

EFFECT OF PREFORM ASPECT RATIO ON PERMEABILITY MEASURED THROUGH 1D FLOW EXPERIMENTS

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SUMMARY: The 1D flow experiment is one of the most common methods to measure the permeability of fiber preform in liquid composite molding (LCM) processes used for manufacturing polymer composites. To estimate the permeability tensor of anisotropic fiber mats, 1D experiments along three different flow directions in the mat need to be performed. The unidirectional nature of flow in a 1D flow mold is an important theoretical assumption invoked while extracting the full permeability tensor from the measured effective permeabilities along the three flow directions. This paper shows that the validity of this assumption, and hence the accuracy of permeability measurement, depends on the aspect ratio of the fiber mat sample used in 1D experiments. The effect of this parameter on the accuracy of the 1D flow technique is demonstrated experimentally for the first time: results show that the accuracy of the permeability measurement increases with an increase in the fiber-mat aspect ratio. The fitted linear and quadric equations are proposed to predict the error measurement for other aspect ratios.

KEYWORDS: Liquid Composite Molding (LCM), permeability, aspect ratio, preform, 1D flow, Resin Transfer Molding (RTM)

INTRODUCTION

LCM technologies, including resin transfer molding (RTM) and Seemann composites resin transfer infusion molding process (SCRIMP), have emerged as important methods for manufacturing polymer composites. In a typical LCM cycle, reinforcing fibers, composing what is known as a preform, are pre-placed in a closed mold, and a catalyzed resin is either injected or sucked by vacuum into this mold. The resin wets the preform while the mold is being filled. Then, the matrix material is allowed to undergo a solidification process after the filling. Prediction of all such mold filling processes is based on Darcy's law, Eqn. (1), which states that the volume averaged resin velocity in a medium is directly proportional to the applied pressure gradient where v is the volume averaged velocity, K is a symmetric, second order tensor known

as the permeability, μ is the viscosity of the liquid, and P is the pore averaged pressure. Numerous studies have reported the measured permeability values for various types of fiber mats. This physical quantity has been measured by several measurement techniques including 1D flow and radial flow methods [1-11]. It has been suggested that the accuracy as well as the underlying assumption of homogeneous unidirectional flow of the 1D flow method are affected by the ratio of the preform's length to its width or the aspect ratio. Numerical mold filling simulations ran by Tan and Pillai [12] clearly showed that the assumption of 1D flow with streamlines aligned with the flow direction, so essential for the physics of the method, is not possible at small aspect ratios. Lundstrom, Gebart and Sandlund [13] numerically confirmed the effect of increased aspect ratio on improving the accuracy of permeability measurement using the 1D flow method. In this paper, experimental steady-state flow investigations are carried out in a rectangular 1D flow mold under the constant injection rate condition to validate this effect of aspect ratio on the accuracy of the permeability measured through the 1D flow method.

THEORY

For an anisotropic fiber mat, the permeability is a tensor rather than a scalar quantity, and the permeability included as a scalar in Eqn. (1-left) is only the effective permeability (K_{eff}) of the anisotropic fiber mat along a particular flow direction. It is essential to know the relation between the effective permeability and the principal values of the permeability tensor to determine all the components of the permeability tensor. Incidentally the Darcy's law can be expanded from a vector form to a matrix form as

$$\bar{v} = -\frac{K}{\mu} \cdot \nabla p, \quad \begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix} = -\frac{1}{\mu} \begin{bmatrix} K'_{11} & K'_{12} \\ K'_{21} & K'_{22} \end{bmatrix} \begin{Bmatrix} \frac{\partial p}{\partial x_1} \\ \frac{\partial p}{\partial x_2} \end{Bmatrix} \quad (1)$$

where v_1 and v_2 are the average velocity components in the flow x_1 and the transverse x_2 directions, respectively. The analysis of the unidirectional flow observed during the 1D flow experiments assumes that the velocity in the x_2 direction is uniformly zero in the flow domain, i.e. $v_2 \equiv 0$ and the effective permeability K_{eff} can be expressed as a function of principal permeabilities K_1 , K_2 and the angle θ (made by the principal direction 1 with the x_1 axis) [13] as

$$K_{eff} = K_1 \cdot \cos^2 \left[1 + \frac{K_2}{K_1} \tan^2 \theta - \frac{\left(\frac{K_2}{K_1} - 1\right)^2}{\frac{K_2}{K_1 \tan^2 \theta} + 1} \right] \quad (2)$$

Let K_I, K_{II} and K_{III} be the measured effective permeabilities along the angles of $\theta_I = \theta$, $\theta_{II} = \theta + 45^\circ$ and $\theta_{III} = \theta + 90^\circ$ respectively. Using Eqn. (2) and the formulation proposed by Weitzenbock et al. [14], the effective permeability along these three directions can be expressed in terms of K_1, K_2 and the angle θ :

$$K_I = \frac{K_1 K_2}{K_1 \sin^2 \theta_I + K_2 \cos^2 \theta_I}, K_{II} = \frac{K_1 K_2}{K_1 \sin^2 \theta_{II} + K_2 \cos^2 \theta_{II}}, K_{III} = \frac{K_1 K_2}{K_1 \sin^2 \theta_{III} + K_2 \cos^2 \theta_{III}} \quad (3)$$

