Prediction of the Effects of Fiber Architecture on Permeability Using the Stream-Surface Method

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SUMMARY: Accurate permeability data is critical to successful mold filling simulations for processes such as resin transfer molding (RTM). While permeability measurement techniques are technically mature, full characterization of any particular textile is impractical due to the stochastic nature of the textile. As such, permeability models based on the architecture of the fabric are desirable for process design and analysis. This paper describes the 'Stream-Surface' method to predict permeability based on the fabric structure, modeled using a generic textile model, TexGen, developed at the University of Nottingham. The initial systematic validation of the method, which also looked at effects such as tow shape and fiber volume fraction on permeability, is presented here. The method was also applied to cross sections of a twill weave model. Comparisons between the Stream-Surface results and the more computational intensive CFD calculations are promising, whereby the 'Stream-Surface' method predicts values and trends very similar to the CFD method. The significant potential of the 'Stream-Surface' method is in its calculation speed, at least 300 times faster than the CFD method.

KEYWORDS: permeability, permeability prediction, Stream-Surface, textile model.

I. INTRODUCTION

Mold filling codes for processes such as resin transfer molding (RTM) almost exclusively use Darcy's law to describe flow through the porous textile. Darcy's law gives the average velocity of the fluid as a function of the pressure gradient, fluid viscosity and permeability of the porous medium. As such these simulations are only as good as the supplied permeability data. Permeability is normally measured experimentally and while measurement techniques continue to improve, published data continually reports a large permeability distribution.

Permeability is very sensitive to the architecture of the preform, as seen by variations with fiber volume fraction, fiber reorientation and fiber compaction. Additionally, textile reinforcements have an inherent statistical nature. Such complications make a full experimental characterization of any particular reinforcement a time consuming and expensive task.

Permeability prediction models based on the fabric architecture would be valuable to process design and analysis. Early analytical models for unidirectional textiles [1,2] and later, numerical models for more specific types of textiles [3], offer a good insight into the capability of such models. A general model based on structural model of textiles would be more advantageous, as proposed by Lomov et al [4] and the present authors. The former uses Lattice-

Bolztmann to predict permeability and while it can be accurate, it can also be time-consuming, which can be problematic where a large number of simulations are needed.

The 'Stream-Surface' method [5] is a generalized method for predicting permeability developed by the authors. This method has been constructed to be efficient without sacrificing the details. A generic textile model, TexGen, also developed by the authors [6], is used to create the data files for this method automatically. The work on 'Stream-Surface' is still ongoing. The first part of this paper describes the initial results from a systematic study to validate the method. In the second part, the method is applied to a more realistic textile model.

II. MODELING METHODS

TexGen is a textile modeler which can be used to create virtually any description of a textile. It starts of with vectors defining the textile's interlacing pattern, which are smoothed out and volumes created around them to represent the tows. Additional features applicable to the model include in-plane shearing, statistical variation and interference correction algorithms. A specific flow domain can be specified and exported in a variety of formats for further processing, including the output for the Stream-Surface method. Cross sections can also be extracted automatically for analysis.

The Stream-Surface method reduces the complexity of a flow problem by using a network of interconnected planes bisecting basic volumes representing free and porous channels of flow. Flow is assumed to follow Darcy's law, whereby the free channels with height h have a permeability of $h^2/12$ according to the Hagen-Poiseulle relation for flow between two stationary plaques. Tow permeability can be specified using simple analytical model such as Gebart [1]. By solving the flow for these stream-surfaces with known individual permeability values, an effective permeability can be calculated for the domain. While the Stream-Surface was developed for 3D models and further development is needed before this can be implemented, this paper describes its applications in 2D cross-sections.

III. VARIATIONS OF A SINGLE POROUS TOW

A study, as described in [7], has been undertaken which aims to document the effects of the various factors that affect permeability of a textile and also to provide validation for the Stream-Surface method. The systematic way of achieving this is to begin with a simple 2D single tow geometry, progressing to multiple-tows and multi-layers, before going on to 3D structures. In this section, a 2D cross section of a single porous tow is analyzed.

