

Research Article

Muhammad Azhar Ali Khan*

In-Plane Permeability Measurement of Biaxial Woven Fabrics by 2D-Radial Flow Method

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Abstract: The accurate characterization of fabrics used in vacuum assisted resin transfer molding (VARTM) is essential in order to model the flow through these porous preforms. A wide range of these fabrics are available for composite manufacturing through VARTM and thus brings about a need to opt a methodology which characterizes the in-plane permeability of these preforms. These permeability values can then be used in simulations that can track the flow front progression and mold filling time. This work identifies the permeability of an E-glass fabric based on Darcy's law. Woven fabric having areal weight of 200 grams per square meter (gsm) is under consideration. The experiments are conducted at constant pressure conditions using 2D Radial flow method. Stereo microscopy of the preform material is done for detailed study of the weaving pattern. It is concluded that plain woven fabric exhibits anisotropic behavior when tested for in-plane permeability. Permeability is found to be higher in a direction which offers more interspacing between adjacent fibers threads causing more resin to flow in this direction.

Keywords: Vacuum assisted resin transfer molding, Darcy's law, Radial flow, In-plane permeability, Infusion

Nomenclature

K	Isotropic permeability of a porous medium [m^2]
C	Process term
I, II	Test directions
F_i	Material term ($i = I, II$) [m^2/s]
N_i	Nominator of F_i ($i = I, II$) [m^2]
K_i	Permeability in test direction ($i = I, II$) [m^2]
r	Flow front radius [m]
r_o	Inlet radius [m]

*Corresponding Author: Muhammad Azhar Ali Khan: Mechanical Engineering Department, College of Engineering, Prince Mohammad bin Fahd University, Al-Khobar, Saudi Arabia; Email: mkhan6@pmu.edu.sa

t_f	Elapsed time to each current flow front position [s]
α_1	Square of the ratio between actual flow fronts <i>i.e.</i> x_f and y_f
x_o, y_o	Scaled inlet dimensions [m]

1 Introduction

Preform permeability has always been a key issue in infusion processes and in flow modeling. The same is true for vacuum assisted resin transfer molding (VARTM), which is of extreme interest to different composite manufacturers today. It is a process in which a dry preform is placed on a single sided mold plate contrary to resin transfer molding (RTM) where a double sided mold is used. The driving force for transferring the resin into the reinforcement is an applied vacuum, which at the same time also compact the reinforcement. VARTM offers numerous advantages over traditional RTM in terms of higher volume fractions of reinforcements, lower tooling costs, potential for room temperature processing and scalability for large structures [1]. Accurate permeability characterization of the preforms used in VARTM has been found a tricky exercise due to a host of parameters involved in the process. In general, two experimental measurement methods, *i.e.* unidirectional flow or channel flow and radial flow experiments, have been utilized to measure the in-plane permeability of fiber preforms such as woven fabric, non-woven fabric, and multi-layered preform [2].

Permeability measurements are critical to accurate flow modeling and many researchers have investigated the permeability of multi-layered preform from 2D radial flow experiments [2–12]. Mathematical Modeling of flow in VARTM to determine permeability of the preform and to predict the mold filling time is not a new idea, instead a lot of work has already been done in this regard. Adams and Rebenfeld [3] developed a permeability model for radial flow where only preforms with same porosity are considered. In their work, the in-plane permeability was found to be more effective in homogenous assemblies due to the creation of interlaminar pores, however, for heterogeneous

assemblies the high permeable layers or directions governs the effective in-plane permeabilities and anisotropies of the preforms. Shin *et al.* [2] proposed a new analytical model for the advancement of flow front and permeability (in-plane and transverse) which was used to determine the permeability of multi-layered preform analytically and then compared with the experimental results. VARTM processes now offer a great mix of high and low permeable materials with a range of weaving patterns such as uniaxial, biaxial or even multiaxial preforms, making it more difficult to model the exact fluid flow through these preforms. Koefoed [4] performed the 2D radial flow experiments for continuous filament mats (CFM), biaxial and multiaxial preforms to be used in wind turbine blades and obtain the in-plane permeability and position of principal coordinates for both the high permeable as well as the low permeable materials. Sayre [5] adapted radial flow method to determine the principal directions and eventually channel flow method to determine principal permeability. The advancing flow front method was used with a single sided VARTM mold in this work.

