for the simulations with fiber presence.

Table 1: Results with fiber presence

Velocity [m/s]	Pressure Drop [Pa]	K [m²]	Error [%]
0,12	5,44E+06	1,55E-11	0,60%
0,06	2,78E+06	1,54E-11	-0,67%
0,03	1,39E+06	1,53E-11	-0,78%
0,0075	353595	1,51E-11	-2,38%
0,005	233861	1,52E-11	-1,60%

Five simulations were performed considering the presence of fibers. First with a prescribed velocity of 0.12 m/s. The average permeability obtained from results shown in Tab. 1 was $K_{average} = 1.55 \times 10^{-11}$ m².

The error was calculated follows.

$$\text{Error}[\%] = \frac{K_i - K_{average}}{K_{average}} \times 100 \tag{6}$$

where K_i is the permeability calculated and $K_{average}$ the is the average permeability.

For the next step, calculated medium permeability was prescribed in the software so that simulations could be carried out without the presence of fibers. Results for these simulations are shown in Tab. 2.

Table 2: Results without fiber presence

Velocity [m/s]	Pressure Drop [Pa]	K [m^2]	Error [%][a]
0,12	5,44E+06	1,57E+11	1,80%
0,06	2,71E+06	1,57E+11	1,80%
0,03	1,36E+06	1,57E+11	1,80%
0,0075	338910	1,57E+11	1,80%
0,005	225920	1,57E+11	1,80%

Prescribed flow rate (velocity) and calculated pressure drop were used to calculate the medium permeability. In column 4 of Tab. 2, the error between the prescribed permeability (K_{average} and the calculated permeability through the simulation was calculated.

Comparing results presented in Tabs. 1 and 2 it can be seen that all calculated errors remain below 2%. Demonstrating that both approaches are effective with regard to determining the permeability of the medium.

CONCLUSIONS

In this work, two approaches to the micro-sample flow problem of a porous medium formed by a fiber reinforcement were used. The first considers in the computational domain cavities that represent the fibers while the second considers that the cavity has an averaged flow resistance. Both techniques showed good convergence in the results, obtaining values of divergence in relation to the average permeability below 2%. The main advantage of the technique where the fibers are identified is the better visualization of how the flow occurs in the composite, which is very difficult to be achieved in experimental tests. In the approach where flow resistance is considered, the main advantage is the low computational effort.

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