VARIATIONS IN THE UNSATURATED FLOW WITH FLOW DIRECTION IN LIQUID COMPOSITE MOLDING

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ABSTRACT: Liquid Composite Molding (LCM) process includes different technologies used for producing polymer matrix composites. Resin Transfer Molding (RTM), widely used in the industry because of the good dimensional control, consistent quality and fast cycle time, is one such popular LCM technology. In any typical RTM process during mold filling, a thermoset resin is injected/sucked into a mold cavity with a pre-placed preform of fiber mats. The dual-scale nature of these fiber preforms gives rise to the unsaturated flow in RTM process which is characterized by a droop in the injection pressure history due to the delayed absorption of fiber tows (the `sink' effect). In this study, we experimentally investigate the effect of change in flow direction in an anisotropic dual-scale fiber mat on the unsaturated flow. A series of 1-D experiments involving constant flow-rate were conducted for the unidirectional stitched mats. The droop in the inlet pressure history, signifying the strength of sink effect, is found to be strongest for flow along the microchannels aligned with fiber tows. The droop, and hence the sink effect, is observed to weaken progressively for flow directions at 45^{o} and 90^{o} to the principal microchannel direction respectively.

KEYWORDS: LCM, RTM, mold filling, unsaturated flow, dual-scale porous media.

INTRODUCTION

Plastics reinforced with carbon or glass fibers form the polymer-matrix composite, which is gaining popularity in the automobile and aerospace industries due to their low weight and high strength. An increase in the fiber volume fraction increases the strength of the composite part. To achieve a high fiber volume fraction, it is essential that the fibers be arranged with predetermined regularity and packed as bundles of fibers. Liquid Composite Molding (LCM) which includes RTM, Vacuum Assisted Resin Transfer Molding (VARTM), Seemann Composites Resin Infusion Molding Process (SCRIMP), has emerged as an important technology for manufacturing polymer composites. In any typical LCM process, reinforcing fibers in the form of fiber preforms are placed in a closed mold, matrix material in liquid form is either injected under pressure or sucked into the mold due to vacuum to infiltrate the fiber mat. When the mold is full, the matrix material is allowed to undergo a solidification process before the final part is removed from the mold. For the thermoset type polymer-matrix composites, the solidification process is a cross-linking reaction called curing that turns the resin into a hard brittle solid.

RTM is a widely used process for producing polymer matrix composites. A significant amount of work has been done in modeling RTM mold-filling process for optimizing the mold design [1]. Such numerical simulations are essential for predicting the optimum location of resin-inlets and air-vents in the mold, the resin injection pressure, the net clamp-force, and the optimum cooling-circuit design for controlling temperature in the mold during curing. Successful computer simulations are able to improve the mold design in virtual space without the need for the expensive and time-consuming trial-and-error approach to mold design.

PREVIOUS WORK ON UNSATURATED FLOW

In most mold-filling simulations, the resin flow during mold-filling in RTM in porous media created by fiber mats can be modeled by using the continuity equation and Darcy's law [2,3,4,5]. In most flow models, it is assumed that a sharp interface called front exists between the wetted and dry portions of the porous medium during the resin impregnation process and the pores behind the flow front are completely saturated with resin. This assumption leads to the use of the quasi-steady-state approximation for solving the resin pressure behind the moving flow-front in an RTM mold. However, some recent papers [4,5,6,8] show that, the assumption of complete saturation behind the flow-front is often inaccurate for the case when unidirectional, stitched or braided fiber-mats are used. These investigations show that the resin impregnation pattern in these mats is completely different from the pattern in random mats, which is characterized by full saturation behind the front. One idealized model of such fiber-mat architecture is shown in Fig. 1 below.

