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"Numerical permeability measurements of a woven fabric preform for different clear-fluid and porous medium interface conditions"

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Numerical permeability measurements of a woven fabric preform for different clear-fluid and porous medium interface conditions

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***Abstract*-Numerical simulations are widely accepted for permeability measurements of fabric preforms used in liquid composite molding (LCM). The lack of research about interface conditions raises the question of the applicability and reliability of these conditions in the simulations of fluid flow through a porous medium. It is obvious that the well-known Navier-Stokes equation can safely be applied to the clear-fluid region though, for the porous region it is not yet well-established, what interface conditions can best accompany the Darcy and/or Brinkman governing equations. Hence, in this paper, these governing equations are employed, with some of the appropriate interface conditions to signify the variations of permeability results due to different mathematical parameters in a validated numerical model. Commercial software COMSOL is used for our simulations, and permeability measurement results for different interface conditions are presented and discussed. The numerical and experimental results are also compared for a woven fabric preform.**

Keywords: Composite manufacturing process, Interface conditions, LCM, Permeability measurement

I. INTRODUCTION

The growing use of composites in various industries such as, aerospace, sports… led to invention of new approaches for composite manufacturing. One of the most employed methods is liquid composite molding (LCM). [1] Permeability is the most important parameter in LCM molding processes. this parameter directly determines the injection time, inlet and outlet port locations, resin rich regions and voids, thus permeability should be measured beforehand. [2, 3]

Permeability measurement methods have been discussed widely in the literature and the results show that the experimental procedures are the most reliable methods for determining the permeability of fabric preforms. But numerical simulations consume much less time and resources so they're widely accepted. One problem that should be tackled carefully while utilizing numerical simulation is that the accuracy of its prediction is highly questionable and needs to be validated and calibrated against experiments. The numerical methods are reliable as long as all the necessary details whether geometrical or theorical are taken into account for the simulations. [4]

The problem that we are dealing with consists of two regions, which are the fluid (open) region, and the porous medium region. the fluid flows between and inside the bundles (intra-tow & inter-tow respectively). The available space for the fluid to flow through these two regions are of different orders which makes this a dual scale problem. For the open region (inter-tow) the flow is governed by Navier-stokes and for the porous region (intra-tow) Darcy's law and Brinkman's equations are examined. [1]

As said earlier, simulations can never fully reconstruct the real situations, but the equations, conditions and assumptions should be implemented in a way to make the simulations as close to experimental situation as possible so that the results can be reliable. The important part of the problem that face is the manner in which the aforementioned regions are coupled in the simulations. Many interface conditions exist that can be applied to this problem but there are not enough data for the operators to decide which conditions best fit the descriptions of their problems. [5] in this paper we examine different interface conditions that are applicable to the governing equations to investigate the discrepancies of the results due to different interface conditions. The results are also compared with experimental ones to study the accuracy of each condition.

II. THEORY AND MODEL

Governing equations

Fig. 1 is a simple demonstration of the problem's domain.

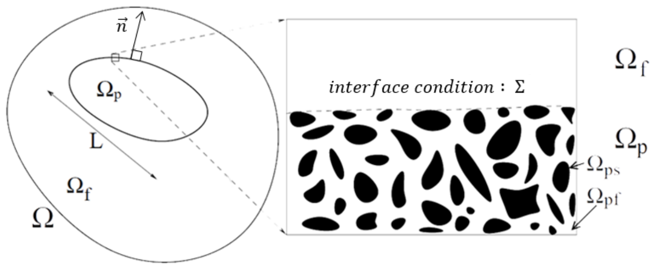


Figure 1: Domain Ω *, pure fluid part* Ω_f *, porous part* $\Omega_p = \Omega_{ps} \cup \Omega_{pf}$

The Darcy and Brinkman equations (in Ω_p) are presented in equations (1) and (2) as:

$$u = -\frac{k}{\mu}.\frac{\Delta P}{L} \tag{1}$$

$$\nabla P = +\mu \nabla^2 u - \frac{\mu}{K} u \tag{2}$$

Interface conditions (IC)

The importance of interface conditions is the fact that it determines the input parameters for porous regions and then with the given data the parameters for the output of clear region are solved simultaneously. Some of the interface conditions provide the possibility of decoupling the two regions. These conditions specify the velocity as an outlet for the Navier-Stokes at the interface and solve the Navier equation for the pressure and velocity of the clear region. The derived pressure at the interface is then used as an input for the porous region and the porous equations are solved. The volume average velocities of the two regions are then back substituted into the Darcy equation to calculate the domain's overall permeability.

