THE EFFECTS OF FIBER ARCHITECTURE AND THICKNESS ON THE PERMEABILITY OF CARBON FIBER PREFORMS

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Keywords: *permeability, preform, VARTM, composite, carbon fiber*

Abstract

The effects of fiber architecture and thickness on the permeability of continuous carbon fiber performs was investigated. The two materials studied were a multi-axial warp-knit fabric (MAWK) and a 5-harness satin biaxial woven fabric. The MAWK fabrics with thicknesses of 1, 2, 4, 8 and 16 stacks were tested at fiber volume fractions ranging from 45% to 59%. The biaxial preform specimens containing ten and twenty layers of fabric were tested at fiber volume fractions ranging from 35% to 55%. Both the in-plane (S_{xx} and S_{yy}) and transverse permeabilities (S_{zz}) in the principal material directions were measured using well established techniques under steady state flow conditions. Results of the tests showed that there was no systematic variation in either the in-plane or through-the-thickness permeabilities for the MAWK material as the stack thickness was increased and for the biaxial material as the layer thickness was increased.

1 Introduction

The vacuum assisted resin transfer molding process (VARTM) is a cost effective technique for the manufacture of complex shape composite structures. A critical step in the fabrication process is the injection of resin into the dry textile preform. The resin must completely infuse and wet-out the preform before gellation occurs at any point. Hence, accurate knowledge of the resin infiltration time is critical for the successful fabrication of the composite part. Flow simulations models of the VARTM process are readily available, but require a detailed knowledge of the flow characteristics of the fiber preforms [1-5]. One of the critical material input properties required for accurate flow prediction is the preform permeability. Permeability is a measure of the preform materials resistance to flow and relates the velocity of the infiltrating fluid to the pressure gradient within the preform. To determine the effects of fiber architecture and thickness, the permeabilities of multi-axial, warp-knit (MAWK) and biaxial woven carbon fiber fabrics were measured. The experiments were conducted over a wide range of compaction levels typically found in the VARTM process. The results of the experiments were fit to empirical equations and will be used as material input parameters in a flow simulation finite element model of the VARTM process.

2 Permeability Measurements

2.1 Background

Fibrous preforms are deformable and anisotropic porous materials. Flow of resin into the preform can be modeled using Darcy's law for flow in porous media [1-5]. Permeability is defined as the resistance to flow through porous media and is often related to the porosity using an empirical model. The three-dimensional form of Darcy's Law for an anisotropic material is written in Cartesian coordinates as:

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \frac{1}{\eta}\begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{bmatrix}\begin{bmatrix} \partial P/\partial x \\ \partial P/\partial y \\ \partial P/\partial z \end{bmatrix} \quad (1)$$

where S_{ij} are the components of the permeability tensor, q_i are the components of the superficial velocity vector, η is the viscosity of the fluid and P is the pressure. For preform architectures that are orthotropic, the components S_{xy}, S_{xz} and S_{yz} are zero and only the permeabilities in the principal material directions, S_{xx}, S_{yy} and S_{zz}, need to be measured.

Several models have been developed in the past to estimate the permeability of fiber preforms. The Kozeny-Carmen capillary model was developed and successfully predicted permeability in granular beds consisting of ellipsoids [6]. However, this method is deficient in prediction of permeability in continuous fibrous preforms. Gebart and others [7, 8] developed models to approach this problem based on a geometry of ordered arrays of cylinders. These models were found to more accurately predict the axial and transverse permeabilities of fibrous preforms. Gokce and Advani further developed these models to include the influence of intra-tow flow on preform permeability determination [9]. The technique uses a micromechanical approach incorporating the Method of Cells in which a unit cell of the preform contains sub-cells with the characteristics of one fiber tow bundle. The characteristics include the geometry of the fiber tow, the porosity or air gaps surrounding the tow and the pressure distribution along the tow. The properties of the fiber tow must be determined experimentally. The sub-cells are organized in the unit cell according to the particular fabric geometry and the unit cells are then structured according to the desired composite part geometry. Use of this method in conjunction with Darcy's law and the continuity equation allows for a more general approach to the prediction of the permeability tensor for a variety of fiber architectures and final part geometries.