These in turn can be reformulated to extract the principal permeability components as well the direction from the measured K_I, K_{II} and K_{III} as

$$K_1 = K_I \frac{A-D}{A+D} \cos 2\theta, K_2 = K_{III} \frac{A+D}{A-D} \cos 2\theta, \theta = \frac{1}{2} \tan^{-1} \left\{ \frac{A^2 - D^2}{K_{II} D} - \frac{A}{D} \right\} \quad (4)$$

where

$$A = \frac{K_I + K_{III}}{2} \quad \text{and} \quad D = \frac{K_I - K_{III}}{2} \quad (5)$$

EXPERIMENT

A stack of nine layers of bi-axial fiber mat provided by Owens Corning was used as preform in our permeability experiments. The test liquid, motor oil SAE 10W-40, flowed through the preform during the steady 1D flow experiments at a constant flow rate of $2.81 \times 10^{-6} \text{ m}^3/\text{s}$. A pressure transducer interfaced through LabView with a PC (Fig. 1-a) was used for recording the inlet pressure as well as flow rate. The width of the mold cavity in a 1D mold was altered through the use of a rectangular spacer to create different aspect ratios in the rectangular mold cavity. (Aspect ratio of the preform is defined as the ratio of its length to its width.) Four different aspect ratios were used in this investigation (Table 1). Experiments for three different orientations at 0, 45 and 90 degrees were performed for each aspect ratio of the preform. The experiments were conducted multiple times for each aspect ratio to establish acceptable repeatability in experiments. A radial injection experiment using the bi-axial fiber mat (Fig. 1-b) was also conducted to establish its isotropic nature. Scattering analysis is done for the measured experimental data. A scatter of $\pm 19\%$ was observed for the effective permeability in the aspect ratio 4.

Table 1 Details of the 1D flow experiments for different aspect ratios of the preform

Aspect ratio	Dimensions	$K_{eff} 0^\circ (\text{m}^2)$	$K_{eff} 45^\circ (\text{m}^2)$	$K_{eff} 90^\circ (\text{m}^2)$	$K_I (\text{m}^2)$	$K_2 (\text{m}^2)$
1.0	5" × 5"	8.40E-10	1.79E-09	1.81E-09	8.44E-10	2.02E-09
2.0	10" × 5"	1.21E-09	1.45E-09	1.47E-09	2.50E-09	1.48E-09
3.0	15" × 5"	1.67E-09	1.95E-09	1.65E-09	1.95E-09	1.44E-09
4.0	20" × 5"	2.16E-09	2.10E-09	1.65E-09	1.97E-09	1.54E-09

RESULTS AND DISCUSSION

In the radial flow experiment conducted with the bi-axial fiber mat, completely circular flow front of the liquid penetrating the preform (Fig. 1-b) established that the principal permeability components are identical, i.e. $K_1 = K_2$. (Circularity of the flow front is also demonstrated by the fact that the three pressure transducers, placed symmetrically and at equal distance from the central injection hole, lie on the front.) However the differences in K_1 and K_2 values listed in Table 1 indicate that there is some error in permeability estimation through the 1D flow experiment and it changes with the preform aspect ratio.

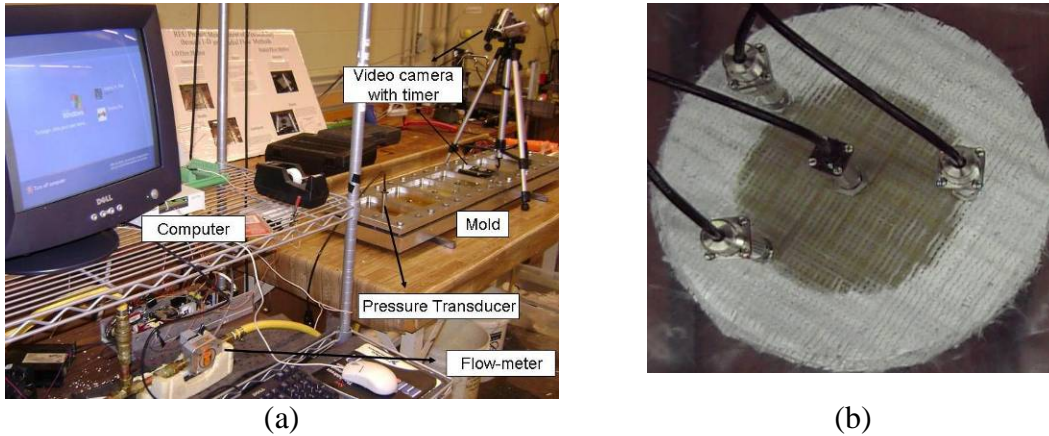


Fig. 1 (a): 1D flow Experiment setup, (b):Radial (point-injection) flow experiment showing a circular flow front in the biaxial fiber mat.