These interface conditions are presented as follows:

No-slip condition

No slip is the default boundary condition to model solid walls. A no-slip wall is a wall where the fluid velocity relative to the wall velocity is zero.

$$\vec{u}\Big|_{\Sigma} = 0 \tag{3}$$

Slip velocity

The slip option prescribes a no-penetration condition. It is implicitly assumed that there are no viscous effects at the slip wall and hence, no boundary layer develops.

$$\vec{u}.\vec{n}\Big|_{\Sigma} = 0 \tag{4}$$

No-viscous stress

The no viscous stress condition specifies vanishing viscous stress on the boundary.

$$\mu\left(\nabla\vec{u} + (\nabla\vec{u})^T\right)\vec{n} = 0 \tag{5}$$

Navier-Darcy-Brinkman coupling

Some interface conditions help to solve the equations simultaneously. In this method, unlike the previous one, the velocity magnitude at the interface is not specified beforehand and needs to be calculated from the porous region. The derived pressure from the Navier-Stokes at the interface is taken as an input for the porous region. The velocity within the porous region is then governed by the input pressure and the Brinkman/Darcy law. To assure coupling of the regions, the output velocity of the Navier equation at the interface should be set equal to the Brinkman/Darcy solution for the velocity at the interface. The following interface conditions are the ones that are used for the fully coupled situation.

Interior wall condition

$$P\Big|_{fluid} = P\Big|_{porous}, \quad \vec{u}\Big|_{fluid} = \vec{u}\Big|_{porous} \tag{6}$$

Saffman's modification of Beaver-Joseph condition

Saffman proposed a modification of the Beavers-Joseph condition which contains only variables in clear fluid region.

$$\vec{u}\Big|_{\Sigma} = \frac{\sqrt{K}}{\alpha_{BJ}}\frac{\partial u}{\partial y}\Big|_{\Sigma} \tag{7}$$

Continuous stress condition

$$\overleftrightarrow{T}\vec{n}\Big|_{\Sigma_f} = \overleftrightarrow{T}\vec{n}\Big|_{\Sigma_p}, \quad \overleftrightarrow{T} = \mu\nabla\vec{u} - p\overleftrightarrow{I} \tag{8}$$

Jump stress condition

$$\left(\overleftrightarrow{T}\Big|_{\Sigma_f} - \overleftrightarrow{T}\Big|_{\Sigma_p}\right).\vec{n} = \overleftrightarrow{M}\vec{u}, \quad \overleftrightarrow{M} = \mu\frac{1}{\sqrt{K}} \tag{9}$$

III. SIMULATION METHOD

The results are compared with the experimental results of a PET 61 plain biaxially weave preform published by Adam et al. [4]. Fig. 2 shows the fabric preform and Fig. 3 shows the representative volume element (RVE) of the fabric preform. COMSOL commercial software is used for the simulations. Adam [6] obtained this value to be 25 Darcy (Darcy = 9.87×10^{-9} cm^2).