While predictive models for the determination of preform permeability are both cost effective and extremely important to develop a physical understanding of flow through porous materials, experimental methods are still commonly used. Experimental techniques for measuring the permeabilities of fibrous materials, especially for RTM applications, are well developed in the literature [10-12]. Trevino, et al. [10] measured the in-plane and transverse (through-thickness) permeabilities by placing the fiber mats into rigid steel molds. Fluid was pumped into the closed molds at a constant flow rate and the pressure differential was measured between the fluid entry and exit on either side of the compacted preform. The pressure was recorded after the fabric was fully saturated and the measured fluid pressure had reached steady state conditions. The permeability was then calculated based on Darcy's law and the steady-state pressure difference. The mold was designed with a fixed cavity volume. In order to vary preform porosity, additional layers of fabric were simply added to the mold. The in-plane and transverse permeabilities of both randomly oriented and continuous bi-directional fabrics were characterized as a function of porosity. Trevino determined that for the fabrics studied, the transverse permeability was always lower than the in-plane values and that part infusion times would be greatly affected by the fiber anisotropy.

Hammami [12] determined that flow in VARTM differs from the traditional RTM process. The flexible vacuum bag and varying pressure inside the mold cavity result in a variation of the preform thickness and, hence, the fiber volume fraction of the preform during infusion. The variation of compaction pressure during infiltration necessitates measurement of the preform permeability at varying fiber volumes. Hammami also stressed the importance of determining the permeability of the distribution media, or "flow enhancement layer."

Work by Sommerscales [13] and others [14] found that because the wetting characteristics, namely surface tension and contact angle, of various infiltrating fluids differ, their use can influence the measured permeabilities of the preform. Steenkamer, et. al. [14] determined the effect of fluid type on permeability. The fluids investigated included diluted corn syrup (viscosity = 0.19 Pa·s), SAE 10W-30 motor oil (viscosity = 0.16 Pa·s), and a vinyl ester resin (viscosity = 0.14 Pa·s). The corn syrup exhibited the highest contact angle on the woven glass mat at 45^o, followed by the resin at 38^o. The contact angle of the oil could not be measured because it spread too quickly. The work of spreading was measured for each fluid and found to be -189.0 μN/cm for corn syrup, 16.0 μN/cm for oil and -74 μN/cm for resin. The negative value of work of spreading means that pressure had to be applied to achieve fiber wetting. The results of permeability characterization with these three materials showed that the fabric tested with the motor oil had the highest in-plane permeability of 1.74×10^{-9} m^2, followed by the resin with an intermediate in-plane permeability of 1.23×10^{-9} m^2 and the syrup with the lowest in-plane permeability of 0.70 $\times 10^{-9}$ m^2. This indicates that the surface tension of the fluid rather than the viscosity has the largest influence on permeability. The author concluded that the permeability measurements should, ideally, be conducted using the resin that will ultimately be used to infuse the composite part. Luo, et al. [15] and Hammond and Loos [16] found that the effect of different fluids was within the scatter of the measured permeabilities.

2.2 Experimental

In the present investigation, experiments were conducted to measure the in-plane (S_{xx} and S_{yy}) and the transverse (S_{zz}) permeabilities of the carbon fabric preforms at fiber volumes ranging from 35% up to 60%. The permeability measurement system is composed of a permeability fixture, constant flow rate pump, and a data acquisition system. A real time data acquisition and data reduction system is comprised of a DAQ board, signal conditioning and multiplexing hardware, and LabVIEW data acquisition software. The tests were performed at or below the VARTM injection pressure of 101.5 kPa and each fabric specimen was tested over a range of fiber volumes. The data were fit to empirical models which relates permeability to fiber volume fraction.

2.2.1 Materials

The carbon fiber materials used in this investigation were a biaxial woven fabric and a multi-axial warp-knit (MAWK) fabric. The 5-harness satin biaxial woven fabric is composed of Hexcel 6k IM-7 fiber tows. The balanced fabric, shown in Figure 1, has 16 tows in both the warp and fill directions and a fiber areal weight of 280 g/m^2.

