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Modeling Unsaturated Flow in Dual-Scale Fiber Mats of Liquid Composite Molding: Some Recent Developments

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ABSTRACT: Unsaturated flow, characterized by a partially-saturated region behind a moving resin-front, is often witnessed during mold-filling in liquid composite molding (LCM) molds when parts are made from woven or stitched (dual-scale) fiber-mats. In this paper, the unsaturated flow is modeled as a coupled, two-scale flow at the gap (inter-tow) and tow (intra-tow) levels. The simpler, isothermal mold-filling is tackled using two different approaches: 1) A faster, 'lumped' algorithm is proposed to estimate the mass sink term using a sink function developed from the tow impregnation simulation in a unit cell. 2) A more accurate, multiscale algorithm is proposed to couple the gap-level flow with the microscopic, tow-level flow. (A coarse global mesh is used to solve the global gap flow over the entire domain, and a fine local mesh in form of the unit-cell of periodic fabrics is employed to solve the local tow-impregnation so as to compute sink terms required for solving the gap flow.) The algorithms are implemented in our in-house code PORE-FLOW©, a simulation tool for the mold-filling type flows. Fairly good comparisons between predictions of the two models and experiments are achieved without the use of any fitting parameters. Later the multiscale algorithm is extended to solve the unsaturated flow under non-isothermal, reactive conditions and an example of LCM mold-filling simulation is presented.

KEYWORDS: Liquid Composite Molding, LCM, RTM, Unit Cell, Mold-filling, Permeability.

INTRODUCTION

The mold-filling simulation of liquid composite molding (LCM) is one of the most effective approaches to optimize the LCM process and mold design. It has been demonstrated that the flow-modeling approach for the single-scale fiber preforms (made from random mats) has difficulties in accurately predicting the wetting in the dual-scale fiber preforms (made from woven and stitched fabrics); the latter are characterized by the presence of two distinct length-scales of pores (i.e. large pores outside the tows and small pores inside the tows) in the same media. The liquid resin flowing through such dual-scale media is accompanied by the delayed impregnation of fiber tows due to a higher flow resistance offered inside the tows, where the resin inside the tows is practically stationary with respect to the resin traveling through the gaps around the tows.

LUMPED ALGORITHM

We have demonstrated that for flow through dual-scale fabrics in LCM, the macro-flow equation is coupled with micro-flow equation through the sink term [1, 2]. In the lumped algorithm, we characterize the sink term as a function of some macroscopic quantities, such as the gap-averaged pressure and tow-saturation, and which is obtained by simulating the micro-flow in a unit-cell beforehand; we later solve the macro-flow equations by incorporating the obtained sink function. Although we lose the detailed tow-impregnation information in the subsequent global simulation, such a method (of solving the micro-flow in advance) makes the full-scale mold-filling simulation of dual-scale preforms in a short time and at a low computational cost quite feasible. Only one computational domain representing the gaps of a dual-scale preform is needed in the current lumped method.

Following Wang & Grove[3], We express the sink term in the macroscopic continuity equation as a function depending on the tow saturation, the inter-tow gap pressure, and the capillary pressure :

$$S_g = \varepsilon_{\text{tow}} \left(1-\varepsilon_{\text{gap}}\right) \frac{A_1 P_{\text{gap}}}{a\mu} \left\{ e^{\left[A_2 (1-S_{\text{tow}})^{A_3}\right]} - 1 \right\} \tag{1}$$

where S_g is sink term, ε_{gap} is the porosity of the gap network, ε_{tow} is tow porosity, μ is viscosity, P_{gap} is inter-tow gap pressure, S_{tow} is the tow saturation. A_1, A_2, and A_3 are three fitting parameters determined by the tow properties. We estimate three parameters in the sink function (Eq.(1)) by matching its predictions with those of the tow-impregnation simulation in a stand-alone 3-D unit cell which represents the periodic structure of fiber mats. The details about determining parameters in the sink function using the unit-cell simulation can be found in [4]. Once the sink function is determined, it is assigned to each node in the FE mesh, which represents the liquid disappearing into the tows within an imaginary unit cell associated with each node. The algorithm of integrating the macroscopic mold flow with the tow-impregnation during the unsaturated flow is detailed in [4].