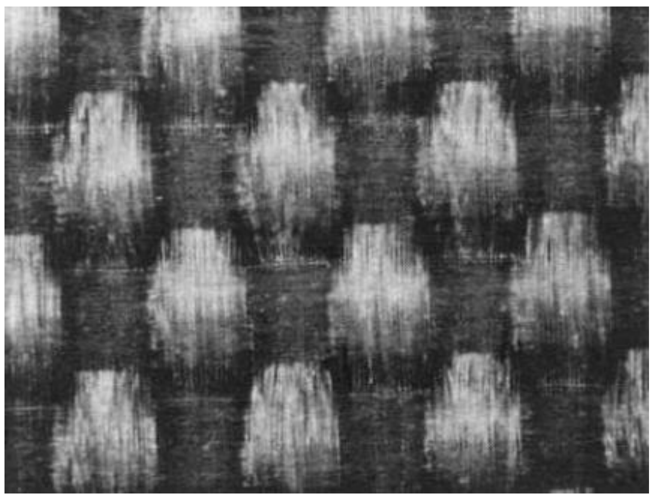


Figure 2: PET-61 fabric preform

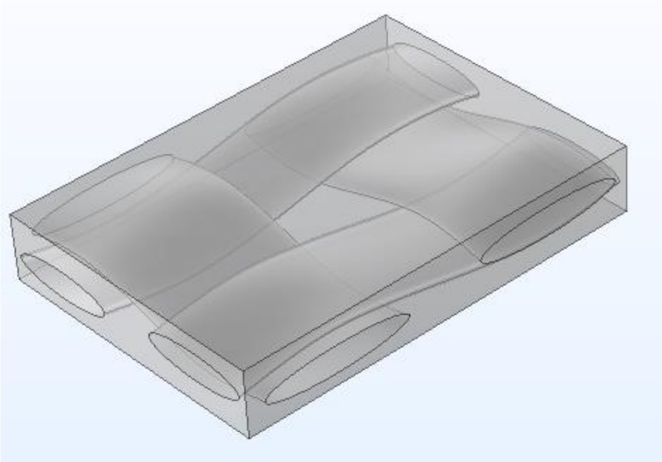


Figure 3: the RVE of PET 61 preform

The local permeability of tows are needed as an input for the calculation of the global permeability. By the assumption of idealized tow arrangement, their permeabilities can be calculated by using the famous analytical Gebart's Eq. The hexagonal arrangement is assumed and using the parameters provided in the table the permeability of warp and weft tows are obtained.

The permeability of tows in flow direction:

$$K_{\parallel} = \frac{8R^2}{c}\frac{\left(1-V_f\right)^3}{V_f^2} \qquad (10)$$

The permeability of tows in transverse direction:

$$K_{\perp} = C_1\left(\sqrt{\frac{V_{fmax}}{V_f}}-1\right)^{\frac{5}{2}}R^2 \qquad (11)$$

Table 1. variables for calculating the permeability of tows

Fiber arrangement	C_1	V_{fmax}	c
Quadratic	$\frac{16}{9\pi\sqrt{2}}$	$\frac{\pi}{4}$	57
Hexagonal	$\frac{16}{9\pi\sqrt{6}}$	$\frac{\pi}{2\sqrt{3}}$	53

The simulation conditions are provided in table 2.

Table 2. the simulation conditions

Parameters	**Quantity/definition**
Imposed pressure gradient (X-direction)	0.1 Mpa
Outlet pressure	0 Mpa
Boundary conditions	Symmetry/Walls
Viscous model	Laminar
Kinematic viscosity	0.01 Pa. s
Experimental results for K_{xx}	25 Darcy (9.87×10^{-9} cm^2)
PET-61 Fiber volume fraction	58.5%
RVE Fiber volume fraction	52.7%
Software	COMSOL