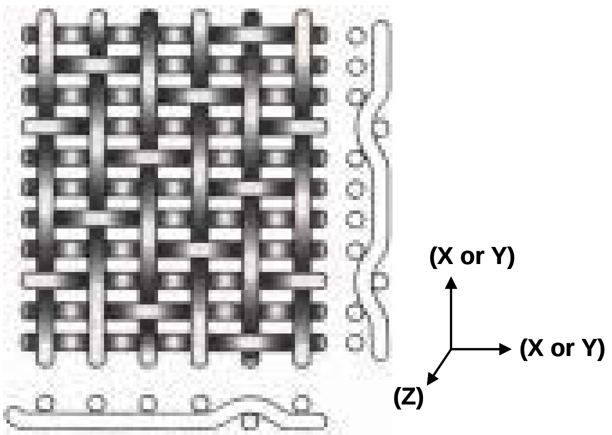

Fig 1. Five-harness satin biaxial woven fabric

The SAERTEX® MAWK material is shown in Figure 2. It is composed of seven plies of both AS-4 and IM-7 carbon fibers with a single-stack, total areal weight of 1423 g/m^2. The plies are stacked, not woven, and then knitted with an alternating polyester tricot/chain knit thread in the stacking sequence described in Table 1. In this work, the 0° fiber tows are designated as the fabric x-direction. A fiber density of 1.78 g/cc was used for both the biaxial and MAWK fabrics.

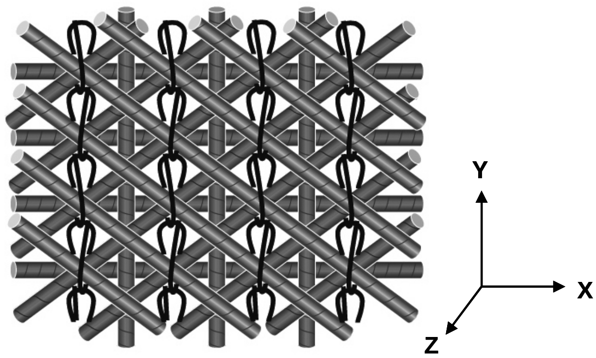

Fig. 2. Graphical depiction of a multi-axial warp knit (MAWK) fabric

The wetting fluid used in the experiments was SAE 40 motor oil. The fluid was selected for its stable properties during test conditions. Prior to the permeability tests, the temperature of the SAE 40 oil was recorded and the viscosity was measured using a Brookfield® model DV-III viscometer. The viscometer was calibrated using standards supplied by Brookfield®.

Table 1. Ply stacking sequence in SAERTEX MAWK fabric.

Ply Number	**Yarn Material**	**Yarn Orientation**	**Areal Weight g/m^2**
1	3K-AS4	+45°	156
2	3K-AS4	-45°	156
3	12K-IM7	0°	314
4	6K-AS4	90°	171
5	12K-IM7	0°	314
6	3K-AS4	-45°	156
7	3K-AS4	+45°	156

2.2.2 Permeability Test Fixtures

The test fixtures were designed to direct a one-dimensional flow of fluid through the preform to measure the in-plane (S_{xx} and S_{yy}) and the transverse (S_{zz}) permeabilities. A schematic diagram of the in-plane permeability test fixture is shown in Figure 3. The fixture, fabricated from tool steel, was instrumented with diaphragm pressure sensors to measure fluid pressure in the test cavity and thickness sensors to measure the preform thickness changes. The fixture was mounted in a compression test frame. The fixture was designed to characterize preform specimens 15 cm in length by 15.3 cm in width, at thicknesses up to 2.5 cm. Two linear voltage differential transducers (LVDT) were mounted on opposite ends of the fixture to ensure uniform thickness across the 15.0 cm length of the specimen. Four pressure sensors were installed in the fixture. The sensor located at the inlet side was used to measure the inlet fluid pressure, required for determining the permeability under steady-state conditions. The remaining three pressure sensors mounted in the cavity were used in the measurement of the advancing-front permeability.

