Some Studies on Modeling the Unsaturated Flow in Woven, Stitched or Braided Fiber Mats in LCM

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Summary: The liquid composite molding (LCM) processes for manufacturing polymer composites involve injecting a thermoset resin into a fiber-packed mold cavity. Very often, the fiber preform behind the resin front is partially saturated during mold-filling giving rise to the unsaturated flow behind the flow front. This paper discusses the implications of the recent experimental, numerical and analytical work done by the authors' research group in advancing the state of research in this area. The experimental work describes the type of fiber mats in which the unsaturated flow is likely to occur, and the dimensionless parameters that are effective in predicting the unsaturated flow. Numerical work highlights the inadequacy of the conventional flow model when the 'sink' effect is not incorporated during the reactive and nonisothermal unsaturated flow in dual-scale porous media created by certain fiber mats. A new set of governing equations for such media is presented that incorporate the effect of delayed absorption of tows through various sink terms in the mass-balance, temperature, and cure equations.

Keywords: preform, unsaturated flow, sink, dual-scale porous media, RTM, LCM

Introduction

In Liquid Composite Molding process, a thermoset resin is injected into a mold cavity, which is packed with a preform made of fiber mats to create a cured part. LCM process includes Resin Transfer Molding (RTM), Vacuum Assisted RTM (VARTM), Seemann Composites Resin Infusion Molding Process (SCRIMP) and few others. All of the LCM technologies consist of the following major steps: the reinforcement of carbon or glass fiber is placed in the mold cavity, matrix material like thermoset resin is either injected under pressure or sucked into the mold cavity due to vacuum, once the fiber mat infiltrated, the matrix is allowed to cure and harden to its final shape, finally, the mold is opened and the part is taken out for final operations. For the thermoset type polymer-matrix composites, the solidification process is a cross-linking reaction that turns the resin into a hard brittle solid.

Numerical simulations of the mold-filling process in LCM provide a thorough insight in optimizing the mold design. Numerous softwares [1,2] are available to optimize the mold filling process.

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The basic assumption used in these simulations is that preform behind the flow-front is fully saturated with resin and the flow in such a region can be modeled using the equation of continuity (Eqn. 1) and Darcy'c law for momentum balance (Eqn. 2) given below.

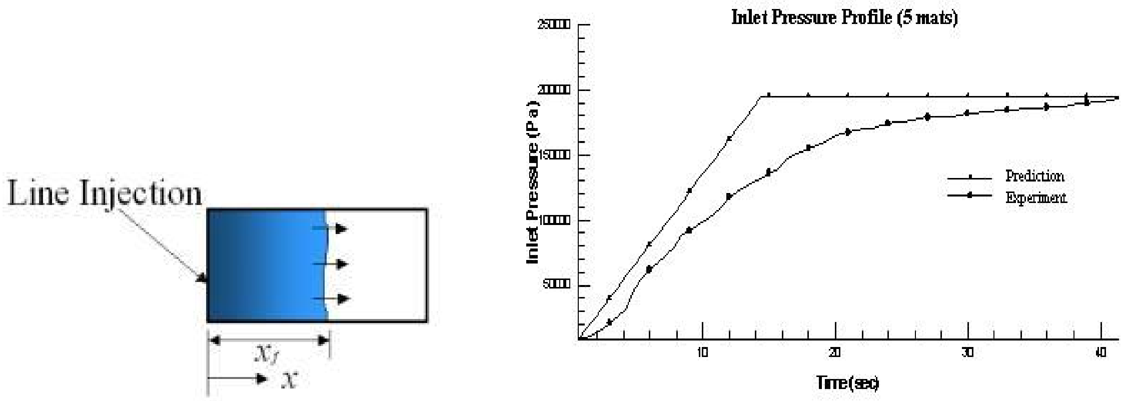
$\nabla.\mathbf{u} = 0$ …….(1) $u = -(\mathbf{K}/\mu)\,\nabla P$ ………(2) $\nabla.[\mathbf{K}.\nabla P] = 0$ ……… (3)

Here **u** is the volume averaged velocity of resin in fibrous porous media, P is the volume-averaged pressure, **K** is the permeability tensor of the fibrous performs and μ is the resin viscosity. For non-isothermal flows in porous media equation 1 and 2 can be combined with convection-diffusion type transport equations for energy and cure to predict temperature and degree of chemical reaction in the resin [3,4].