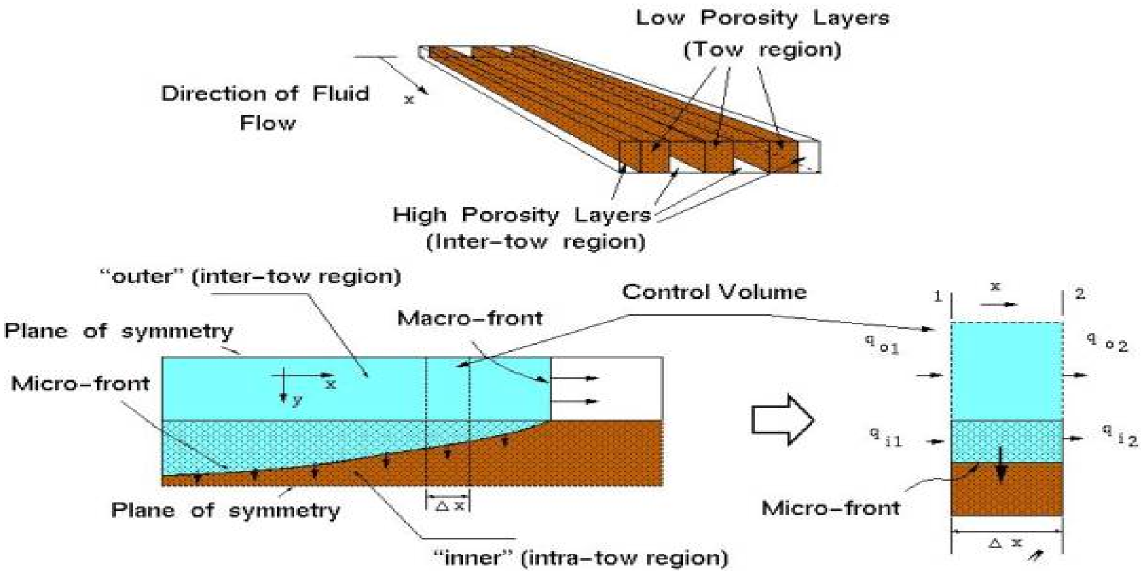
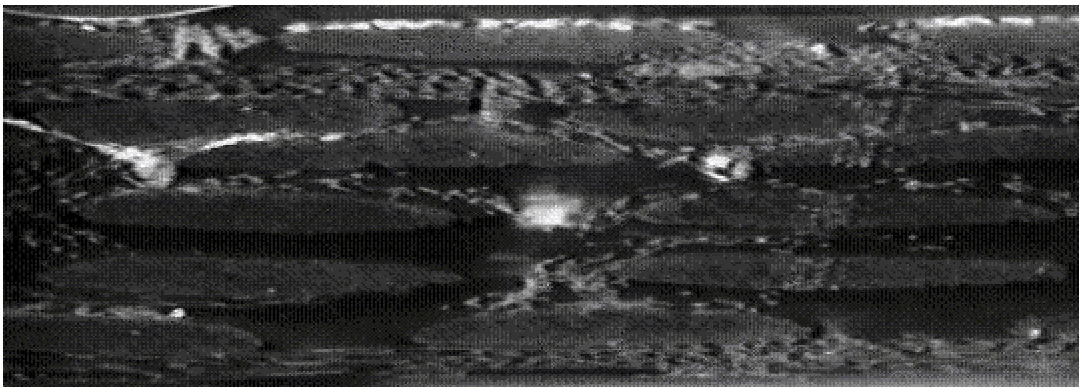
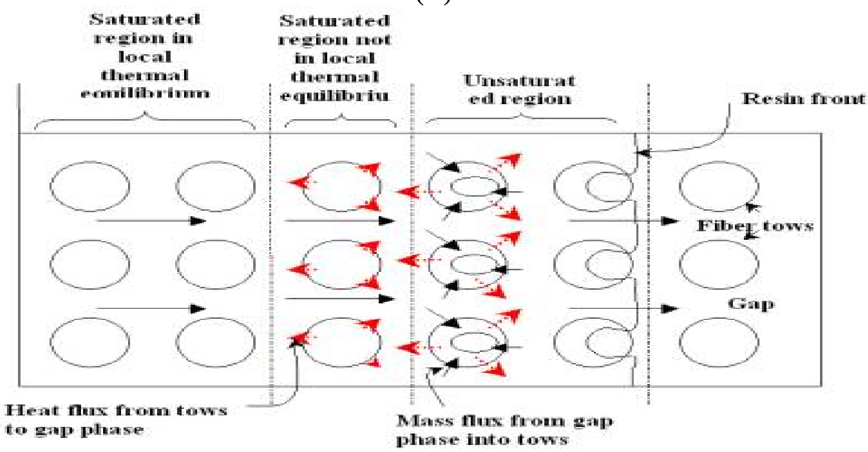


Fig. 1. Schematic of an ideal dual scale media showing intra-tow and inter-tow spaces and flow front propagation along the macro and micro channels.