The inaccuracies in exact flow modeling through the preforms usually arises due to manual means of recording the flow progression along with controlling all other process variables. For this reason, Carter *et al.* [6] introduced a process of automated determination of permeability tensor in the radial setup to avoid errors that arises in manual data treatment. The basic idea was to introduce a series of graphical checks of data *i.e.* plotting the development of flow front in x and y directions with the aid of high resolution digital pictures captured by a video camera. Another important parameter in VARTM processes is the infusion arrangement which has a significant impact especially on mold filling time. Lee *et al.* [7] investigated the in-plane permeability of fiber preforms using the established numerical models and studied the effect of infusion arrangements, Parallel or Fish-bone, based on the scale of the application whether the composite structure to be made by the process is large or small.

Comas *et al.* [8] developed an experimental methodology to measure permanent deformations related to unidirectional compression of fiber reinforcements. These compression tests were further used to develop reliable and generic measurement methods that provides the in-plane and transverse permeabilities. It was reported that the proposed method is effective in minimizing the drawbacks such as edge effects or mold deflections, commonly associated with injection methods. Lee Y. J. *et al.* [9] studied the in-plane permeability of single and multi-layered fibers using experiments. A new parameter “thickness porosity” was proposed to derive the in-plane permeability of fiber

laminates under the VARTM process. Simulations and experimental results were determined and compared for a ship hull with two infusion scenarios *i.e.* parallel and fish-bone. It was reported that the parallel configuration is suitable for a slender and large structure, whereas, fish-bone configuration is applicable to structures having a small aspect ratio.

Grössing *et al.* [10] commented on various aspects and process parameters of permeability measurement experiments. It was inferred that injection pressure does not have a significant impact on permeability, rather, reproducibility is a function of material quality. Higher standard deviations in permeability measurements are due to inhomogeneous areas in the fabric. Also, the number of layers does not matter much if a constant fibre volume fraction is used. It was recommended that appropriate handling of preform is mandatory without which the permeability results can be fairly inaccurate. Recently, Karaki *et al.* [12] reviewed the progress in experimental and theoretical evaluation methods for textile permeability. It was reported that permeability values for same preforms are not in a good agreement when measured using different methods. Minor changes in experimental techniques are reflected as huge discrepancies in the measured values. However, an international benchmark [13] is already available which should be adopted as a reference. Numerical modeling has aided in permeability measurement, yet, the computational limitations makes it more challenging and often requires to compare the results with the values determined using analytical models. The advances in numerical methodology were also reported where a FE model was found to be very efficient in modeling the permeability of different fiber volume fractions for various textile architectures in both warp and weft directions. Simulations using this model could be done much faster with no computer limitations and in most cases, the results are in good agreement with the experimentally measured permeability values. In another recent review by Naresh *et al.* [14], the use of X-ray computed tomography (XCT) for design and process modelling of aerospace composites was presented. With this technique, the time and labor involved in the process can be reduced significantly together with in-situ monitoring of the complete manufacturing process. The scanned data can be used to predict various process parameters via numerical models. It was concluded that current characterization techniques coupled with XCT and CFD tools can bring about modern material models leading to a better design of manufacturing processes.

This paper presents the in-plane permeability of a biaxial woven fabric by extensively utilized 2D radial flow method. Owing to the fact that the scale of plane flow (x-

y plane) is much larger than that of the transverse flow (z-plane) in VARTM processes, this paper considers only in-plane permeability determination in order to simplify the problem. Moreover, the main advantage offered by 2D radial flow method is the possibility of determining the position of the principal coordinate system together with the permeability measurements. Despite a 2D radial flow experiment is more time consuming, it is convenient to perform a single experiment for permeability measurement compared to at least two for the 1D channel flow method. Also, for engineering structures with large surface areas, it is required to know the permeability estimates in both directions of the plane to make necessary arrangements for complete infusion of the preform.

