DETERMINATION OF PERMEABILITY OF POLYMER MATRIX COMPOSITES PRODUCED BY VARTM

Abhinav Tripathi[1], Mukul Shukla[2,3]
[1]Post Graduate Scholar , [2]Associate Professor
[1,2]Department of Mechanical Engineering, MNNIT, Allahabad, India
Email:proabhi9@gmail.com[1], mukulshukla@mnnit.ac.in[2]
[3]Department of Mechanical Engineering Technology
University of Johannesburg, Johannesburg, South Africa
Email:mshukla@uj.ac.za[3]

Abstract—Vacuum assisted resin transfer molding (VARTM) is cost effective large scale composite manufacturing process. To reduce the risk of failure simulation of resin infusion before manufacturing is necessary. Most variants of VARTM have been aimed at reducing the fill time of resin infusion through the preform during the process. During the infusion the several compaction dependent parameters like permeability, thickness etc. are required to be accounted and controlled for good quality part. This study focused on deriving the fiber permeability and its analytical solution.

I. Introduction

When composites are made in the most economical way, they are inferior to those that take much time and money to construct. Developing a method that is fast and reliable is a critical issue. A controlled infusion setup must be designed to get optimized infusion. The setup and process through which infusion is accomplished is called VARTM. In this process a vacuum pulls resin in the form of a feed tube to distribute it evenly into the preform. A flexible plastic bag material is placed over the top to form a vacuum tight seal. The compaction of the preform is due to the differential pressure outside and inside the plastic bag cause the changes in the preform permeability and the thickness of the preform as the infusion progresses. Therefore unlike the RTM, the permeability and the thickness of the preform are compaction dependent parameter in VARTM. Vacuum assisted resin transfer molding (VARTM) has the potential advantages of relatively low cost processing with sufficiently high volume fractions of reinforcement and can be readily applied to large scale structures. However, for many aircraft applications, VARTM does not currently provide sufficient repeatability or control of variability. Such variability is commonly observed when processing with the VARTM process. In order to routinely produce VARTM parts of aircraft quality, the sources of the process variability must be understood and minimized.

The certification requirements for structural airframe components have led to a much higher demand for modelling of the VARTM process. Aerospace certification requirements are much stricter than in less regulated industries, and the preforms which may be used are more complex in shape and frequently more expensive. Control of the infusion and compaction process is therefore more important and careful modelling allows processes with more consistent results to be designed. All these factors have led to an increased interest in modelling of the VARTM process.[1].

II. VARTM process parameters and their effects

The VARTM process is governed by variables and parameters that are dependent on each other. Their combination affects the process and the quality of the finished product.

Consequently, they need to be carefully determined. The most important parameters, which cannot be neglected in the design, are pressure, temperature, viscosity, permeability, volume fraction, and filling time of the process [1, 2]. There are also a multitude of parameters that must be considered independently, such as the angle of attack of the nozzle, the orientation of the fibers, the paths of flow and shear rates, the stratification.

In fact, the resin tends to flow more quickly in the fiber direction, thus the flow dynamic depends mainly on the type of fabric used and the number of overlapped layers.[3] Sometimes it may be necessary to have a certain number of skins, not for structural reasons, but to obtain a homogeneous distribution of the resin. The thickness of the part to be manufactured can also affect the flow progress and the impregnation of the fibers, causing a high percentage of voids and dry spots [2, 4]. The thickness becomes a critical design constraint especially in the case of the inclusion of reinforcements and ribs.

Devalve et al. 2012 in their study mentioned that the permeability values were calculated using the relationships with the fiber bundle volume fraction shown graphically in Fig. 1, which presents the permeability non-dimensionalized by the square of the individual fiber filament radius. The longitudinal permeability values in Fig. 2.1 are based on an analytical permeability model presented in (DeValve et al. 2012) and the transverse permeability values are adapted from (Bruschke et al.1993).

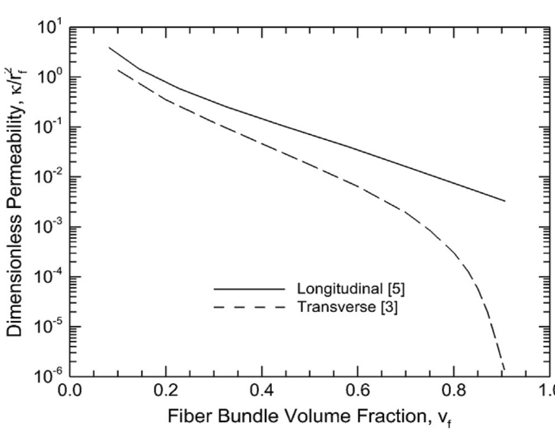

Figure 1 Macro level permeability vs. fiber volume fraction [5]

Humbert D. R. in his work Modeling of Resin Transfer molding of Composite Materials, shows the dependence of fiber permeability on injection pressure and time (Fig. 2 & 3).