Here the tows are made of thousands of individual fibers with inter-fiber distances of the order of micrometers, whereas the distances between the tows are the order of millimeters. This order-of-magnitude difference in length scales in the same medium lead to its classification as a `dual-scale' medium (Fig 2 A). Because of this dual-scale nature of fiber mats, when resin is injected into an LCM mold, it quickly passes through the inter-tow channel without impregnating the tows. After the front has passed, resin from the surrounding gap region continues to impregnate the tows. This delayed impregnation of tow leads to the unsaturated flow in LCM process as shown in Fig. 2 (B). It also causes a sink term S to appear in the macroscopic equation of continuity $\nabla \bullet \mathbf{v} = -S$ for such dual scale porous media [5,11,12]. (**v** is volume averaged velocity.) This delayed impregnation is also behind the appearance of a `droop' in the inlet pressure vs time (inlet pressure history) plot for the constant flow-rate 1-D flow experiment [5,6,9]. Dimensionless parameters `pore volume ratio' and `sink effect index' based on previous flow models for dual scale porous media [5,9] have been successfully used to link the appearance of the inlet pressure droop to the sink effect caused by the dual-scale type microstructure of the fiber mats [8,10].



(A)



(B)

Fig.2: (A) A typical micrograph of an LCM part made from the directional fiber mats. The elliptical patches are the cross-sections of fiber bundles (or tows) consisting of thousands of a-few-microns-thick fibers. The dark spaces around the bundles are the large gaps surrounding the bundles. (B) Schematic describing the absorption of resin by fiber bundles behind the flow-front and creation of a sink effect

PROPOSED WORK

In this paper our aim is to study variation in the inlet-pressure droop, and hence the sink effect, due to changes in the flow direction within a dual-scale fiber mat. This will be first such study exploring the dependence of the sink effect on flow direction in an anisotropic dual-scale fibrous porous medium.

1-D FLOW EXPERIMENT

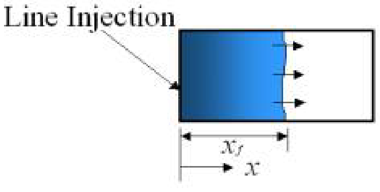
Fig. 3(A) shows the schematic of a simple 1-D flow experiment used for detecting the unsaturated flow. (The experimental setup is described in greater detail elsewhere [6,9,10].) In Fig. 3(B), a typical `drooping' inlet-pressure history, a characteristic of the unsaturated flow [6,10], is compared with the inlet-pressure predicted by the conventional physics after assuming full saturation behind a moving resin front. The linearly increasing portion of this theoretical pressure profile is predicted using

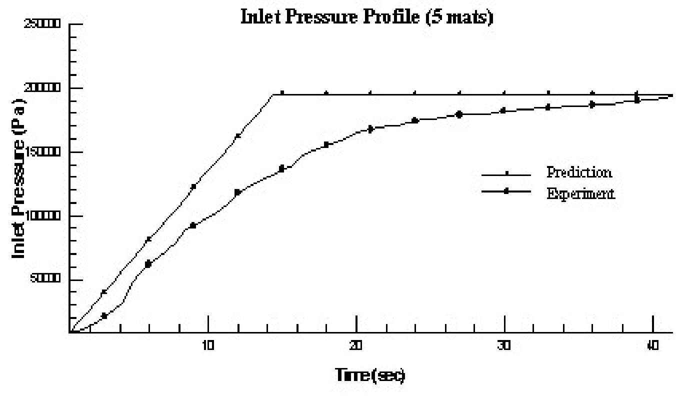
$$P_{in} = \left(\frac{Q}{A}\right)^2 \frac{\mu}{k_{sat}\varepsilon} t \quad \cdots\cdots\cdots(1)$$

where P_{in} the inlet pressure, k_{sat} is the saturated permeability of the preform, Q is the constant flow-rate, μ is the viscosity of the liquid, A is the cross-sectional area of flow, and ε is the porosity of the preform. Here Q is measured using a flow meter. The flow meter and Pressure transducer (for measuring ΔP) reading is gathered every after 0.6 seconds using National Instrument Data Acquisition/Lab view system). μ is measured using the Brookfield viscometer. ε is measured using the dipping experiment. In this experiment one sample of the fiber mat is dipped inside a calibrated jar, which is initially filled with water of known volume. Once it is dipped the volume change in the jar is recorded. So this volume is actually the fiber volume without any pores. Once this volume is known pore volume is calculated by subtracting the fiber volume from the total volume. So, porosity is pore volume/total volume. The parameters k_{sat} and $t_{fill-time}$ are estimated using