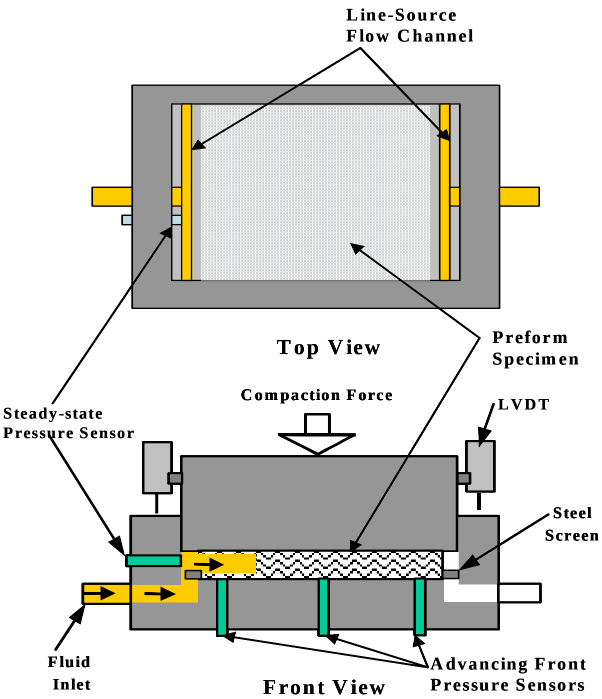

Fig. 3 In-plane permeability test fixture

In testing the MAWK fabric, the specimen was placed so that the 0° rovings (as described in Table 1) were length-wise, or parallel to the direction of resin flow for determination of S_{xx}. For S_{yy}, the specimen was placed so that the 0° rovings were perpendicular to the direction of flow. Due to the architecture of the biaxial fabric, the S_{xx} and S_{yy} permeabilities were assumed to be equal. Therefore, tests were conducted to determine only the S_{xx} and S_{zz} permeability of this fabric.

The transverse, or through-thickness, S_{zz}, fixture (Figure 4) was designed with a test cavity to accommodate 5.08 cm x 5.08 cm preform specimens up to 3.20 cm thick. The concept is identical to that of the in-plane fixture except that the fluid is directed through the thickness of the specimen by rigid distribution plates mounted in the plunger and in the bottom of the cavity. The plates were machined with 0.50 cm holes drilled every 0.64 cm.

A single linear voltage differential transducer (LVDT) was used to measure the thickness of the preform specimen. A pressure transducer was located at the inlet and used to measure the inlet fluid pressure.