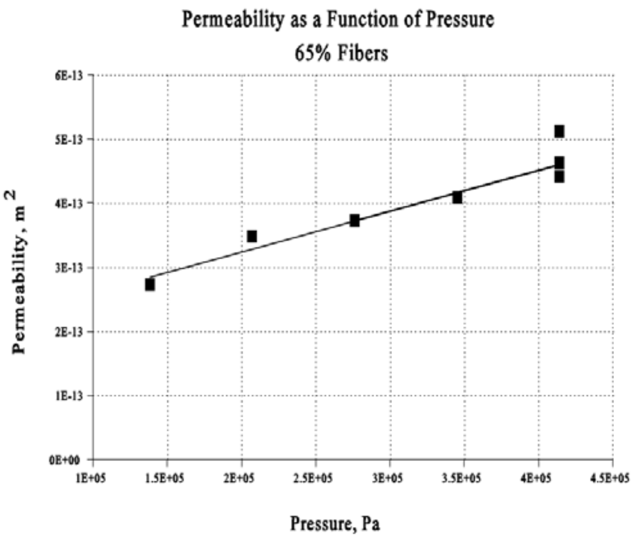

Figure 2 Permeability vs. Injection pressure

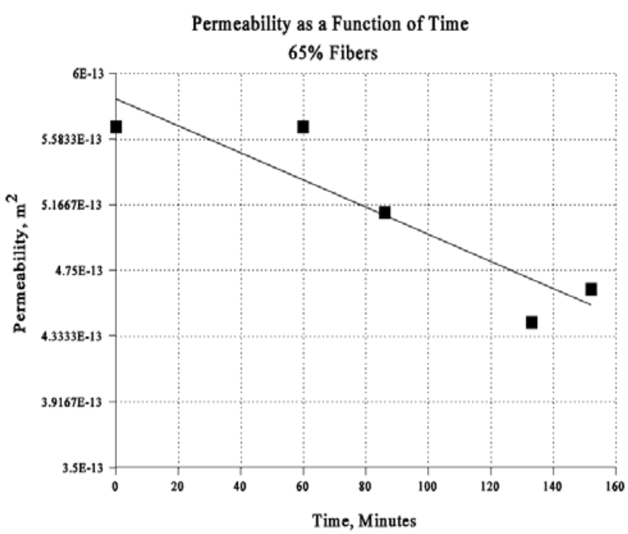

Figure 2 Permeability variation vs. infusion time

III. Experimental and flow measurements for fiber permeability

The permeability *K* is in general a symmetric tensor, which for an isotropic material, as random mat, is a scalar number. For a given stationary porous medium, it is necessary to know 6 scalar values *Kij* to completely determine the tensor K. If the selected directions of the reference system are along the principal directions of the preform, the matrix becomes diagonal. Therefore, choosing the coordinate system along the main axes of the preform, the principal values of the permeability can be measured. Then, not diagonal terms can be calculated using a coordinate transformation system.

$$K = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix} \qquad (1)$$

Permeability must be determined experimentally. There are basically two methods for this: radial flow and linear flow methods. The simplest way to determine the permeability is the use of 1D version of Darcy's equation (linear method). For a 1D flow in the direction of the axis (assumed to be the x-axis) Darcy’s equation can be written as

$$\frac{dx}{dt} = -\frac{K_x}{\Phi \mu} \frac{\partial P}{\partial x} \qquad (2)$$

Where $\Phi=1-V_f$ is the porosity of the material and Vfis the fiber volume fraction, Kx the permeability in the x direction, μ is the fluid viscosity and $\partial P / \partial x$ is the pressure gradient between the injection point and the flow front. Since the injection pressure and the vent pressure are constant, we can transform the partial derivative in a finite difference, so we have

$$K_x = \frac{\mu \Phi \, slope of [x_f^2(\mathrm{t}_f)]}{2 \Delta P} \qquad (3)$$

IV. Software package used for Analysis

LIMS (Liquid Injection Molding Software)

Liquid Injection Molding Simulation (LIMS) is a software tool that simulates the mold filling stage of Liquid Composite Molding (LCM) processes by modeling flow through porous media by Finite Element / Control Volume Method. It provides a simple and cost-effective way to verify and optimize filling process design by providing a “virtual” mold filling process. This allows one to avoid or reduce the actual physical trial and error process which tends to be resource-intensive. LIMS has been successfully used to design and simulate intelligent or adaptive filling process that utilizes sensors mounted on the part and controllable injection hardware, either as a stand-alone program or as a simulation engine for other programs. Because of the scripting capability, various LCM process variants were successfully modelled. LIMS capabilities are used in our research to calculate the time of mould filling during VARTM.