$$k_{sat} = \frac{Q\mu L}{A\Delta P} \cdots\cdots(2) \quad t_{fill-time} = \frac{\varepsilon A L}{Q} \quad \cdots\cdots\cdots(3)$$

where ΔP is the pressure drop across a length L under steady-state flow conditions and $t_{fill-time}$ is the filling time for the fiber mat. ($t_{fill-time}$ is the time after which the linerly increasing P_{in} in Fig 3(B) becomes the horizontal P_{in} = constant line.)





(A) (B)

Fig.3. (A) Schematic of a simple 1-D flow experiment. (B) Typical measured and theoretical inlet-pressure profiles for dual-scale fiber mats [6,8].

A few 1-D flow experiments were conducted using unidirectional fiber mats shown in Fig. 4. The main characteristic of these fiber mats is that the fiber tows are oriented in one direction only. According to the unsaturated flow theory, if these fiber mats are placed such that their tows are in the x-direction with flow taking place in this direction as well, then the resin will flow easily through the inter-tow channels aligned with the fiber tows and the characteristic inlet-pressure droop (and hence the sink term magnitude S [8]) will be maximum along the x direction. In case of the flow being along the y direction in Fig. 4, which is perpendicular to the orientation of the x direction inter-tow channels, will see no such preferential flows and the inlet-pressure droop is expected to vanish, and hence S can be inferred to be reduced to zero.

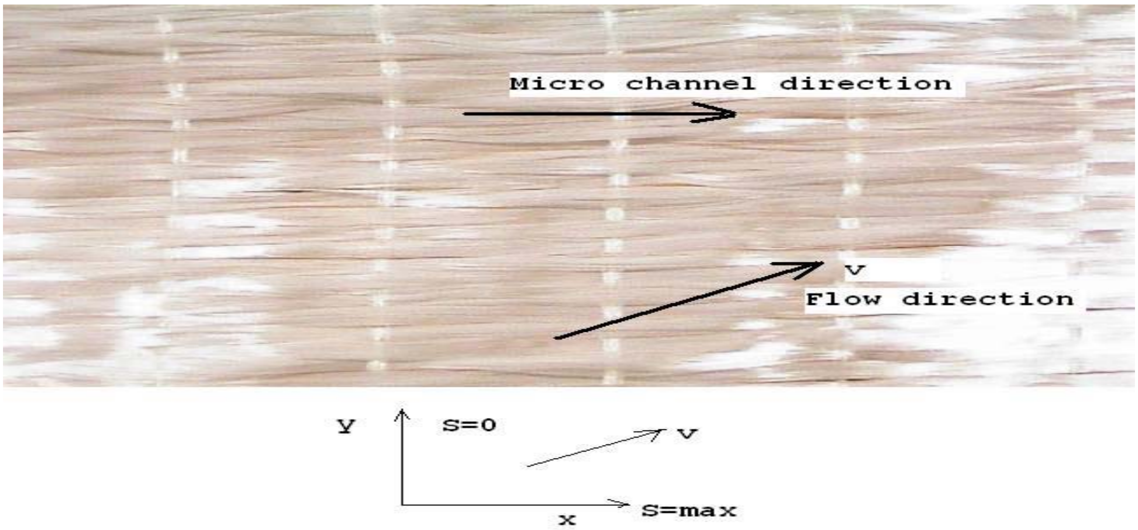


Fig 4: Unidirectional fiber mat and the anticipated directional dependence of the sink effect. (S is the magnitude of the sink term.)

RESULTS AND DISCUSSION

Three experiments were conducted: 1) flow along the x direction; 2) flow at 90^o to the x direction (i.e. along the y direction); 3) flow at 45^o to the x direction. Fig. 5 shows the inlet pressure profile when the flow is along the fibers tows (x) direction. Because of the high-pressure build up inside the mold, local distortions and shifting were observed in the mats, and which caused the inlet pressure profile to be rather tortuous. But the important observation is that there is a significant droop in the inlet pressure profile vis-à-vis the theoretical pressure profile.