Previous work on the unsaturated flow

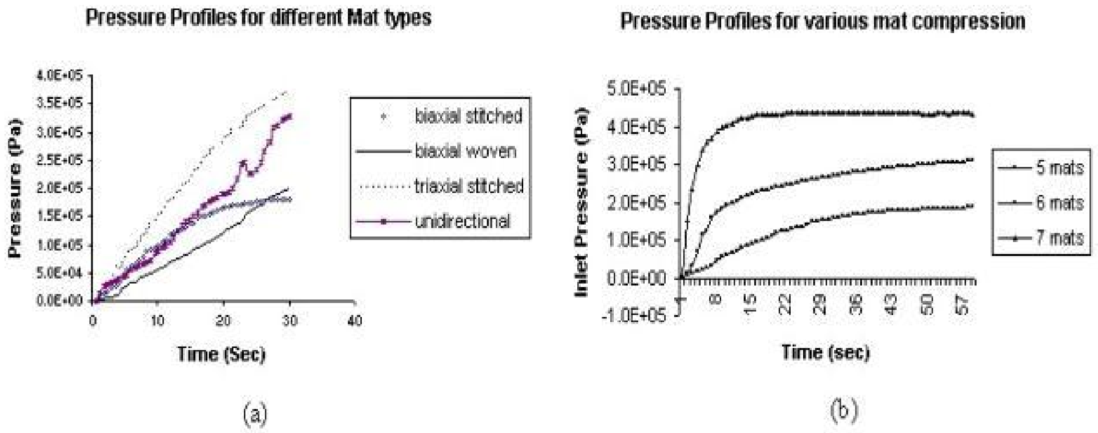
In the last few years it has been discovered that the physics used to simulate mold filling in LCM is inadequate for woven, stitched & braided fiber mats [5-7,9,13] which is being attributed to the dual-scale porous medium created due to the presence of large gaps between dense fiber tows. Figure 1(a) shows the schematic of a simple 1-D flow experiment used for detecting the unsaturated flow.

In figure 1(b), a typical "drooping" inlet-pressure history, a characteristic of the unsaturated flow [10], is compared with the inlet-pressure predicted by the conventional physics using Eqn. 3 after assuming full saturation behind a moving resin front.



1(a)   1(b)

Figure 1.(a) Schematic of a simple 1-D flow experiment.
(b)Measured and theoretical inlet-pressure profiles for 5 biaxial stitched mats.



(a) (b)

Figure 2: Comparison of measured inlet pressure history for various mat types and mat compression.

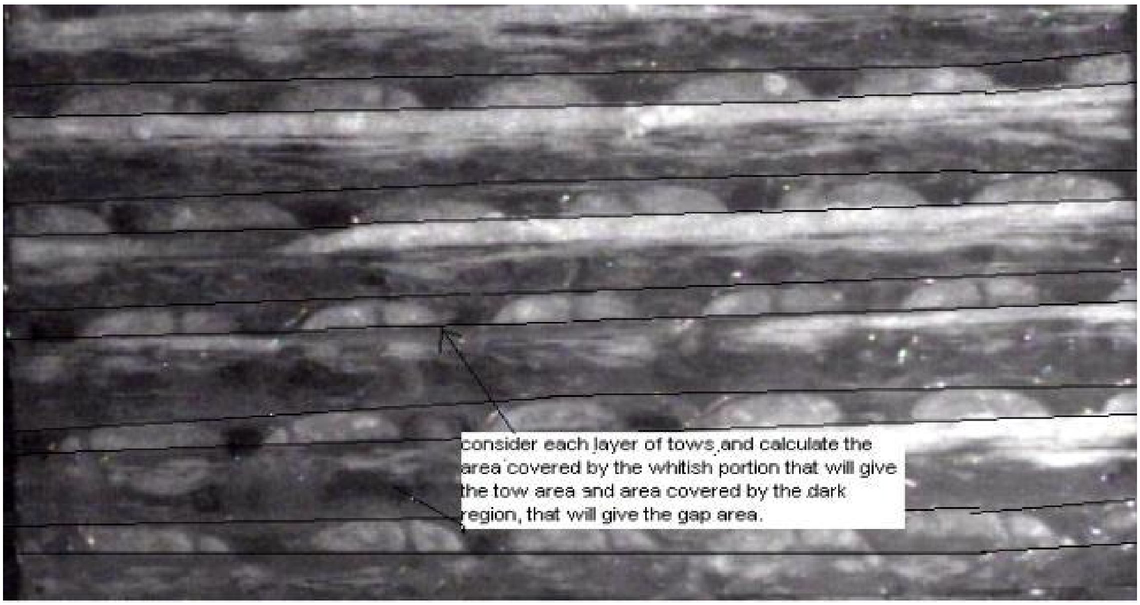
Recently, it has been observed that not all woven, braided or stitched mats showed the “droop” – only the stitched mats with long uninterrupted channels aligned along the flow direction manifested this aberrant behavior [9,10]. It was also observed that the inlet pressure profile becomes flatter with increasing number of mats (Fig. 2(b)). Theoretical models anticipated such a flattening of inlet pressure profile for the unsaturated flow as a direct function of the dimensionless parameters *pore volume ratio* and *sink effect index* [5-7]. These indices as an outgrowth of the sink model are demonstrably more scientific in modeling the unsaturated flow [12].