Calculation methods

Figure 1 shows the 2D single tow flow domain and the steps in generating the 1.5D Stream-Surface mesh. Each of the nodes in the 1.5D mesh has an associated height corresponding to the volume (or area) it represents. This is used to calculate the 'permeability' of the free channels and also ensures that continuity is satisfied. The Stream-Surface flow is solved using a finite difference solver while flow in the 2D mesh was solved using a commercial CFD package, FLUENT™.

The permeability of the cell can then be calculated from the resultant pressure distribution using Darcy's law. Results obtained using the Stream-Surface method are compared to that obtained from the more computationally intensive CFD method.

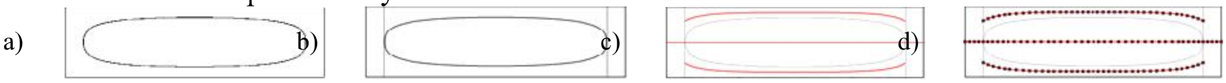

Figure 1 – Schematic of the 2D single tow case and the steps in generating the Stream-Surface mesh: a) initial domain, b) identification of basic flow volumes, c) identification of bisecting curves and d) the final Stream-Surface mesh.

Permeable boundary

The Stream-Surface method assumes that flow in the free channel is similar to that between two stationary solid boundaries. However, this assumption is flawed in the presence of a porous tow, whereby one (or more) of the boundaries surrounding the free channel is permeable [8]. An effective height is recalculated for the free channel using the following equation, which ensures the continuity of flow at the permeable boundary:

$$h_{effective} = h_i \left(1 + \frac{3}{\sigma} \left(\frac{\sigma + 2\alpha}{1 + \alpha} \right) \right)^{1/3} \quad \text{with } \sigma = \frac{h_i}{\sqrt{k}} \tag{1}$$

h_i is the original height of the free channel, k is the permeability of the bounding porous material and α is a dimensionless quantity dependant on the structure of the bounding porous material. At the moment, α is used as a fitting parameter. This issue will be studied in more detail to find a more intelligent way to account for the permeable boundaries.

2D CFD vs 1.5D Stream-Surface

The shape of the tow is defined using the following generalised ellipse equation:

$$y = \pm \left(1 - \frac{x^2}{a_t^2} \right)^n \tag{2}$$

The effects of four geometrical parameters have been studied. The first (P1) is the tow aspect ratio, a_t (width/height). The second (P2) is the power n, which defines the shape of the tow. The third parameter (P3) is the cell fiber volume fraction. Values chosen for this are in multiples of the maximum cell fiber volume fraction for the nominal case (when the cell's height and width is equivalent to that of the tow). The last parameter (P4) is the cell aspect ratio. 17 combinations of the four parameters were simulated. The tow permeability is calculated using Gebart's model [1] for tows perpendicular to flow with quadratic fiber arrangement and fiber diameter of 15.8 µm (8.065×10^{-13} – 2.132×10^{-12} m^2 for tow fiber volume range of 0.416 – 0.500). α has a value of 0.15, from fitting the Stream-Surface result of nominal case 1 to the CFD calculation.

The predicted effects of parameters P1, P2, P3 and P4 on permeability obtained using the Stream-Surface and CFD methods are compared in Figures 2a to 2d respectively. A drop of permeability with increasing tow aspect ratio is observed in Figure 2a. This is because the free channels on top and below the tow are becoming narrower and longer, constricting the flow of resin which primarily flows around the tow. Figure 2b shows an increase in permeability as the tow shape changes from a rectangular-like shape to an ellipse.