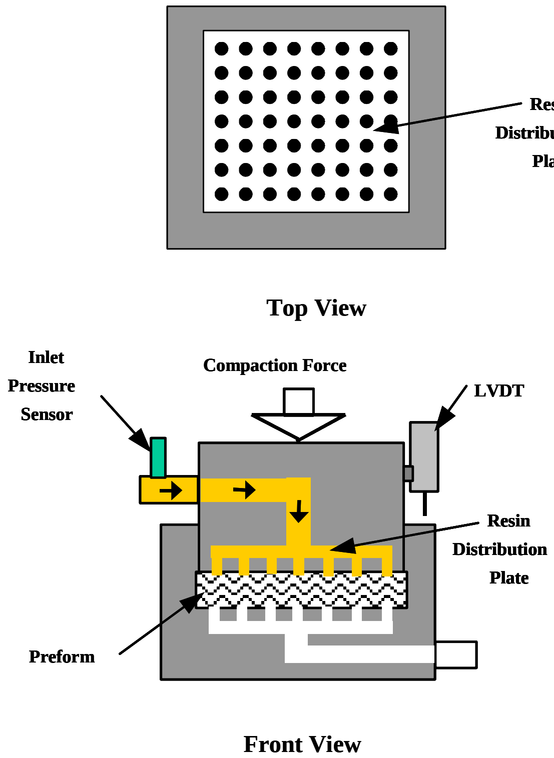

Fig 4. Transverse permeability fixture

2.2.3 Test Procedures

Each fabric specimen was tested over a range of fiber volumes. For the MAWK fabric, the specimens were initially compacted to approximately 45% fiber volume fraction, measured by the LVDTs mounted on the fixture. The oil was supplied to the fixtures by a Parker Zenith® Precision Gear Metering Pump. The constant flow rate was set at the pump control unit and measured using a Mettler-Toledo® model (SB1600) balance. Once steady-state flow conditions were reached the inlet pressure was measured. At each fiber volume fraction, the inlet pressure at four different flow rates was measures and the data used to construct a curve of volumetric flow rate versus pressure drop. Measuring the slope of the curve gave the average permeability for the preform at the specified fiber volume fraction. Permeability measurements were made at fiber volume fractions ranging from 45% to 60%, in 2% increments. The test procedures for the biaxial fabric specimens were identical except that the permeabilities were measured at fiber volumes between 35% and 55%.

2.2.4 Data Reduction

During the experiments the fluid inlet pressure, fluid flow rate and preform thickness were measured. The fiber volume fraction, V_f is calculated by the expression

$$V_f = \frac{FAW}{t\rho_F} \tag{2}$$

where, *FAW* is the fiber areal weight of the preform specimen, ρ_F is the density of the carbon fiber and *t* is the measured preform thickness. The superficial or filter velocity, *q*, is calculated as

$$q = \frac{M}{\rho_R A} \tag{3}$$

where, ρ_R is the density of the fluid, *M* is the mass flow rate and *A* is the cross-sectional area of the preform normal to the flow direction. The permeability constant, *S*, is then calculated at each compaction or thickness level from the one-dimensional form of Darcy's Law

$$S = \frac{q\eta L}{\Delta P} \tag{4}$$

where, η is the viscosity of the fluid, ΔP is the measured pressure difference and *L* is the length of the preform specimen in the direction of flow.

Shown in Figure 5 is a typical result of the permeability tests. Results shown in the figure represent the in-plane permeability, S_{xx} for one stack of the MAWK material. The symbols represent the measured permeability of each specimen at the set fiber volume fraction. The data for each specimen were fit to a power law equation as follows

$$S = a(V_f)^b \tag{5}$$

where, a and b are constants. The solid line in the figure represents the best fit power law model to the permeability data from all the specimens tested. The error bars represent the maximum error between the power law fits to the individual specimens and the best fit to all the data. The best fit power law model for each thickness will be used for comparisons in the next section.

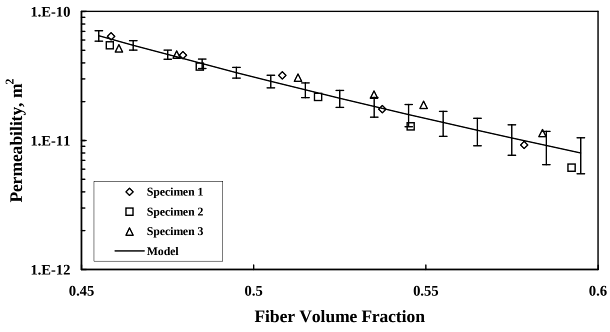

Fig. 5 In-plane permeability, S_{xx}, as a function of fiber volume fraction of a one-stack MAWK preform

3 Results

3.1 MAWK Materials

Specimens containing between one and sixteen stacks of the MAWK material were tested to determine the effects of preform thickness on permeability. The results for the permeabilities in the three principal material directions are shown in Figures 6 – 8.

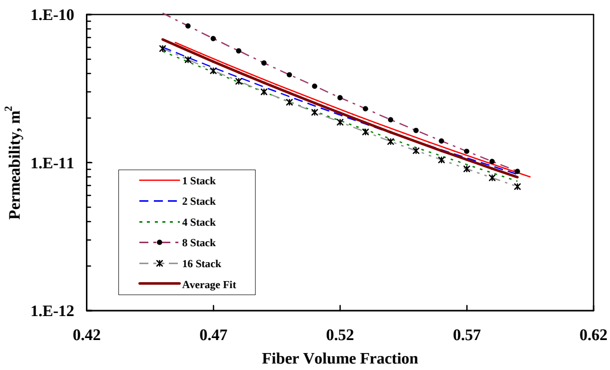

Fig. 6. In-plane, x-direction permeability, S_{xx}, as a function of fiber volume fraction for 1, 2, 4, 8 and 16 stacks of MAWK fabric