Validating the sink model using the pore volume ratio and sink effect index

Pore volume ratio (γ) and sink effect index (ψ) are defined as

$$\gamma = V_{tow}\,\varepsilon_i / V_{gap} \quad \text{….(4)} \qquad\qquad \psi = (K_t/K_{ch})(L/b)2\tau \quad \text{…..(5)}$$

where V_{tow} is the volume of tows, V_{gap} is the volume of gaps between tows, ε_i is the tow porosity, K_t is the tow permeability, K_{ch} is the channel permeability, L is the characteristic length in the flow direction, b is the characteristic length in the transverse direction and $\tau = \pi$ a b Ns is the tow area fraction which is equal to the total cross-sectional area of tows in a unit area of cross-section of the fiber mat. These dimensionless numbers characterize the magnitude of liquid absorbed by the tows and are a function of the relative resistance to flow in the tow and inter-tow regions, and the packing density of the tows. Recently, γ and ψ were computed from the micrograph samples of biaxial and triaxial stitched mats displaying the unsaturated flow [11]. (One of the micrograph of biaxial stitched mats is shown in Fig. 3.) It was observed that as γ and ψ increase, the `droopiness’ of the inlet pressure profiles also increases [11], thus matching the trend predicted by the earlier sink models [6,7].



consider each layer of tows,and calculate the area covered by the whitish portion that will give the tow area and area covered by the dark region, that will give the gap area.

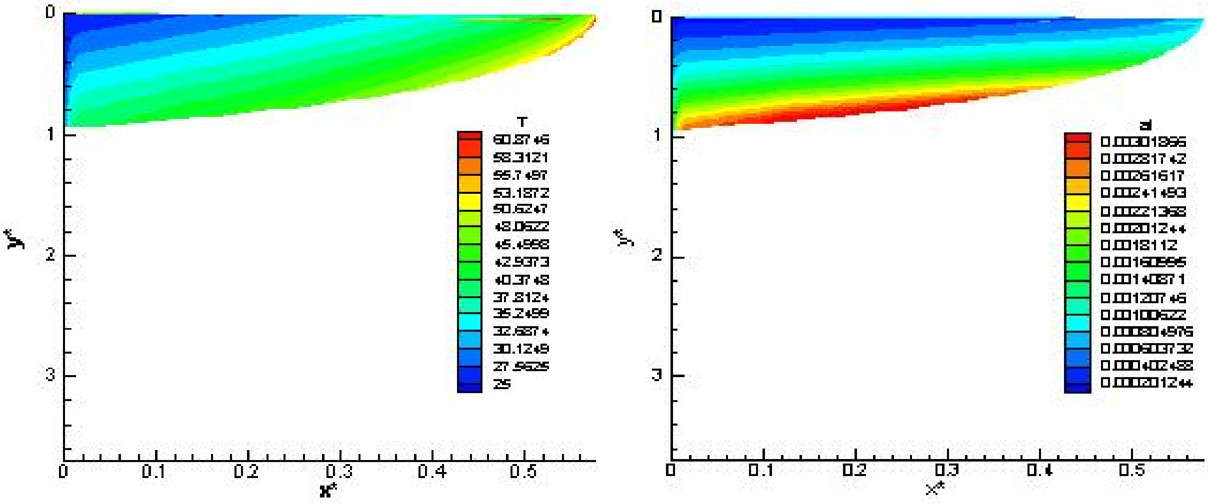
Figure 3: Measurement of tow area and gap area of a biaxial stitched mat. Tow area is the area covered by the whitish portion and gap area is the dark portion in each layer.

Study of temperature and cure distributions in dual-scale porous media

This numerical study was aimed at studying changes in temperature and cure distributions due to the sink effect in a dual-scale porous medium created by the stitched fiber mats. An iterative, control-volume approach based on energy and cure balances was used for developing discretized equations in the channels and fiber tows of the two-layer model of the dual-scale porous media [14,15].