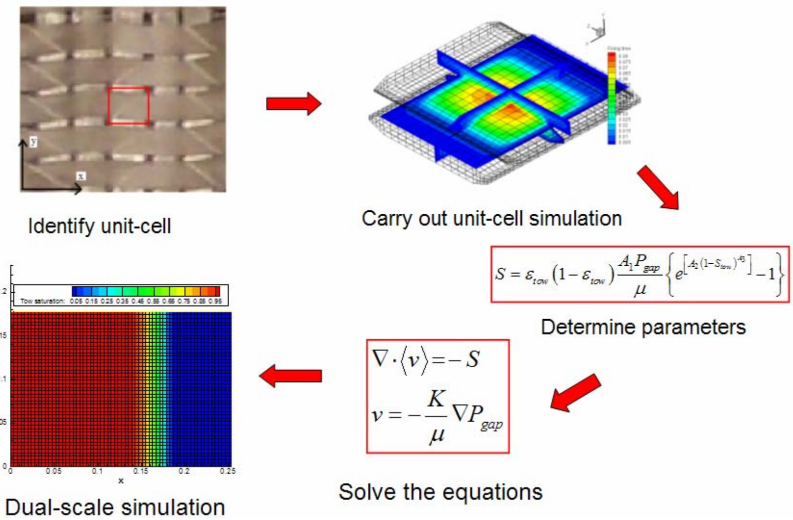

Figure 1: the lumped algorithm of modeling dual-scale flow in LCM

To validate the lumped algorithm for modeling dual-scale flow, we compare the numerical predictions to experimental measurements. We had earlier carried out a constant injection-rate flow experiment with a stack of ten layers of a bi-axially stitched fiber-mat in the 1-D flow mold. The experimentally recorded inlet-pressure history was compared with the numerical predictions using both the proposed dual-scale computational model and the conventional single-scale analytical model as shown in Figure 2 (a) and (b). It is very encouraging to note that the dual-scale model yields a pressure history that compares favorably with the experiments, while the conventional single-scale modeling fails in its predictions. An overhead snapshot of the transparent mold showing the impregnation of the bi-axial fiber mat after 24 seconds of the x-direction flow entering the fiber mats is shown in Figure 3(a): a partially saturated region behind the flow front can be clearly identified from the presence of the lighter shaded fiber-mat immediately behind the front. A prediction of unsaturated region using our dual-scale simulation at the same flow-time is shown in Figure 3(b). It is clear that, in this comparison of the tow saturation distributions, a fair match between the experimental observation and the dual-scale simulation prediction can be seen in Figure 3.

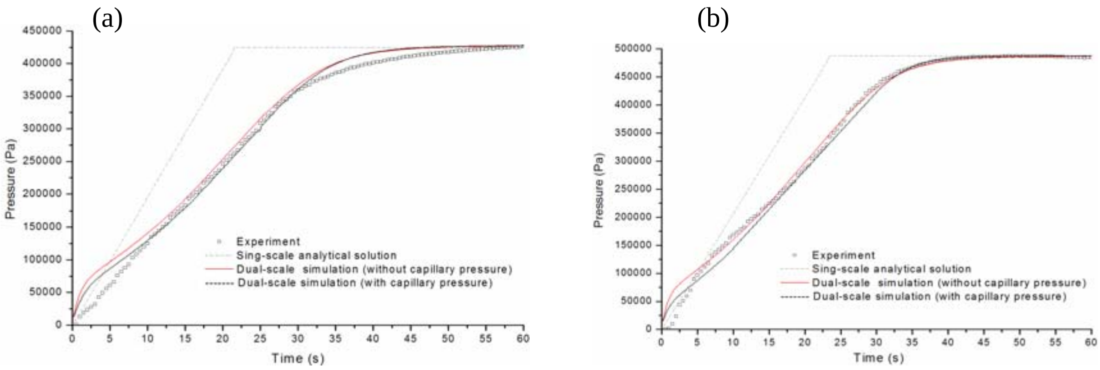

Figure 2: Comparison of the experimental inlet-pressure history with the numerical predictions: (a) the x-direction flow; (b) the y-direction flow.