V. Permeability determination using LIMS and analytical solution

As from the analysis of two phase void and resin flow during VARTM we found that resin flow profile is greatly influenced by fiber permeability. Void velocity would be higher for the fibers which are less permeable. So it is important to develop a method to determine the permeability using computation and analytical solution. The analytical solution as described earlier is used here. Plots of LIMS are imported in TECPLOT to determine the radial flow location and time related data for plotting the G (ρ□□□vs. time graph.

Data show clearly that porosity and permeability are depend on each other. Porosity of any composite sheet can be calculated by physical data like no. of layer, weight of composite, fiber density and preform thickness. We have adopted following steps while analysing this problem (Fig. 4).

- Preform dimensions 24 X 14 X 0.3 cm, prepared using ABAQUS.
- Brick elements are used for meshing.
- Nodal information is saved in “.inp” format.
- Injection nozzle is employed at central location, using set gate option of LIMS.
- Injection pressure is p=86.4 kPa.
- Resin viscosity η=0.2
- Fiber Volume fraction in material property section is defined as ε=0.74.
- Four vents are provided as outlet with p=0 kPa.
- After the simulation run results saved in “.tec” format so as to import the information in TECPLOT.
- Total fill time required to fill each empty node is 408 seconds.

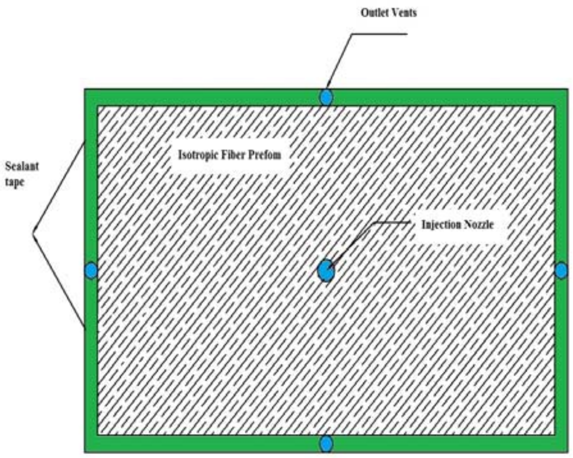

Figure 4 Schematic of simulation setup

All the results are presented in Figures 5-7 and in Tables 1-2.

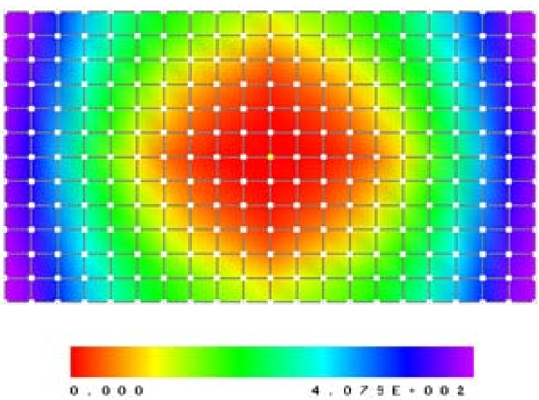

Figure 5 Fill time (s) plot in LIMS during VARTM process

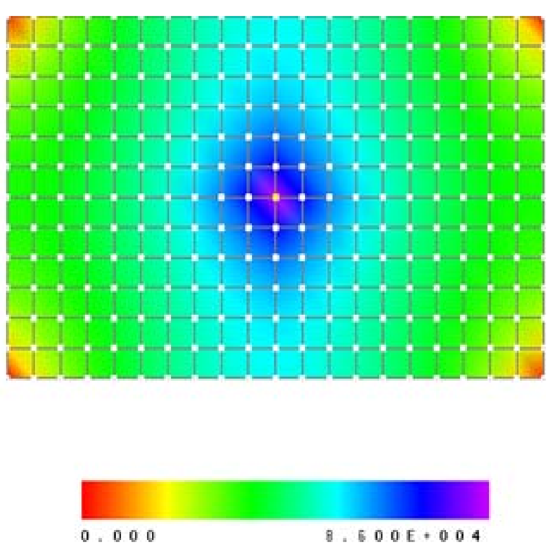

Figure 6 Pressure Variation plot in LIMS during VARTM process

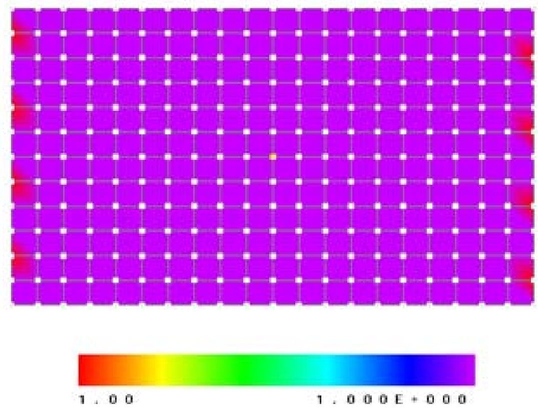

Figure 7 Fill factor plot in LIMS during VARTM process

Table 1 Data extracted from Tecplot of location of resin with time in radial direction