In the second experiment, the flow is along the y direction such that preferential flow along inter-tow channels is absent. In such a situation, the flow is likely to behave like a flow in a single-scale porous medium (where no inter-tow channels exist) and the inlet pressure profile is expected to match the theoretical pressure profile. Fig. 6 shows the inlet pressure profile when the fiber tows in the mat are oriented perpendicular to the flow direction. Except for a little shift, which is due to the fiber rearrangement and reorientation, one can see that the inlet pressure plot more or less matches the theoretical pressure profile. But after reaching a maximum, the pressure gradually decreases because of the race tracking along the edges and slow slippage of the mats inside the mold. (Since these fiber tows are very flexible, they start to bow down under high inlet pressure creating some preferential flow path at the edges.)

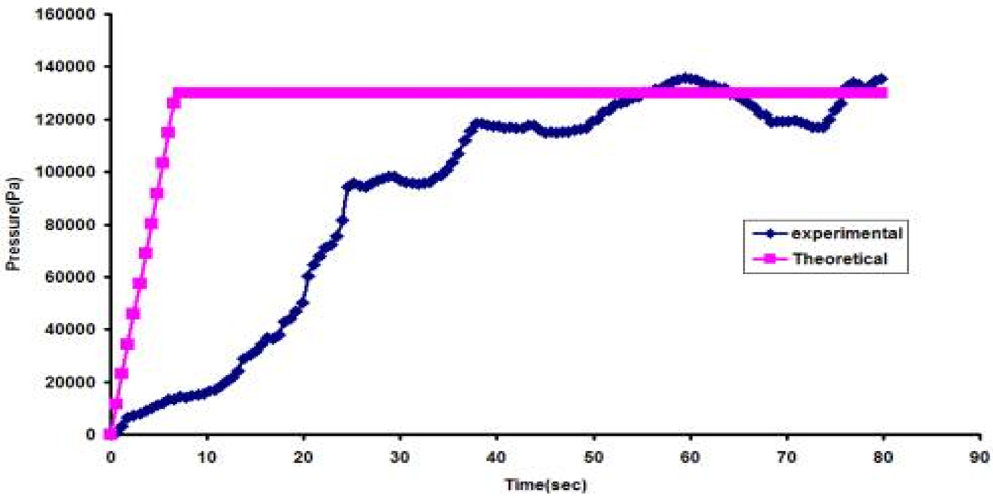


Fig.5. Comparison of the experimental inlet-pressure history with the theoretical prediction for the unidirectional mat when the flow is along its x direction

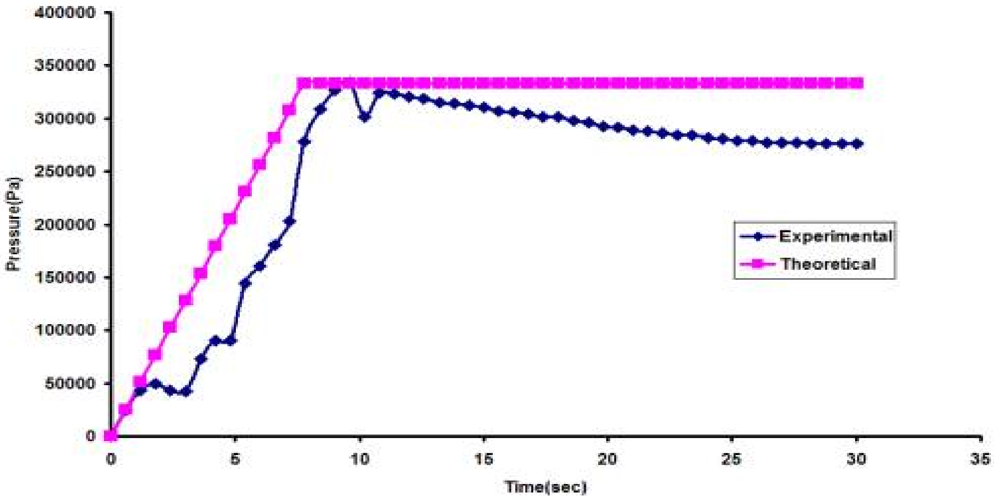


Fig.6. Comparison of the experimental inlet-pressure history with the theoretical prediction for the unidirectional mat when the flow is along its y direction

If these effects after the maximum point are neglected, one can say that the experimental pressure profile follows the theoretical one without the characteristic droop, and one can infer that the sink term S in the macroscopic continuity equation is zero. So clearly the sink effect for flow across fiber tows, as described simplistically in Fig. 2(B), does not work for this particular fiber mat! [A single-scale flow model involving saturated flow in a network of low and high permeability regions (Shih and Lee [13]) is perhaps a better representation of this cross flow.]