In this work, the preform consists of seven layers of the fabric in order to manufacture composite panels of 1.5mm thickness via VARTM process. Experimental work is conducted at constant pressure conditions owing to the fact that maintaining the constant flow conditions during VARTM is quite cumbersome. Moreover, constant pressure conditions are viable when constructing the large structures such as wind turbine blades and ship hulls etc. [7]. The flow front progression is monitored by non-intrusive means to have no influence on the infusion process. Video of infusion process is recorded by a camera and an automatic data processing program is used to report position of flow fronts as a function of elapsed time. These plots and the process parameters such as porosity, resin viscosity and the pressure gradient are then used to evaluate the final permeability of the preform.

2 Theoretical Background

In-plane permeability can be measured by two methods: unidirectional *i.e.* channel flow method and two-dimensional *i.e.* radial flow method. The latter is preferred due to the fact that it can determine not only the principal direction but also the principal values of permeability tensor in the plane direction at the same time. In addition, the radial flow experiment avoids edge effects which are usually accompanied in the unidirectional flow experiment [15].

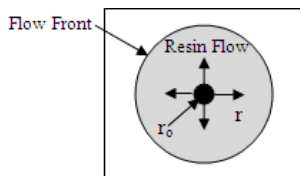


Figure 1: Geometry of 2D Radial Flow Experiment

The 2D radial flow method is based on a square or rectangular preform in which resin is introduced through a circular central hole having an initial radius of r_0 . A schematic diagram of the 2D radial arrangement is shown in Figure 1.

The impregnation of the resin into the preform can be described by the Darcy's law which is empirically derived as follows.

$$u = -\frac{K}{\eta} \nabla P \quad (1)$$

Where u is the velocity vector, η is the resin viscosity, ∇P is the gradient of pressure and K is the permeability tensor. It is assumed that for an isotropic material the flow front is circular whereas an anisotropic material usually revealed an elliptical flow front as shown in Figure 2.

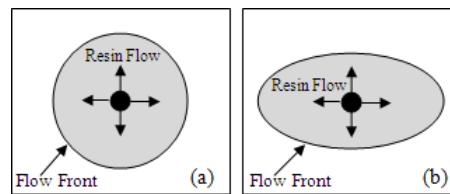


Figure 2: Shapes of flow front in 2D Radial Flow experiments (a) Isotropic (b) Anisotropic

3 Mathematical Model

A mathematical model for resin flow, describes the system behavior by a set of mathematical equations, which represents the physical process of resin advancement. In VARTM processes, there is insignificant transverse flow, hence, they lend themselves to two dimensional flows in the plane of the preform. For this reason, this study is restricted to the solution of the mathematical model that will be based on a two-dimensional radial flow. The basis of modeling the resin flow through porous media is Darcy's law as discussed in the theoretical background. Ahn *et al.* [16] presented the equation for determining the in-plane permeability using 2D radial flow method as follows.

$$K = \frac{\mu \phi}{4 \Delta P} \left(r_f^2 \left[2 \ln \left(\frac{r_f}{r_0} \right) + 1 \right] - r_0^2 \right) \frac{1}{t_f} \quad (2)$$

Equation (2) is transformed into

$$K = F_I C = \frac{N_I}{t} C \quad (3)$$

where C is a process term containing variables that can be adjusted irrespective of the test material and is equal to

$$C = \frac{\mu \phi}{4 \Delta P} \quad (4)$$

and N_I is designated as a material term since it depends on the specific fabric and the lay up. This N_I is equal to

$$N_I = r_f^2 \left[2 \ln \left(\frac{r_f}{r_o} \right) + 1 \right] - r_o^2 \quad (5)$$

Equation (2) is true for isotropic materials however, for anisotropic materials when the flow front is measured in two mutually perpendicular directions *i.e.* x and y , the permeabilities in these two directions are designated as K_I and K_{II} where

$$K_I = \frac{\mu \varphi}{4 \Delta P} \left(x_f^2 \left[2 \ln \left(\frac{x_f}{x_o} \right) + 1 \right] - x_o^2 \right) \frac{1}{t_f} \quad (6)$$

and

$$K_{II} = \frac{\mu \varphi}{4 \Delta P} \left(y_f^2 \left[2 \ln \left(\frac{y_f}{y_o} \right) + 1 \right] - y_o^2 \right) \frac{1}{t_f} \quad (7)$$

