EVALUATION OF FIBER PREFORM PERMEABILITY TENSOR CONSIDERING FLOW INLET FINITE SIZE

Viktor Grishaev*, Oleg V. Lebedev, Sergey G. Abaimov, and Iskander S. Akhatov

Center for Design, Manufacturing and Materials, Skolkovo Institute of Science and Technology, 3 Nobel Street, 143026, Moscow, Russia.
*Email address for correspondence: V.Grishaev@skoltech.ru

Keywords: Permeability, Textile preform, Flow modeling, Liquid composite molding (LCM)

ABSTRACT

To manufacture high-performance fiber-reinforced polymers using liquid composite molding it is necessary to have a deep understanding of the fiber preform filling process and, therefore, of its parameters. This is important because such parameters are used in numerical simulations of the resin flow during the filling process. One of the parameters that determines the process is the permeability of the fibrous preform.

In spite of the fact that permeability has been studied by many researchers, there are divergences of experimental results provided by different methods. Therefore, to help to standardize permeability measurements, two international benchmark exercises were conducted. Although the results of these benchmarks were promising, further steps to standardize the measurement procedure were required. In the context of the 2017 benchmarks (one on the in-plane permeability, one on the out-of-plane permeability), an experimental setup was developed to measure all components of a permeability tensor.

The crucial aspect of our study is that the theoretical method developed earlier was implemented to predict values of both in-plane and out-of-plane permeability. This method takes into account the finite size of the inlet gate (when the thickness of the preform is equal to the inlet's diameter or smaller). To develop the method further, in our study we observed flow front pattern of the silicon oil on both sides of the preform and used this information for the evaluation of the permeability components.

We analyzed the permeability for different layups of the preform changing thereby both the compression pressure on the preform and the volume fraction of fibers. To test the response of the preforms on different values of the compression pressure, load relaxations were monitored for both dry and wet states of the preforms.

1 INTRODUCTION

Polymer composite materials reinforced with fibers are widely used in the production of high-tech products due to their high mechanical properties and low weight. One of the technologies for manufacturing fiber-reinforced composites is the liquid composite molding method, in which a liquid resin impregnates a dry fiber preform [1]. After impregnation, the resin solidifies, and the finished product is taken out of the mold.

The quality of the fiber-reinforced polymer composite materials is determined by how well the resin has impregnated the preform and how good is the contact between the fibers and the resin. The impregnation of the preform by the resin is simulated as the unsaturated flow of the Newton incompressible fluid through a porous medium [2,3]. Such flow is governed by the continuity equation for incompressible fluid [1]

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

and the tensor form of Darcy's law

$$\mathbf{v} = -\frac{\mathbf{K}}{\mu}\nabla p \tag{2}$$

where $\mathbf{v}$ and p are volume averaged fluid velocity and pressure, μ is the fluid viscosity and $\mathbf{K}$ is the permeability tensor of the preform. In spite of the fact that permeability has been studied by many researchers, there are divergences of the experimental results provided by different methods [4–9]. Therefore, to help to standardize permeability measurements, two international benchmark exercises were conducted [10,11]. Although the results of these benchmarks were promising, further steps to standardize the measurement procedure were required. In the context of the 2017 benchmarks (one on the in-plane permeability, one on the out-of-plane permeability), we developed experimental methods to measure all components of permeability tensor and to investigate the compressibility of preforms. We will present them in the next section.

2 EXPERIMENTAL METHODS

The developed setup comprised two transparent plates made of PMMA, three cameras, and a liquid supply system (Fig. 1). A continuous-fiber preform was compressed between the plates. One of the plates had an inlet gate for liquid feeding to the preform (different diameters of the inlet gate for in-plane and out-of-plane permeability). Three cameras monitored the movement of the liquid front from both sides of the preform. The output from all of the cameras was synchronized in time so that the images were processed together to obtain the full information on the filling process. In the course of the liquid feeding, the constant liquid pressure was maintained, and the flow rate was measured.

Both in-plane and out-of-plane unsaturated permeability measurements were conducted with the aid of the same test setup. Transparent upper and lower plates allowed observing the unsaturated flow fronts directly. The flow front is determined using the image processing technique as shown in the Fig. 2.

The in-plane permeability tensor was found by the well-known mathematical analysis of the 2D flow front. On the contrary, the out-of-plane permeability measurements involved a non-traditional approach to the flow front propagation analysis based on the solution of Laplace’s equation developed in the previous works [12–14].