Again, the main factor is the change of the resistance in the free channels which open up as the tow becomes more elliptical. Figures 2c and 2d predict a drastic drop in permeability with increasing cell fiber volume fraction and aspect ratio respectively. Change in these two parameters has a direct impact on the geometry of the free channels which become very narrow at either a high cell fiber volume fraction or aspect ratio. More importantly, the Stream-Surface and CFD results show a very good agreement, quantitatively and qualitatively.

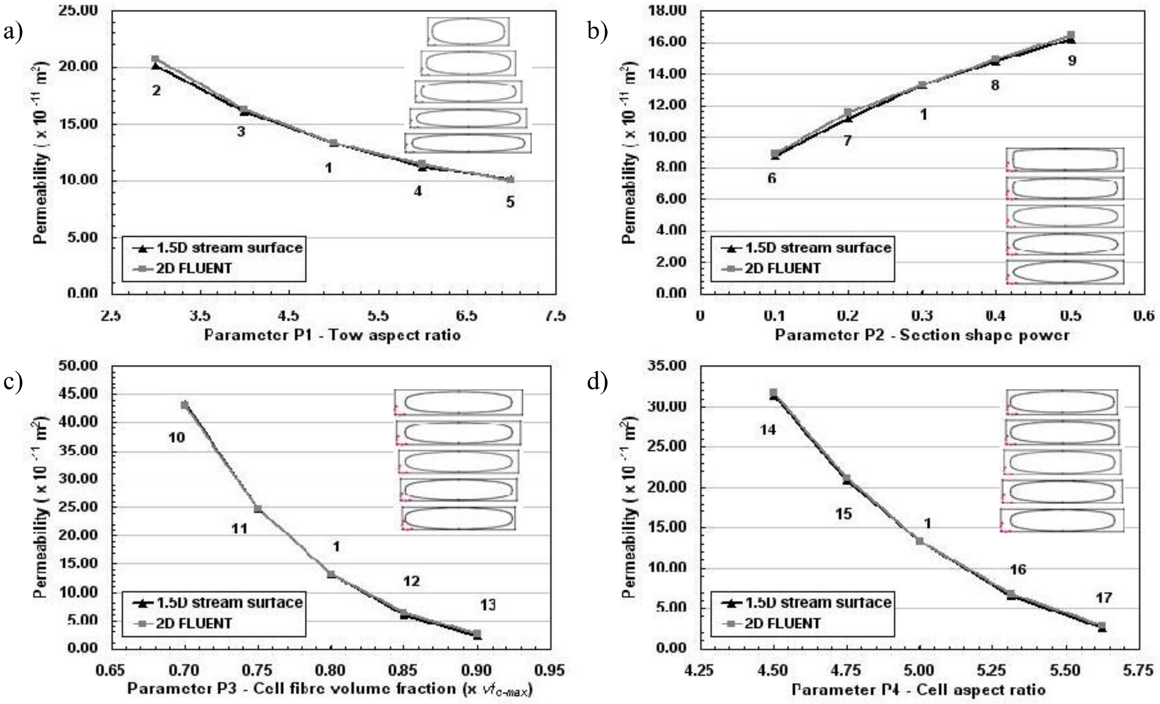

Figure 2 – The effects of: a) tow aspect ratio, b) section shape power, c) cell fiber volume fraction, and d) cell aspect ratio, on the cell permeability.

IV. SHEAR IN 2:2 TWILL WEAVE

A study using the unit cell of a 2:2 twill weave was performed in [9] to demonstrate the generic permeability modeling approach for 3D models. In this section, 2D cross sections of the same textile model were analysed using Stream-Surface and compared to CFD calculations. Figure 3 shows the textile models considered with tows at the nominal ply angles of ±45° and sheared by 30° in two directions. Sections taken at tow crossovers and between crossovers were analysed for both flow along the x and y-axes. Isotropic tow permeability was assumed (4.38 x 10^{-12} m^2 with 50% V_f based on Gebart [1]). The height of the free channels has not been modified to account for permeable boundaries as the fitting method is not sufficient to cover the complicated flow in these cases.