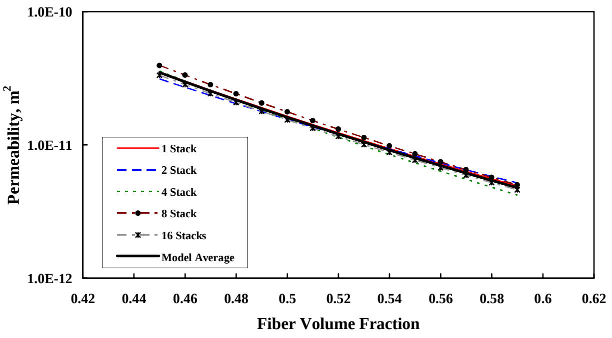

Fig. 7. In-plane, y-direction permeability, S_{yy}, as a function of fiber volume fraction for 1, 2, 4, 8 and 16 stacks of MAWK fabric

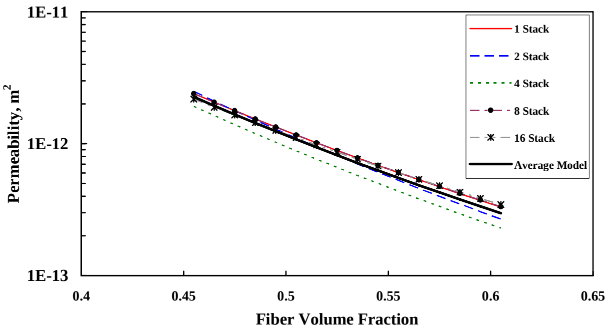

Fig. 8. Transverse, z-direction permeability, S_{zz}, as a function of fiber volume fraction for 1, 2, 4, 8 and 16 stacks of MAWK fabric

From the figures, it can be observed that the permeabilities in the three principal material directions decrease with increasing stack thickness for the 1, 2 and 4 stack materials. However, the permeabilities of the 8 and 16 stack thickness materials either remained about the same as the 4 stack materials or actually increase. Hence, there appears to be no systematic affect of stack thickness on permeability in all three principal material directions. Note, that the curve denoted "average fit" represents the average power law model fit to all stack thickness data in each figure.

By comparing the in-plane and transverse permeabilities for the MAWK materials in Figures 6 - 8, the following observations can be made. As expected the S_{yy} values are slightly lower than S_{xx} due to the greater number of 0^{o} fiber tows in the x-direction of the fabric architecture. The S_{zz} values were found to be about an order of magnitude lower than the in-plane values. A lower transverse permeability is generally the case with all continuous fiber preforms.

3.2 Biaxial Fabric

The in-plane permeabilities of the 10- and 20-layer biaxial fabric are shown in Figure 9. Again, there does not appear to be any change in permeability with an increase in number of layers. However, the scatter found in the data for the 20-layer specimen set is about twice that found for the 10-layer specimens. A possible reason for the larger data scatter in the 20 layer specimens may be due to the poor handling characteristics of the fabric. Since the biaxial fabric is woven, even careful handling of the material can result in disruption of the tow alignment. Further, tows can be lost from the edges of the fabric during cutting and when loading the specimen into the fixture cavity. This would certainly have some influence on the repeatability of permeability measurements. Increasing the number of layers would most likely increase the magnitude of the error as observed in the permeability tests.