In this study, we investigated out-of-plane permeability of an anisotropic multi-layered fibrous preform. The quasi-isotropy assumption allowed us to simplify the analysis because in that case, the permeability tensor is diagonal in any coordinate system, one plane of which coincides with the plane of the preform. We chose the coordinate system, so its X and Y axes were positioned in the plane of the preform layers while its Z axis was normal to them. As it was discussed, the permeability tensor in this coordinate system is diagonal with the first two diagonal elements equal to one another:

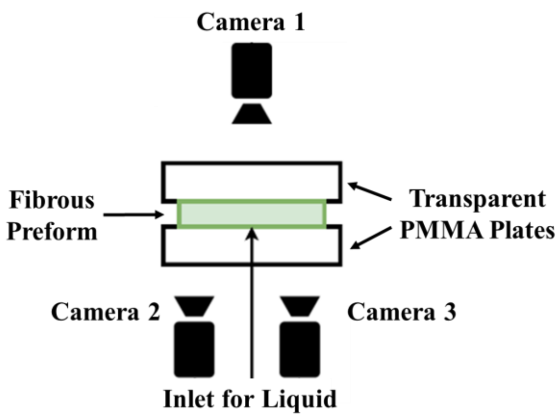

Figure 1: Schematic diagram of the experimental setup for 3D liquid flow tracking in a porous medium.

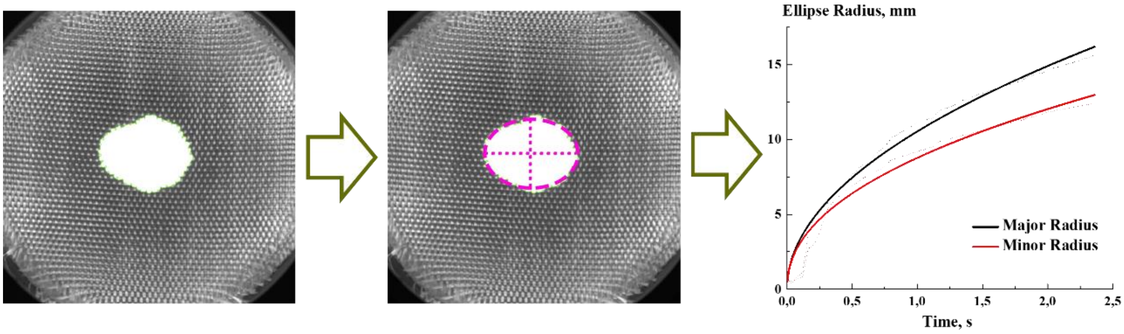

Figure 2: Processing of the data obtained from the cameras.

$$K = \begin{bmatrix} k_e & 0 & 0 \\ 0 & k_e & 0 \\ 0 & 0 & k_z \end{bmatrix}. \tag{3}$$

The profile of the flow front is axisymmetric and is presented in Fig. 3 schematically.

Substituting Darcy's law (2) for the continuity equation (1), we found the second order differential equation

$$k_e \frac{\partial^2 P}{\partial x^2} + k_e \frac{\partial^2 P}{\partial y^2} + k_z \frac{\partial^2 P}{\partial z^2} = 0 \tag{4}$$

which determines the 3D pressure profile within the preform. The boundary conditions were

$$\begin{aligned} P &= P_0 \; for \; inlet \\ P &= P_f \; for \; front \end{aligned} \tag{5}$$

To solve Eq. (4), the coordinates have to be transformed as

$$\begin{aligned} X &= \left(\frac{k_z}{k_e}\right)^{1/6} x \\ Y &= \left(\frac{k_z}{k_e}\right)^{1/6} y \\ Z &= \left(\frac{k_e}{k_z}\right)^{1/3} z \end{aligned} \tag{6}$$

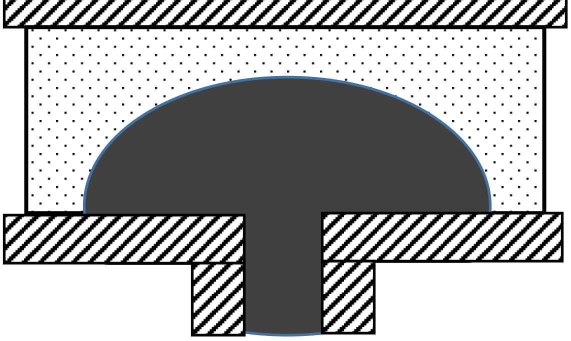

Figure 3: Flow front of the unsaturated out-of-plane permeability.