On comparing Equations (6) and (7) with Equation (2), it is evident that equations are alike except that K_I and K_{II} for anisotropic material are a function of x and y instead of the radius r for the isotropic case. It is now possible to use Equation (5) to find N_I & N_{II} as follows.

$$N_I = x_f^2 \left[2 \ln \left(\frac{x_f}{x_o} \right) + 1 \right] - x_o^2 \quad (8)$$

$$N_{II} = y_f^2 \left[2 \ln \left(\frac{y_f}{y_o} \right) + 1 \right] - y_o^2 \quad (9)$$

This model assumes that the resin inlet is same as the shape of the flow front. Therefore, for anisotropic materials the size of the inlet hole is changed to x_o and y_o and can be calculated by scaling the inlet dimensions. The ratio between the principal axes is determined by plotting x_f vs. y_f measured at the same instant of time, and making the best line fit. The square of the line fit parameter is denoted α_1 and it is given as

$$\alpha_1 = \left(\frac{x_f}{y_f} \right)^2 \quad (10)$$

The size of x_o and y_o is hereafter calculated as

$$x_o = \sqrt[4]{\alpha_1} r_o \quad (11)$$

and

$$y_o = \sqrt[4]{\frac{1}{\alpha_1}} r_o \quad (12)$$

The term α_1 is a direct measure of level of anisotropy in the material. Both isotropic and anisotropic materials can be characterized for permeability with the only difference of modifying the inlet dimensions in case of anisotropy.

4 Materials

4.1 Fabric

The preform selected in this study is plain woven E-glass fabric in which threads are woven over and under to form a checkerboard pattern. The weaving is unbalanced in the sense that the number of threads in warp and weft direction is unequal. The material specification of the fabric is listed in Table 1.

Table 1: Material specifications of fabric

Areal Weight	200±30 gsm
Thickness	0.2±0.05 mm
No. of Threads	Warp 17±3 / cm
	Weft 13±2 / cm

4.2 Microscopic Examination of Fabric

The weaving pattern of the preform material is studied in detail using stereo microscopy which can provide a magnification of 10X – 40X. The light reflected from the surface of an object is used to form an image using stereomicroscope. This microscope is equipped with two objectives and eyepieces to provide slightly different viewing angles to both eyes. With such an arrangement, it produces a three dimensional view of the sample under examination. The preform arrangement selected for this study is centered on the stage properly and the image is magnified twenty times as of the original fabric to examine the weft and warp directions designated as 1 and 2 respectively in Figure 3. It is found that

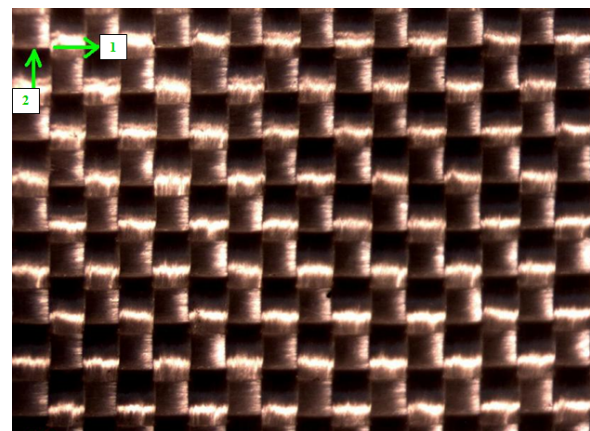


Figure 3: Stereo microscopy of 200 gsm woven fabric

the number of threads per cm is more in the warp direction compared to that in weft as already discussed in Table 1. Moreover, an important observation is that threads in the warp direction are thicker one allowing no internal space between the adjacent threads which can be clearly seen in the weft direction.

4.3 Resin System

The resin system used in this study is Epoxy 6010. Chemical compositions *i.e.* resin, hardener and solvent, gel time and viscosity of the resin system is shown in Table 2.