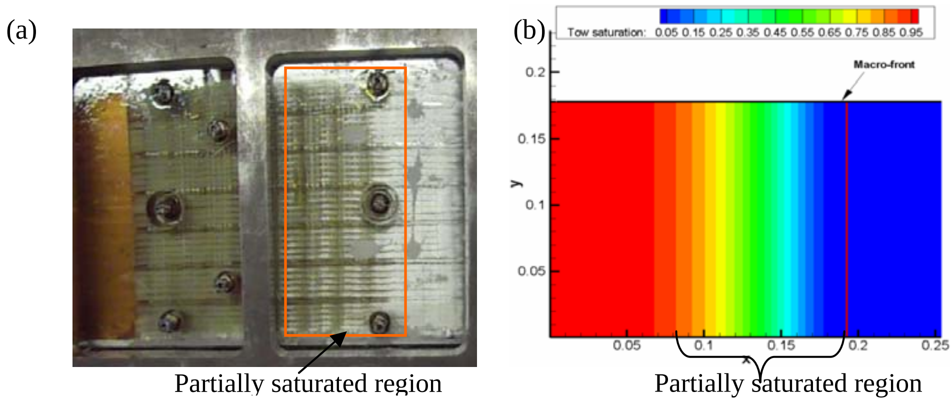

Figure 3: Snap shots of the tow-saturation distributions at t = 24s during the 1-D flow experiment: (a) from the experiment; (b) from the dual-scale mold-filling simulation.

MULTISCALE APPROACH

It is very difficult to extend the lumped method to non-isothermal conditions, because it's not possible to formulate the unit-cell based sink-functions for the mass, energy and species equations during the reactive, non-isothermal flow due to the nonlinear dependence of sink functions on multiple flow quantities including pressure, saturation, temperature, and cure. Instead of using one computational domain in the lumped algorithm, we develop a multiscale approach to simulate unsaturated flow through dual-scale fiber mats, in which a coarse global mesh is used to solve the global flow over the entire domain and a fine local mesh in form of a typical unit-cell is employed to solve the tow-impregnation flow inside the local tows so as to provide sink terms required for solving the global flow. In this way, one does not need to formulate a lumped equation to characterize the tow impregnation; hence the method can be easily extended to non-isothermal case. The relation between the global FE model and the unit-cell based FE models is illustrated in Figure 4. The multiscale approach, presented elsewhere in detail [5], has been implemented in our in-house code PORE-FLOW©, a simulation tool for the mold-filling type flows.

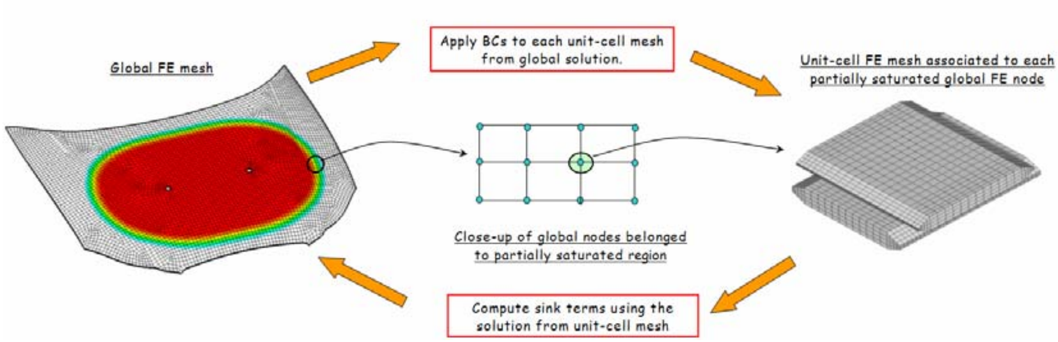

Figure 4: Relation between the global and local unit-cell FE models.