Eq. (4) thereby transforms into Laplace's equation:

$$\frac{\partial^2 P}{\partial X^2}+\frac{\partial^2 P}{\partial Y^2}+\frac{\partial^2 P}{\partial Z^2}=0 \tag{7}$$

where the new radius of the flow inlet, R_0, and the new thickness of the preform, H, are connected to the original radius r_0 and the original thickness h as:

$$R_0=\left(\frac{k_z}{k_e}\right)^{1/6} r_0 \qquad H=\left(\frac{k_e}{k_z}\right)^{1/3} h \tag{8}$$

To apply boundary conditions directly, the second coordinate transformation was required:

$$X=R_0\cosh\xi\,\cos\eta\,\cos\phi \qquad Y=R_0\cosh\xi\,\cos\eta\,\sin\phi \qquad Z=R_0\sinh\xi\,\sin\eta \tag{9}$$

In the new coordinates, the solution of Laplace's equation is:

$$F(\xi_f,\eta)=\frac{k_e(P_0-P_f)t}{\mu\varepsilon r_0^2} \tag{10}$$

where

$$F(\xi_f,\eta)=F_1(\xi_f)+\sin^2\eta F_2(\xi_f) \tag{11}$$

$$F_1(\xi_f)=\frac{1}{6}\left\{\left(4\arctan e^{\xi_f}-\pi\right)\sinh^3\xi_f-\frac{1}{2}\left(\cosh 2\xi_f-1\right)+2\ln\cosh\xi_f\right\}$$

$$F_2(\xi_f)=\frac{1}{2}\left\{\left(4\arctan e^{\xi_f}-\pi\right)\sinh^3\xi_f-2\ln\cosh\xi_f\right\}$$

and $\xi_f(\eta,t)$ is the flow front dependence on time and position along the front.

To find the front position along the inlet plate, it was assumed that $\eta=0$ in these equations:

$$F(\xi_f,0)=\frac{k_e(P_0-P_f)t}{\mu\varepsilon r_0^2} \qquad r_f=r_0\cosh\xi_f(0,t) \tag{12}$$

On the contrary, for front propagation along Z axis, it was assumed that $\eta=\pi/2$

$$F\left(\xi_f,\frac{\pi}{2}\right)=\frac{k_e(P_0-P_f)t}{\mu\varepsilon r_0^2} \qquad z_f=\left(\frac{k_z}{k_e}\right)^{1/2} r_0\sinh\xi_f\left(\frac{\pi}{2},t\right) \tag{13}$$

Since we knew both r_f and z_f from the experiments, the presented equations allowed us to calculate the in-plane permeability, k_e, and the out-of-plane permeability, k_z. Although the transparency of the plate with the inlet gate allowed us to measure r_f in the course of the whole experiment, only one value of z_f could be obtained, $z_f=h$, in the moment when the front touches the opposite plate.

To test the response of the preforms on different values of the compression pressure, load relaxations were monitored for both dry and wet states of the preforms [15]. The test was conducted on the static testing system Instron 5985 (Fig. 4a). The preform was placed on the top surface of the base platen. The upper platen was moving at constant speed up to the point when the distance between the platens reached the determined through fiber volume fraction calculations value. After that, it was halted for a certain period. The distance was controlled by an extensometer fastened via elastic ties to the platens with sandpapers glued on them (Fig. 4a). After a specific time, the platens were moved apart at the same speed as for the first part of the experiment. During the whole process, the load on the preform was recorded (Fig. 4b).

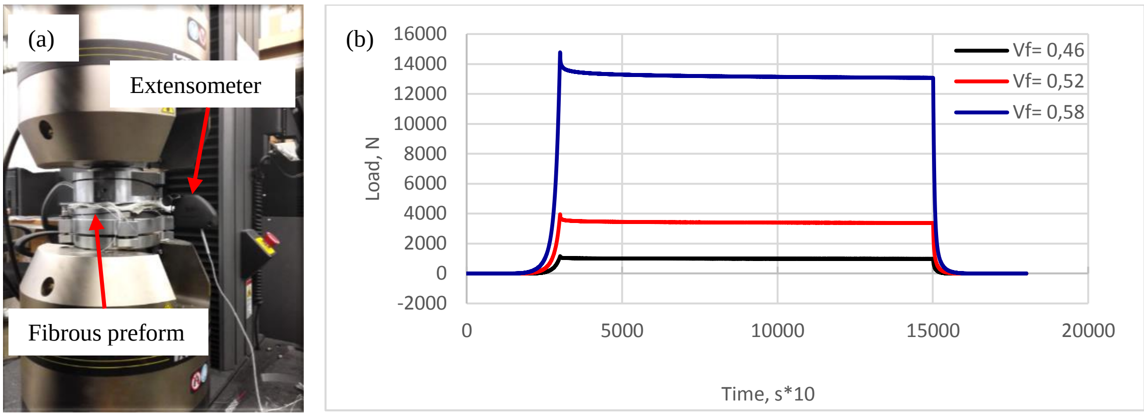

Figure 4: (a) Photo of the setup used for the compressibility tests of fibrous preforms and (b) load-time curves for different final volume fractions of glass fibers.