Results are shown in Figure 4. Some of the CFD simulation did not converge and were generally limited by difficulty in mesh generation. As most of the resin flowed around the tows, the geometries of the free channels are the main factor in determining the permeability of the cells. More encouraging perhaps is that the two methods predicted very similar permeability trends, even though the permeable boundary conditions were ignored in Stream-Surface.

This further strengthens the applicability of the stream-surface method for predicting permeability, demonstrating the fact that it can model a more complex case than a single tow.

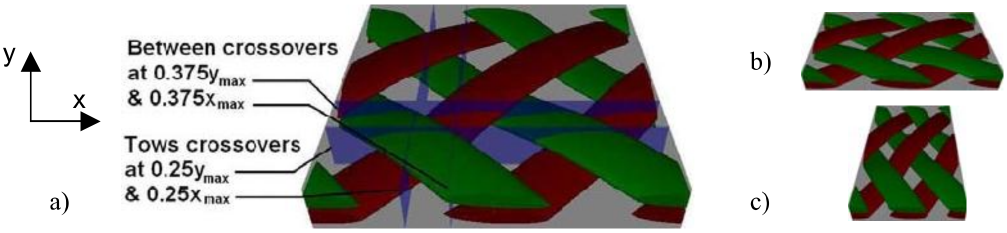

Figure 3 – 2:2 twill weave fabric models. a) Nominal ±45° case with cross sections taken as shown. Model sheared to ply angles of (b)±30° and (c)±60° with respect to x-axis.

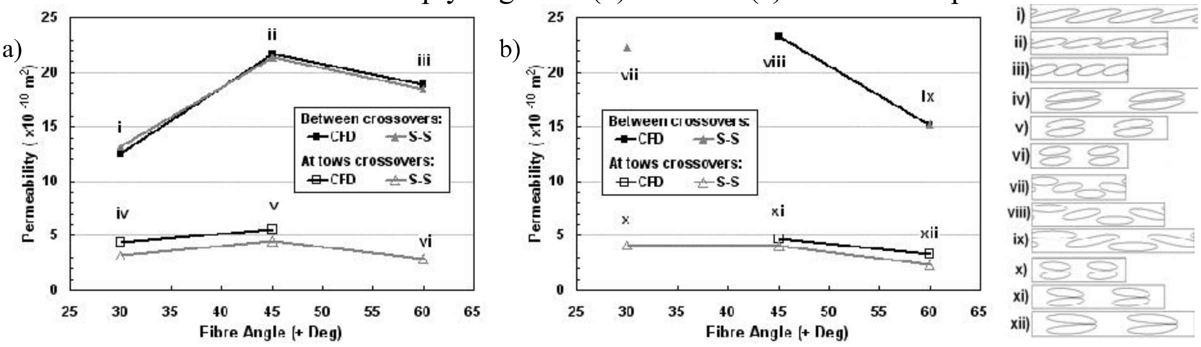

Figure 4 – Predicted permeability of the cross sections for flow along (a) x and (b) y-axes.

IV. CONCLUSIONS

The Stream-Surface results compared extremely well with the CFD calculations for both sets of analyses: single tow and twill weave. While these 2D calculations are of limited use in predicting the permeability of actual preforms, it is an integral part in the development of the Stream-Surface method, further strengthened by the good agreement of the results.

The overall execution time including mesh generation and flow simulation for the two methods in both set of analyses are approximately:

- Single tow analyses: CFD vs. Stream-Surface – 6 minutes vs. 1 seconds
- Twill weave analyses: CFD vs. Stream-Surface – 30 minutes vs. 5 seconds

All analyses were performed on a standard PC (P4 1.7GHz). Whilst one might use the CFD method to get a more accurate solution, the Stream-Surface method may be more efficient when a large number of predictions are needed.

Future work will proceed with further validation of the Stream-Surface method with expansion to include 3D models. Several issues such as isotropic tow permeability in the current analyses and also permeable boundary conditions need to be studied in detail.

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