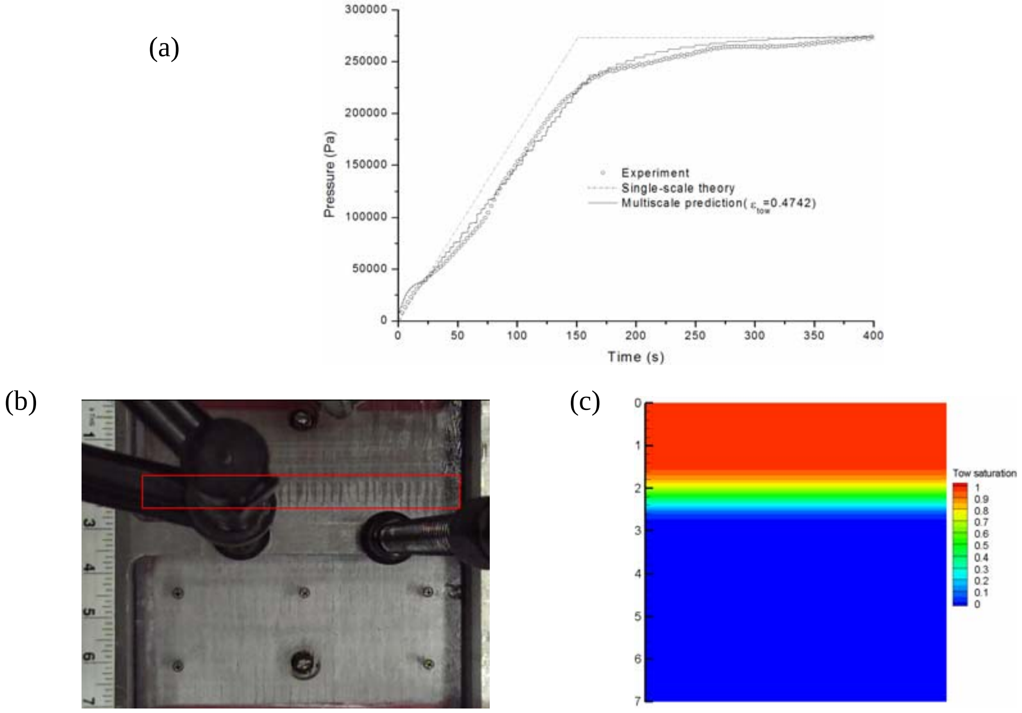

Figure 5: (a) Comparison of the experimental inlet-pressure history with the numerical predictions; (b) tow-saturation distribution from the experiment at 67s; (c) tow-saturation distribution from the multiscale prediction at 67s.

To validate the multiscale method for modeling the dual-scale unsaturated flow, we carried out the 1-D flow experiment with a stack of 6 layers of the bi-axial stitched fiber-mats. Figure 5(a) compares the experimentally recorded inlet-pressure history with the numerical predictions using both the dual-scale computational model and the conventional single-scale analytical model. It is encouraging to note that the multiscale model yields a pressure history that compares *very favorably* with the one observed in experiments. Overhead snapshot of the transparent mold showing the saturation of the bi-axial fabrics at 67s during the 1-D flow is shown in Figure 5(b): a partially saturated region behind the flow front can be clearly identified from the presence of the lighter shaded fiber-mat immediately behind the front. The unsaturated region predicted by PORE-FLOW© using the multiscale method at 67s is shown in Figure 5(c). It is clear that a fair match between the unsaturated regions seen in the experiment and predicted by the multiscale simulation can be seen in Figure 5(b) and 5(c).

We apply the multiscale approach to 1-D non-isothermal reactive flow. A similar example has been studied by Pillai and Jadhav using two-layer model [6]. The results of simulation are presented using the dimensionless variables. The gap temperature and average tow temperatures at $t=2t_{ch}$ are plotted in Figure 6. It is clear that there is significant difference between the gap and tow regions, which provides a strong justification for multiscale simulation. The two-layer model has very limited application for modeling non-isothermal dual-scale flow in LCM due to its over-simplification of architecture of dual-scale fabrics, whereas the multiscale approach can easily cope with the complex fabric architecture with the help of unit-cell model.

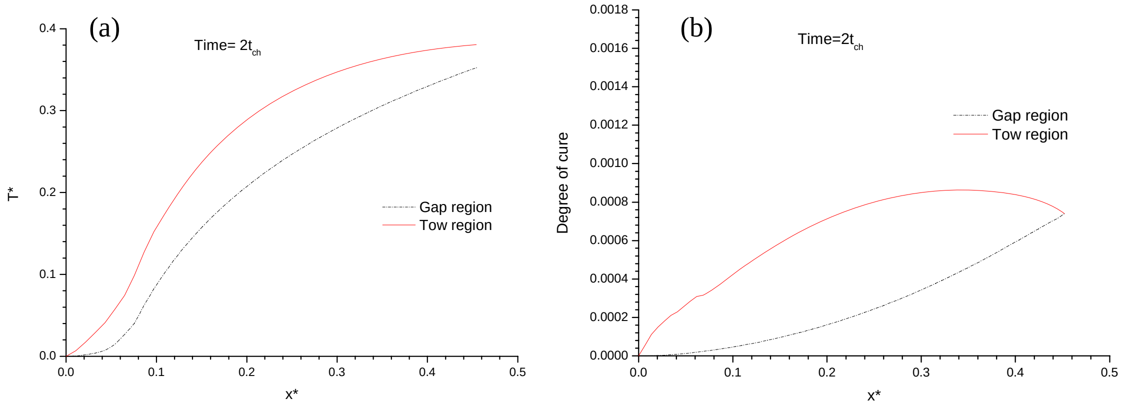

Figure 6: At time=$2t_{ch}$ (a) temperature; (b) degree of cure.

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