3 CONCLUSIONS

To study permeability in composite fiber-reinforced preforms, the experimental setup for the measurements of both in-plane and out-of-plane permeability tensor components was developed. The methodology that takes into account a finite size of the inlet gate was used to calculate all components of permeability tensor of a fibrous multi-layered preform. We also investigated compressibility of the preforms to determine their relaxation behavior and to better understand the conditions for permeability evaluation experiments.

REFERENCES

[1] V. Michaud, A Review of Non-saturated Resin Flow in Liquid Composite Moulding processes, Transp. Porous Media. 115, 2016, 581–601, (doi:10.1007/s11242-016-0629-7).

[2] A. Shojaei, S.R. Ghaffarian, Modeling and simulation approaches in the resin transfer molding process: A review, Polym. Compos. 24, 2003, 525–544, (doi:10.1002/pc.10050).

[3] F.D. Dungan, A.M.Sastry, Saturated and Unsaturated Polymer Flows : Microphenomena and Modeling, J. Compos. Mater. 36. 2002, 1581–1602, (doi:10.1106/002199802023179).

[4] N.K. Naik, M. Sirisha, A. Inani, Permeability characterization of polymer matrix composites by RTM/VARTM, Prog. Aerosp. Sci. 65, 2014, 22–40, (doi:10.1016/j.paerosci.2013.09.002).

[5] S. Sharma, D.A. Siginer, Permeability measurement methods in porous media of fiber reinforced composites, Appl. Mech. Rev. 63, 2010, (doi:10.1115/1.4001047).

[6] P.B. Nedanov, S.G. Advani, A Method to Determine 3D Permeability of Fibrous Reinforcements, J. Compos. Mater. 36, 2002, 241–254, (doi:10.1106/002199802021462).

[7] K.K. Han, C.W. Lee, B.P. Rice, Measurements of the permeability of fiber preforms and applications, Compos. Sci. Technol. 60, 2000, 2435–2441.

[8] G. Rieber, J. Jiang, C. Deter, D. Kreutz, M. Glawe, P. Mitschang, V. Gmbh, Influence of Textile Parameters on the Permeability of Reinforcement Textiles, Compos. Part A. 52, 2013, 89–98, (doi:10.1016/j.compositesa.2013.05.009).

[9] E.E. Swery, T. Allen, S. Comas-Cardona, Q. Govignon, C. Hickey, J. Timms, L. Tournier, A.

Walbran, P. Kelly, S. Bickerton, Efficient experimental characterisation of the permeability of fibrous textiles, J. Compos. Mater., 2016, (doi:10.1177/0021998316630801).

[10] N. Vernet, E. Ruiz, S. Advani, J.B. Alms, M. Aubert, M. Barburski, B. Barari, J.M. Beraud, D.C. Berg, N. Correia, M. Danzi, T. Delavière, M. Dickert, C. Di Fratta, A. Endruweit, P. Ermanni, G. Francucci, J.A. Garcia, A. George, C. Hahn, F. Klunker, S. V. Lomov, A. Long, B. Louis, J. Maldonado, R. Meier, V. Michaud, H. Perrin, K. Pillai, E. Rodriguez, F. Trochu, S. Verheyden, M. Weitgrefe, W. Xiong, S. Zaremba, G. Ziegmann, Experimental determination of the permeability of engineering textiles: Benchmark II, Compos. Part A Appl. Sci. Manuf. 61, 2014, 172–184, (doi:10.1016/j.compositesa.2014.02.010).

[11] N. Vernet, F. Trochu, In-plane and through-thickness permeability models for three-dimensional Interlock fabrics, J. Compos. Mater. 50. 2016, 1951–1969, (doi:10.1177/0021998315597989).

[12] S. Mekic, C.A. Ulven, I.S. Akhatov, E. Jerke, E. Kerr-Anderson, Evalutation of in-plane and transverse permeability of flax fiber preforms for biocomposite materials, J. Biobased Mater. Bioenergy. 3, 2009, 156–164,(doi:10.1166/jbmb.2009.1020).

[13] S. Mekic, I.S. Akhatov, C.A. Ulven, Analysis of a Radial Infusion Model for In-Plane Permeability Measurements of Fiber Reinforcement in Composite Materials, Polym. Compos. 30. 2009, 1788–1799, (doi:10.1002/pc.20750).

[14] S. Mekic, I.S. Akhatov, C.A. Ulven, A Radial Infusion Model for Transverse Permeability Measurements of Fiber Reinforcement in Composite Materials, Polym. Compos. 30, 2009, 907–917, (doi:10.1002/pc.20632).

[15] Y. Luo, I. Verpoest, Compressibility and relaxation of a new sandwich textile preform for liquid composite molding, Polym. Compos. 20, 1999, 179–191, (doi:10.1002/pc.10345).