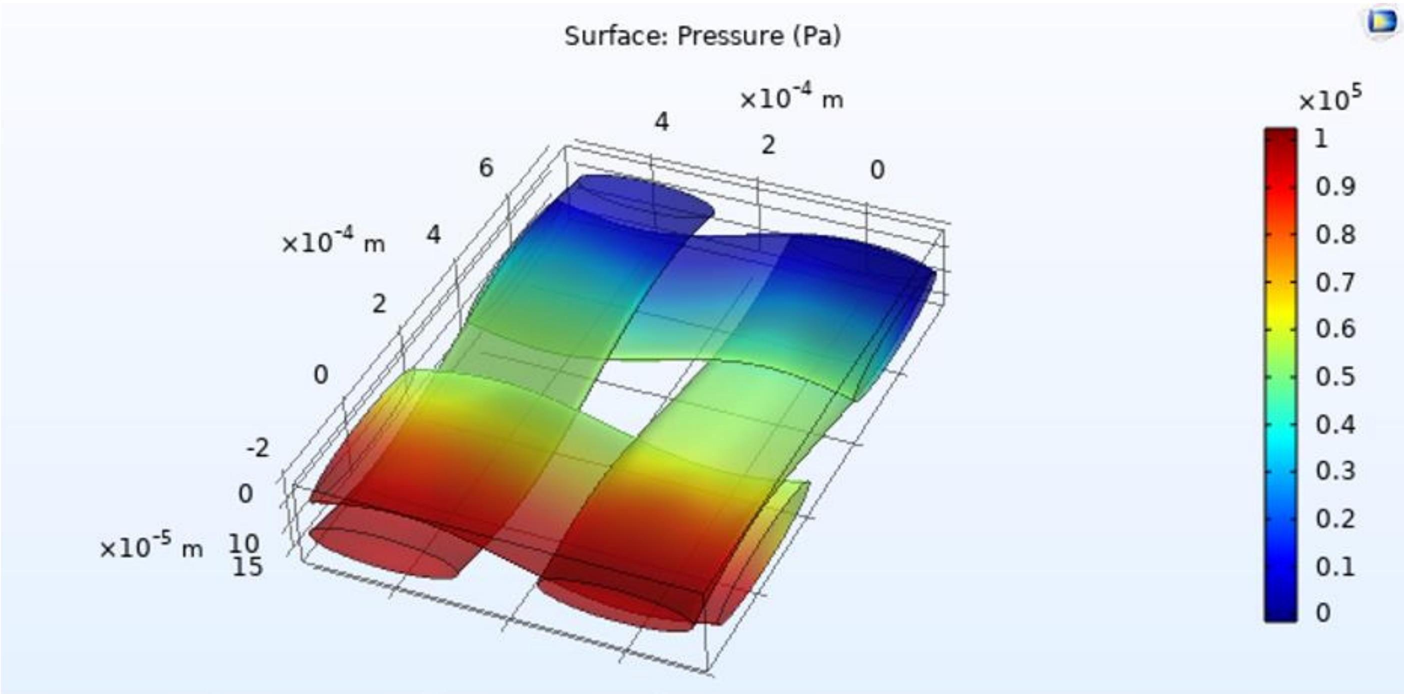
Process of obtaining the results-Slip velocity with Darcy

Fig. 4 shows the results provided by COMSOL for Darcy equation accompanied by slip velocity interface condition.

The first and second column show the average velocity of fluid in the open and porous region respectively and the third column shows the average velocity of fluid in the whole domain. The average velocity of the domain is obtained by weighted multiplying of the average velocity of each region and adding them together. In this problem the fiber volume fraction is 52.7%, this means that the weight of the open region is 0.473 and the weight of the porous region is 0.527.

After obtaining the average velocity of the domain, this parameter is substituted in the Darcy equation as shown, and the global permeability of the domain is calculated.

In this case the K_{xx} is 42.5 Darcy.



Average 1 (m/s)	Average 2 (m/s)	Average 1 (m/s)
0.82304	0.0094825	0.43400

Figure 4: the results provided by COMSOL for Darcy equation accompanied by slip velocity interface condition

$$average\ velocity\ of\ open\ region = 0.82304\left(\frac{m}{s}\right)$$

$$average\ velocity\ of\ porous\ medium\ = 0.0094825\ \left(\frac{m}{s}\right)$$

$$Average\ velocity\ of\ the\ whole\ Domain = (0.527 * 0.82304) + (0.473 * 0.0094825)$$
$$= 0.43400\ \left(\frac{m}{s}\right)$$