A typical temperature distribution is shown in Fig. 4(a). Temperatures at the top edge represent the gap or inter-tow temperatures, whereas temperatures underneath it above the curve represent the inside-the-tow distribution. From the figure it is clear that resin near the curved micro front is at much higher temperatures as compared to the resin in the top, outer region. This can be attributed to the fact that the fibers in the mold are at a higher temperature as compared to the resin, when such fibers are “quenched” by the invading resin at the micro-front, the excess energy passes on to the resin resulting in an increase in temperature near the micro-front.

Similarly, the development of cure in the resin is shown in Fig. 4(b). The cure is at maximum near the micro-front region, which is due to the high temperatures developed inside tows behind the microfront. As a result, the rate of resin cure is also at a maximum. A significant difference in temperatures and cures of the outer (inter-tow) and the wetted inner (intra-tow) regions are observed. The effect of various parameters such as the ratio of liquid and fiber heat capacities, the fiber and resin thermal conductivities, the pore volume ratio, and the resin reaction rates are found to play an important role in the temperature and cure distributions inside and outside the tows.



(a) (b)

Figure 4: Temperature (a) and cure (b) distributions in a two-layered dual-scale medium.

Governing equations for the unsaturated flow

Pillai and Murthy recently developed the physics for modeling the unsaturated flow in dual-scale fiber mats observed during the LCM mold fillings [16, 17]. The mathematically rigorous phase-averaging method was employed to develop a new set of gap- and tow-averaged temperature and cure equations in the dual-scale media. These coupled equations can be used to model the unsaturated flow in fibrous dual-scale porous media under reactive, nonisothermal conditions. These equations for the gap and tow region are compiled in the following tables. (See [16,17] for details of the symbols.)

Table 1: Set of volume-averaged governing equations for the gap region.

Mass	$\nabla.\langle \mathbf{v}_g \rangle = -S$
Momentum	$\langle \mathbf{v}_g \rangle = -(\mathbf{K}/\mu).\nabla\langle P_g \rangle^g$
Energy	$(\rho C_p)_l\,[\varepsilon_g\,\partial\langle T_g\rangle^g/\partial t + \langle \mathbf{v}_g \rangle.\nabla\langle T_g\rangle^g] = \nabla.\mathbf{K}_{th}.\nabla\langle T_g\rangle^g + \varepsilon_g \rho_g H_R f_c + Q_{conv} - Q_{cor}$
Cure	$\varepsilon_g \partial\langle c_g\rangle^g/\partial t + \langle \mathbf{v}_g \rangle.\nabla\langle c_g\rangle^g = \nabla.\mathbf{D}.\nabla\langle c_g\rangle^g + \varepsilon_g f_c + M_{conv} - M_{diff}$

Table2: Set of volume-averaged governing equations for the tow region.

Mass	$\nabla.\, v_t = 0$
Momentum	$v_t = -(\mathbf{K}/\mu).\nabla P_t$
Energy	$[\varepsilon_t(\rho C_p)_l + (1-\varepsilon_t)(\rho C_p)_f]\partial T_t/\partial t + (\rho C_p)_l\,\mathbf{v}_t.\nabla T_t = \nabla.\mathbf{K}_{th,t}.\nabla T_t + \varepsilon_t \rho_g H_R f_c$
Cure	$\varepsilon_t \partial c_t/\partial t + \mathbf{v}_t.\nabla c_t = \nabla.\varepsilon_t \mathbf{D}_t.\nabla c_t + \varepsilon_t f_c$

Conclusions

In this paper we have discussed the unsaturated flow in Liquid Composite Molding process for different fiber mats. The 1-D unsaturated flow in stitched fiber mats, with inter-tow channels aligned with the flow direction, displays the drooping inlet-pressure history characteristic of the unsaturated flow. The droop in the inlet pressure history increases with increasing mat compression. Dimensionless numbers *pore volume ratio* and *sink effect index* are effective in predicting unsaturated flow in biaxial and triaxial stitched mats, and successfully validated the earlier unsaturated-flow theories. A numerical simulation of the reactive, nonisothermal flow in a two-layer, dual-scale porous medium predict high temperatures and resin cures inside tows, thereby contradicting the conventional temperature and cure models that predict high temperature and cures just behind the flow front. Various parameters, such as the ratio of liquid and fiber heat capacities, the fiber and resin thermal conductivities, the pore volume ratio, and the resin reaction rates, are shown to influence the temperature and cure distributions in such dual-scale media. Finally, a new set of governing equations for predicting resin temperatures and curUkGus in dual-scale porous media is presented. These equations, with new sink terms associated with convection and diffusion of heat and cure into the tows during the unsaturated flow, will help in an accurate simulation of the unsaturated flow in dual-scale fibrous media.

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