As these two above experiments are the two extreme cases of the sink effect (in the first case it's very large and in the second case it is negligible), we conducted another experiment where the flow was oriented at an angle of 45^{o} to the inter-tow channel direction to see if we get some intermediate sink effect. The theoretical and experimental pressure profiles for this case are shown in Fig. 7. It is clear from this figure that the inlet pressure plot has a small droop and a small sink effect can be inferred.

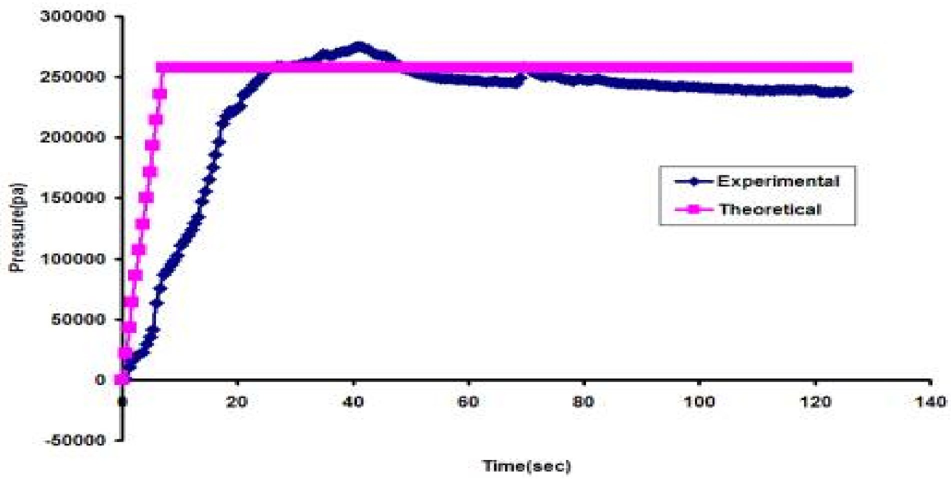


Fig.7. Comparison of the experimental inlet-pressure history with the theoretical prediction for the unidirectional mat when the flow is at 45^0 angle to x direction.

The above-described three experiments are summarized in Table 1. Here the length of the fiber mats, the mold cross sectional area, the test-liquid viscosity, and the porosity are kept constant at 0.254 m, 0.001715 m^2, 0.1875 N-S/m^2 and 0.6129, respectively. As can be seen from the saturated permeability column in Table 1, the permeability along the fiber tow (x) direction is 3 or 4 times more than the permeability across this (or y) direction. So this clearly points to the presence of inter-tow channels along the x direction as such channels are likely to increase permeability along their length.

The drooping of the inlet-pressure profile in case of the dual-scale fiber mats has serious implications as far as governing equations for temperature and cure are concerned. The curing of resin is often an exothermic process where the heat released seriously affects the local flow as a result of temperature and cure dependence of resin viscosities. These observations provide a strong justification for a new set of governing equations for dual-scale fiber mats proposed by Pillai et al. [11,12] where numerous source or sink terms are shown to appear in the governing equations as a result of applying the rigorous phase-averaging method. The current work suggests dependence of such terms on flow direction in an anisotropic dual-scale fiber mat and exploration of such dependence should prove to be a fertile research field in future.

Table 1: Different parameters associated with the three experiments

	Avg.Flow rate Q (m^3/sec)	Saturate pressure ΔP (Pa)	Saturated perm K_{sat} m^2 Eq (2)	Fill time (Sec) Eq(3)
Flow along the fiber	3.8417E-5	135392	7.708E-9	6.9
Flow across the fiber	2.869E-5	333802	2.387E-9	9.3
Flow at 45^0 angle.	3.7386E-5	250000	4.064E-9	7.1

SUMMARY AND CONCLUSION

The effect of fiber-mat orientation on the inlet pressure profile in a 1-D flow experiment was studied successfully. The dual-scale nature of the unidirectional fiber mats gives rise to the drooping inlet pressure profile during injection that deviates significantly from the theoretically predicted profile. Such a droop is shown to vary with the fiber-mat orientation and appears to be strongest along the direction of the inter-tow channels. Future studies will be directed towards developing a direction dependent sink model for flow in the dual-scale fiber mats in RTM.

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