Permeability calculation

$$u_x = -\frac{K_{xx}}{\mu}\frac{\nabla P}{L_x}$$

$$K_{xx} = -\frac{L_x \mu u_x}{\nabla P}$$

$$K_{xx} = -\frac{0.01 * 0.43400 * 0.99 * 10^{-3}}{10^5} = 4.2 * 10^{-11}(m^2) = 4.2 * 10^{-7}(cm^2)$$

IV. RESULTS AND DISCUSSIONS

the rest of interface conditions are used with Darcy and Brinkman separately and the results are provided in the following tables. As can be seen in table 4**,** With the Darcy equation the No-slip velocity and interior wall conditions give the best results with 13 and 18% error respectively. And the slip velocity and no-viscous stress give the worst results.

With the Brinkman Eq. again the No-slip velocity and interior wall conditions give the best results with 13% error. And the slip velocity and no-viscous stress give the worst results. The jump stress condition gives better results with Brinkman Eq. but the Saffman's modification gives better results with Darcy's law.

Table 4. Results for interface conditions and Darcy's law

Interface conditions	**Solver**	**Volume averaged u_p $(\frac{m}{s})$**	**Volume averaged u_f $(\frac{m}{s})$**	**K_{xx} (Darcy)**	**Error (%)**
Interior wall condition	Coupled	0.0094669	0.607604	29.33	18%
Saffman's modification	Coupled	0.0095256	0.70952	34.16	36%
Jump stress	Coupled	0.0094825	0. 74932	36.05	44%
Continuous stress	Coupled	Did not Converge	Did not Converge	Did not Converge	-
No-viscous stress	Segregated	0.0077544	1.224	58.52	133%
Slip velocity	Segregated	0.0086753	0.82304	42.5	70%
No-slip velocity	Segregated	0.0095652	0.58914	28.25	13%

The slight differences in results between numerical and experimental results may be due to the following factors:

First, the fiber volume fraction of the RVE is about 6% lower than the fabric preforms used in the experiment. lower values of FVF means higher values of porosity which leads to less resistance against the fluid flow and overestimation of the permeability values.

Second, assumption of idealized hexagonal packing and the use of Gebart's permeability equations in the intra-tow region is not always accurate since we know that in reality the filaments inside tows are not idyllically aligned.

The results do not outline the effect of porous medium governing equation on global permeability, since due to the low permeability and porosity values of tows the obtained volume average velocities are low. But that much is clear that Darcy overestimates the velocity within the porous medium.

The results signify the effect of interface conditions on global permeability. The choice of interface conditions can greatly affect the obtained results.

It can be implied from the results that, since the inter-tow flow is dominant in this preform and the intra-tow velocity is very small due to low porosities, the interface conditions that consider higher values of shear stress yield better results than the ones that overestimate the interface velocity due to low shear stress assumptions.

Table 5. Results for interface conditions and Brinkman's equation

Interface conditions	**Solver**	**Volume averaged u_p $(\frac{m}{s})$**	**Volume averaged u_f $(\frac{m}{s})$**	***K_{xx}* (Darcy)**	**Error (%)**
Interior wall condition	Coupled	0.0084708	0.59086	28.4	13.9%
Saffman's modification	Coupled	0.0087009	0.80942	38.86	55%
Jump stress	Coupled	0.0087180	0. 62832	30.27	21%
Continuous stress	Coupled	Did not Converge	Did not Converge	Did not Converge	-
No-viscous stress	Segregated	0.0066211	1.224	58.42	133%
Slip velocity	Segregated	0.0077472	0.82304	42.3	70%
No-slip velocity	Segregated	0.0088751	0.58914	28.27	13%

V. CONCLUSION

The results show great discrepancies in permeability results due to different interface conditions. It confirms our claim that interface condition affects the results significantly and needs to be implemented based on the circumstances of the problem. For instance, in this problem the interfaces with higher shear stress values give better results.

Some interface conditions have been ruled out due to difference with experimental results. We believe that the ones which are validated can still be further investigated for different preforms and porosity levels to see what circumstances they better fit into. This way these conditions can be formulated specifically.

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