Table 2: Properties of resin system

Resin System	Epoxy: Hardener: Acetone
Percentage by Weight	45 % : 35% : 20 %
Observed Gel Time	~24 hours
Viscosity (Pa·s)	0.193

Adding solvent like acetone is a quick and simple method of thinning epoxy resin systems which eventually reduces the mold filling time and increases the gel time. Acetone is preferred because it is commonly available and is less likely to be trapped in the cured epoxy [17].

5 Experimental Setup

2D radial flow experiments are time consuming but facilitates the evaluation of in-plane permeability in the principal directions of the preform. The process also avoids race tracking issue which is usually observed in the unidirectional flow experiments. The foundation of the process is the preform with a radial inlet hole. The preform used consisted of seven layers of 200 gsm biaxial woven fabric with inlet hole of diameter 8mm. The hole is punched in order to make surfaces as smooth as possible. The preform was then positioned on the mold plate, which in this study consists of a glass plate with the dimensions $0.48\text{m} \times 0.38\text{m} \times 0.01\text{m}$. A connecting branch is then glued to glass plate to assist the resin infusion process. The preform is then covered with the vacuum bag and the vacuum is applied to the edges of the preform by means of spiral tube. When the compaction in the preform is maintained and it is found air tight the experiment is ready to be executed. A video camera is used to track the progression of flow front during the experiment and this video is then used to determine

the position of flow front as a function of elapsed time. The preform is then infused using epoxy resin with a pressure difference of 95 kPa and the progression of flow front is observed. A schematic diagram of the 2D radial flow experiment is presented in Figure 4 whereas Figure 5 shows a typical experimental arrangement of 2D radial flow setup.

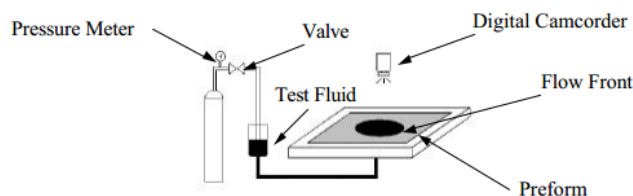


Figure 4: Schematic diagram of 2D radial flow experiment [15]

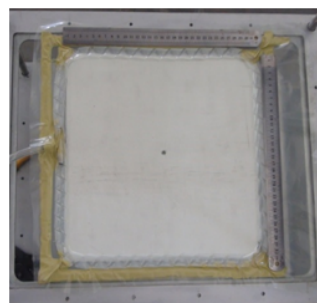


Figure 5: Experimental arrangement for 2D Radial Flow experiment

6 Results and Discussions

The advancement of flow under the conditions described in Section 5 could be circular or elliptical. Figure 6 represents that the resin front advanced with an elliptic shape with its major axis in x-direction. This clearly suggests an anisotropic permeability tensor dictating the flow in

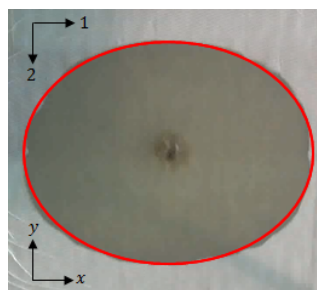


Figure 6: Resin front during 2D injection for 200 gsm woven fabric

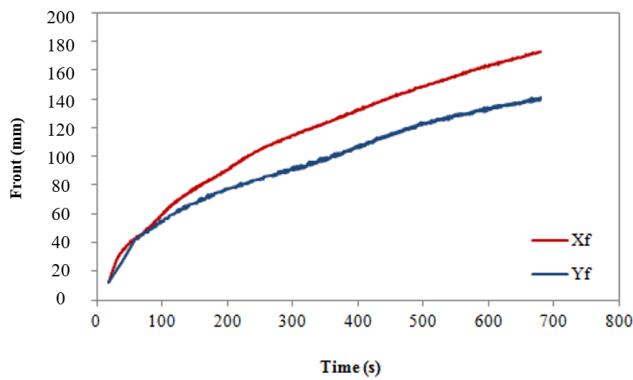


Figure 7: Flow front versus time for 200 gsm woven fabric

x-direction. The experimental data is rearranged in order to express the development of resin front against the elapsed time as shown in Figure 7. Initially, the anisotropic effect is not so clear with an overlap in the x_f and y_f until ~70 seconds from the start of experiment. Afterwards, the preform started to behave typically anisotropic until the end of experiment which lasts for 680 seconds.