Nozzle location	Probe data	Rf	G(pf)	Time (sec)
0.07	0.076667333	0.00666733	0.512316478	1.948246088
0.07	0.089892353	0.01989235	20.24340344	8.869196386
0.07	0.105546459	0.03554646	94.0361668	33.3797784
0.07	0.116072496	0.0460725	180.2803476	67.93623061

Rf is calculated by defining the central nozzle location, and measuring the distance between probe and nozzle location. Now the graph is plotted between G (pf) and time and slope is used to determine the permeability (Fig. 8).

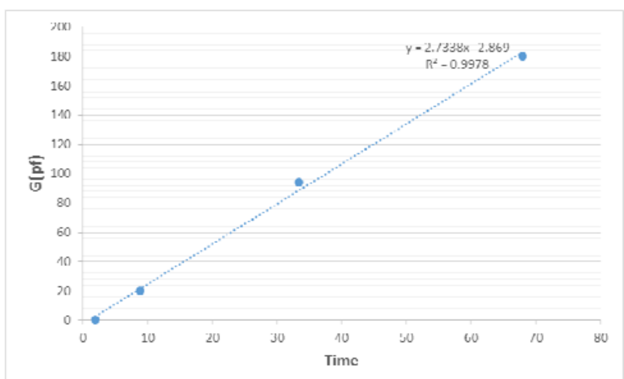

Figure 8 G (ρf) vs. Time plot for slope determination

$$K=\frac{m\varepsilon\mu R_o^2}{\Delta P} = \frac{2.7338\times0.74\times0.2\times0.0035\times0.0035}{86400} =$$

2.09139 E-11 m^2

Table 1 Calculation of error between computed and actual fiber permeability

Computational data Permeability	Actual Permeability	% error
2.09139E-11	2.00E-11	4.57

As provided error is within the permissible limit so we can say that computed permeability is correct. Error is due to the limitations of the software.

VI. Conclusions

The permeability, K, reflecting the flowing ability of fiber laminates affects the velocity profile of permeability of a porous media. Less permeable fiber preform results in reduction of the resin velocity fronts so it is clear that such preform needs much time for filling. Fiber permeability is determined using the computation and analytical solution. It is also clear that porosity and permeability are depend on each other. Porosity of any composite sheet can be calculated by physical data like no. of layer, weight of composite, fiber density and preform thickness.

References

[1] J. M. Bayldon , I. M. Daniel, “Flow modeling of the VARTM process including progressive saturation effects,” *Compos. Part A Appl. Sci. Manuf.*, vol. 40, no. 8, pp. 1044–1052, Aug. 2009.

[2] P. Simacek , S. G. Advani, “Modeling resin flow and fiber tow saturation induced by distribution media collapse in VARTM,” *Compos. Sci. Technol.* , vol. 67, no. 13, pp. 2757–2769, Oct. 2007.

[3] J. J. Gangloff, C. Daniel, and S. G. Advani, “A model of two-phase resin and void flow during composites processing,” *Int. J. Multiph. Flow*, vol. 65, pp. 51 – 60, Oct. 2014.

[4] R. Matsuzaki, S. Kobayashi, A. Todoroki, and Y. Mizutani, “Control of resin flow/temperature using multifunctional interdigital electrode array film during a VaRTM process,” *Compos. Part A Appl. Sci. Manuf.*, vol. 42, no. 7, pp. 782– 793, Jul. 2011.

[5] B. Chen and T. Chou, “Compaction of woven-fabric preforms in liquid composite molding processes : single-layer deformation,” vol. 59, pp. 1519– 1526, 1999.

[6] S. Yang, M. Liang, B. Yu, and M. Zou, “Permeability model for fractal porous media with rough surfaces,” *Microfluid. Nanofluidics*, no. 1991, Oct. 2014.

[7] V. Antonucci, M. Esposito, M. R. Ricciardi, M. Raffone, M. Zarrelli, and M. Giordano, “Permeability characterization of stitched carbon fiber preforms by fiber optic sensors,” *Express Polym. Lett.*, vol. 5, no. 12, pp. 1075–1084, 2011.

[8] Golestanian H., 2008. Preform permeability variation with porosity of fiber glass and carbon mats. J Mater Sci (2008) 43, 6676–6681