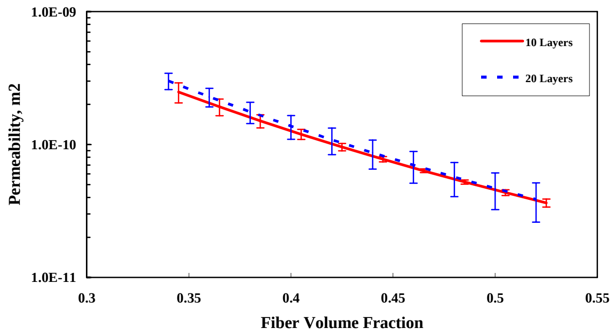

Fig. 9. In-plane permeability (S_{xx}, S_{yy}) as a function of fiber volume fraction for 10 and 20 layers of biaxial fabric

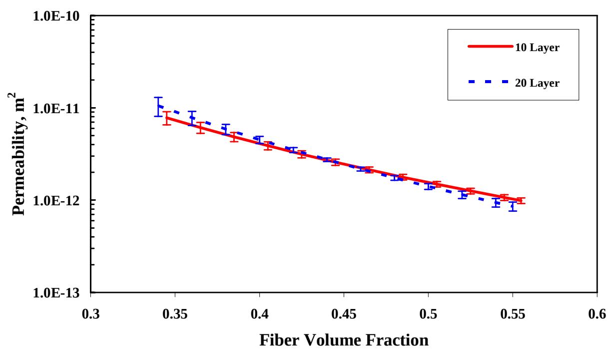

Fig. 10. Transverse permeability (S_{zz}) as a function of fiber volume fraction for 10 and 20 layers of biaxial fabric

The transverse permeability of the 10- and 20-layer biaxial fabric is shown in Figure 10. Again, there does not appear to be any systematic change in the permeability with an increase in number of layers. In addition, the scatter in the transverse measurements is much less than observed for the in-plane values. Obviously, variations in the quality of the edges of the fabric do not impact the transverse permeability as much as the in-plane values.

The in-plane and transverse permeabilities for the biaxial fabric can be compared by observing the results in Figures 9 and 10. Over the range of fiber volumes tested, the transverse permeability of the fabric was found to be more than an order of magnitude lower than the values measured for the in-plane permeability.

4 Conclusions

The flow behavior of MAWK and biaxial preforms was characterized using well established techniques to determine the Darcy permeability. Both the in-plane and transverse permeabilities were determined for various specimen thicknesses under steady state flow conditions. The permeability was calculated from pressure versus superficial velocity data for fiber volume fractions ranging from 35% to 55% for the biaxial specimens and 45% to 59% for the MAWK preforms. The pressure measured at the inlet point of the permeability fixtures never exceeded 101 kPa. In all of the tests performed, the calculated Darcy permeability decreased as the preform was compacted to higher fiber volume levels.

For the MAWK preform the average value for the in-plane, S_{xx}, permeability was found to range from 6.8 x 10^{-11} m^2 to 8.0 x 10^{-12} m^2 for fiber volume fractions ranging from 45% to 59%. The in-plane, S_{yy}, average values were found to range from 3.5 x 10^{-11} m^2 to 4.8 x 10^{-12} m^2 over the same fiber volume fraction range. The higher permeability in the *x*-direction may be due to the increased number of fiber tows that are parallel to the flow direction. The transverse permeability, S_{zz}, was found to vary from 2.3 x 10^{-12} m^2 to 3.0 x 10^{-13} m^2 for the stated fiber volume fraction range. The S_{zz} values are about an order of magnitude lower than the in-plane values because the fluid flow is perpendicular to the fiber tows which create a greater resistance. The thickness of the MAWK fabric ranged from one stack up to a maximum of sixteen stacks. However, no systematic variation in the permeability with thickness change was observed. It is possible that the test procedure was not sensitive enough to determine an interstack influence on permeability.

Tests were performed on the biaxial preform specimens containing ten and twenty layers of fabric. The permeability was determined for both in-plane and transverse flow and no thickness influence was found. The average in-plane permeability values ranged from 3.0 x 10^{-10} m^2 to 3.5 x 10^{-11} m^2 for fiber volume fractions ranging from 35% to 55%. The transverse permeability values (S_{zz}) were found to range between 9.3 x 10^{-12} m^2 and 9.4 x 10^{-13} m^2. The permeability values were higher than the results found for the MAWK due to the higher porosity of the biaxial preform.

5 Acknowledgements

This work was supported by NASA Langley Research Center. The project monitor was Mr. Roberto J. Cano.

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