Two different error-criteria were used to quantify this error. In the Fig. 2, the absolute value of difference between the two principal permeability components K_1 and K_2 is used as a criterion for estimating the accuracy, and the plot shows that this difference decreases with the increasing aspect ratio of the preform.

Fig. 3 describes another measure of error in the permeability measured using the 1D flow experiment: $|K_1 - K_2| / K_1$ is plotted as a function of the aspect ratio. The plot shows this error value also falls gradually as aspect ratio increases. On studying these two figures, one can conclude that *higher aspect ratios of the fiber preform lead to more accurate permeability measurements in the 1D flow apparatus.*

Two different curves, one linear and one quadric, were fitted to these data to help one estimate the probable permeability measurement error for other aspect ratios. If the aspect ratio is represented by X and $(K_1 - K_2) / K_1$ is represented by Y , then the curves are the following:

$$Y = aX + b \text{ where } a = 1.485e-9, b = -0.366e-10 \text{ and } r = 0.855$$

$$Y = a + bX + cX^2 \text{ where } a = 2.660e-9, b = -1.541e-10, c = 0.235e-11 \text{ and } r = 0.986.$$

The correlation coefficient r , presented for each curve as an estimate of the closeness of the fit, clearly indicates that the quadric equation represents more closely the trend of the data points.

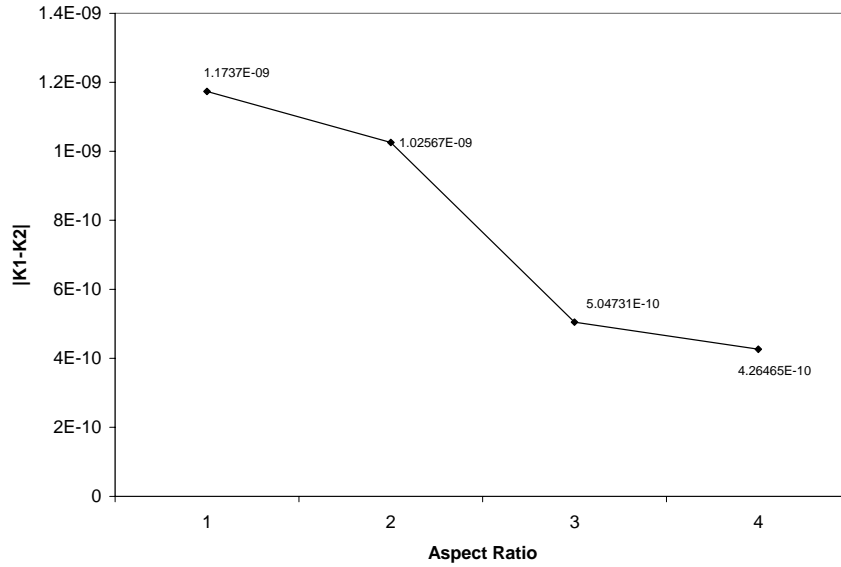


Fig. 2 Permeability measurement error $|K_1 - K_2|$ plotted against the preform aspect ratio.

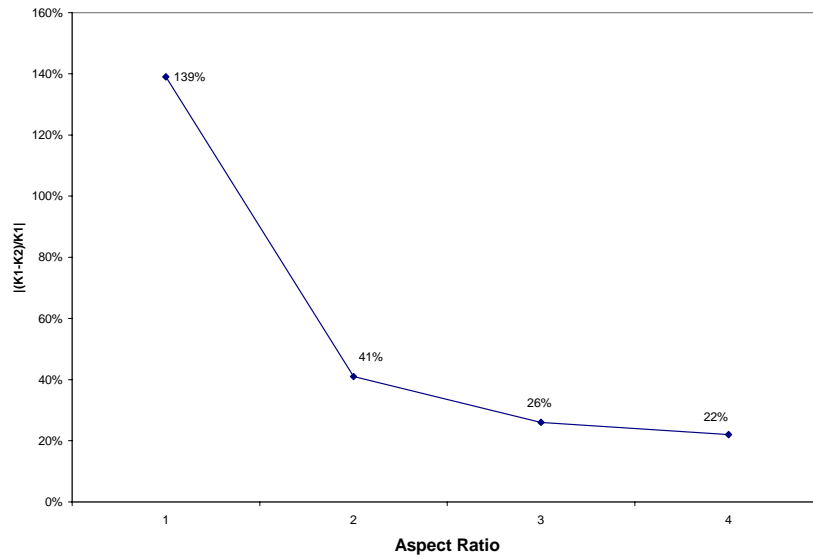


Fig. 3 Permeability measurement error $|K_1 - K_2| / K_1$ plotted against the preform aspect ratio.

CONCLUSION

The accuracy of the 1D flow method for estimating permeability has been investigated experimentally using four different preform aspect ratios for an isotropic biaxial fiber mat. Two different error criteria have been defined to gauge the accuracy of permeability measurement. Plots of both the error criteria against the preform aspect ratio indicate that the accuracy of permeability measured using the 1D flow experiment increases with the increasing aspect ratio. Of the linear and quadric curves fitted to those data points, the latter due to a better fit has an improved capacity to predict the error in permeability measurement as a function of the aspect ratio for the 1D flow experiments.

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