The anisotropic behavior of preform suggests the scaling of inlet dimensions *i.e.* x_o and y_o as discussed in Section 3. Equations (10), (11) and (12) are used to scale the inlet dimensions, and the results for this scaling and the ratio between the actual flow fronts *i.e.* x_f and y_f for the experiment are listed in Table 3.

Table 3: Results of scaling the inlet dimensions

r_o (mm)	$\frac{x_f}{y_f}$	α_1	x_o (mm)	y_o (mm)
4	1.199741	1.439378	4.381	3.652

These values of x_o and y_o are used to calculate N_I & N_{II} using Equations (8) and (9) respectively. N_I & N_{II} are then plotted against the elapsed time and using best linear fit, slopes are obtained as shown in Figure 8. The linear line fit is found to be excellent in both directions, shown by the fit parameter R^2 being very close to 1. The slopes of these line fits F_I and F_{II} are then used to calculate the final permeabilities of the preforms. The values of F_I and F_{II} along with the process term 'C' and final permeabilities are listed in Table 4.

Table 4: 2D permeability results for 200 gsm woven fabric

F_I (mm ² /s)	F_{II} (mm ² /s)	C (s)	K_I (mm ²)	K_{II} (mm ²)
389	255	2.964×10^{-7}	1.15×10^{-4}	7.56×10^{-5}

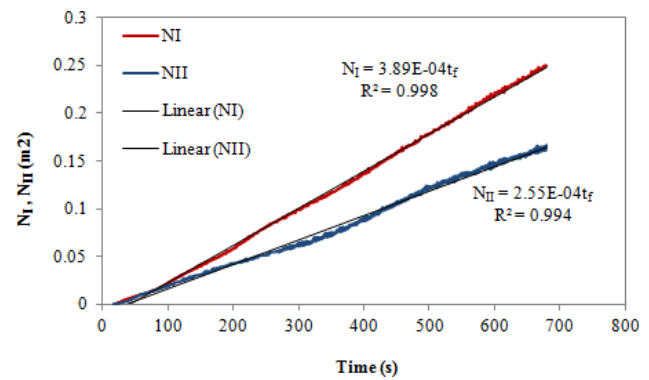


Figure 8: N_I and N_{II} versus the elapsed time

The different value of permeability in I and II directions confirms anisotropy in the preform material. Source of this anisotropy is the different interspacing in warp and weft directions as observed in microscopic examination. Interspacing among threads provides porous space and these spaces or voids connect together so that resin can pass more easily compared to where less porous space is available. Since weft direction provides more interspacing among the individual fiber threads as compared to the warp direction, therefore, the preform was found to be more permeable in this direction.

The results obtained can have profound impacts on any infusion process in terms of fabric lay-up and mold filling time. Anisotropic nature of the preform under consideration suggests that the fabric lay-up must be done by considering the aspect ratio *i.e.* length and width of the structure being prepared by infusion. The high permeable directions dictating the resin flow should be placed in the longer dimension of the structure so that the mold filling time can be reduced. Similarly, the less permeable directions avoid wastage of resin through vacuum lining applied on the whole periphery of the structure.

7 Conclusions

Resin flow experiment is performed to determine in-plane permeability of biaxial woven fabric. The experiment results in anisotropic nature of the preform owing to the fact that permeability is dependent on the interspacing among the fiber threads. The preform is found more permeable in the weft direction *i.e.* in a direction which offers more interspacing between adjacent fibers threads causing more resin to flow in this direction at the same point of time. For the preform under consideration, the permeability in weft direction was found to be 1.5 times more than in warp di-

rection and thus dictates the flow in that direction. This method of permeability measurement can be used to evaluate permeability of almost any preform material with any lay-up arrangement to be used as an input in VARTM simulations.

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