Studies on unsaturated flow in dual-scale fiber fabrics

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Abstract. Fiber fabrics in liquid composite molding (LCM) can be recognized as a dual-scale structure. As sink theory developed, this unsaturated flow behavior has already been simulated successfully; however, most of simulated results based on a unit cell under ideal status, thus making results were not agreement with experiment. In this study, an experimental method to establish sink function was proposed. After compared the simulation results by this sink function, it shows high accuracy with the experimental data. Subsequently, the key influencing factors for unsaturated flow have been further investigated; results show that the filling time for unsaturated flow was much longer than saturated flow. In addition, the injection pressure and permeability were the key factors lead to unsaturated flow.

1. Introduction
Liquid composite molding (LCM) is a competitive manufacturing technology with high quality and low cost. The fundamental principle of LCM is as follows: First, place the fiber reinforcement material, such as glass fiber or carbon fiber fabrics, into the cavity, inject the precatalytic resin with the liquid state and then wait for the cure. Finally, the product will be obtained after knockout. And the flow characteristic of a resin in fiber fabrics is the essential factor that affects product quality.

Fiber fabrics in LCM is often woven or stitched by glass fiber or carbon fiber fabrics, the gap between fiber tows is at the millimeter level, and the gap inside the fiber tow is at the micron level. This geometric structure is recognized as dual-scale porous media. Once resin is impregnated into the fiber preform, unsaturated flow would be generated because of different impregnation rates[1, 2]. Figure 1 shows the typical unsaturated flow pattern within the dual-scale fiber preformation. The figure shows that Area A is a completely saturated region, which fiber fabrics are fully impregnated. Area B is a partially saturated region; in this region, the fiber tow is not completely impregnated by the resin. Last, Area C is an unsaturated region that waiting for impregnation. And the saturated flow front is at the interface of area A and B, whereas the unsaturated flow front is between area B and C. The partially saturated region means the length between saturated flow front and unsaturated flow front.
To explain this phenomenon, scholars used the “sink model” to explain the unsaturated flow behavior in porous fiber perform [3, 4]. This theory divides unsaturated flow into micro intra-tow flow and macro inter-tow flow among fiber fabrics, as shown in Figure 1. The proposed sink function was used to represent delay impregnation in the unsaturated region [5, 6]. This sink function is integrated into the equation of continuity to obtain the control equation of macro flow. With the development of computing technology in recent years, sink theory has been the focus of considerable attention and is increasingly accepted by many scholars.

From Sink theory, the following expression can be expressed as follows:

\[ \nabla \cdot \left( - \frac{K}{\mu} \nabla p \right) = -S \quad (1) \]

where \( K \) is the permeability tensor, \( \nabla p \) is the pressure gradient, \( \mu \) is the liquid viscosity, and \( S \) is the sink function. \( S \) represents the rate of unit volume change when resin impregnates the fiber tow and is can be expressed as follows:

\[ \nabla \cdot \left( \frac{K}{\mu} \nabla p \right) = \varepsilon_{\text{gap}}(1 - \varepsilon_{\text{tow}}) \frac{dS_{\text{sat}}}{dt} \quad (2) \]

where \( \varepsilon_{\text{gap}} \) is the porosity between fiber tows (excluding porosity inside the fiber tow), \( \varepsilon_{\text{tow}} \) is the porosity inside the fiber tow, \( S_{\text{sat}} \) is the saturation inside fiber tow. When \( S_{\text{sat}} = 0 \), the gap of intra-tow is empty; when \( 0 < S_{\text{sat}} < 1 \), intra-tow gap is partially filled; when \( S_{\text{sat}} = 1 \), intra-tow gap is filled fully. At this moment, \( S = 0 \) and the fiber preform is saturated completely. \( \frac{dS_{\text{sat}}}{dt} \) is the saturated rate inside the fiber tow, and can be recorded as \( \dot{S}_{\text{sat}} \). In recent years, most scholars have done the numerical calculation for unit cell which used to determine sink function \( S \), thus enabling the simulation of the unsaturated flow in dual-scale fiber preform [8]. However, they ignored the otherness during actually production environment, such as fiber fabrics would deform under injection pressure and the complicated ply sequences for fiber perform. Unit cell simulation can easily obtain the sink function, but has high requirements on the accuracy of the unit cell. Moreover, the simulation result often deviates from experimental result to a certain extent. Therefore, further experimental research on sink function is important to improve simulation accuracy, optimize mold design, and reasonably determine molding pressure, mold filling time, and injection port.

2. Experimental Materials and methods

2.1. Experimental setup

In this study, a visualization experimental device was developed. Figure 2 shows a simple schematic of the above process. This experimental facility can realize constant flow or constant pressure injection, which can be used in measurement for different parameters. To assure that the flow is along the 1D dimension, a buffer between the injection port and the fiber performs was utilized to protect the liquid flowing along the one dimensional direction. The mold was made of alloy aluminum. The mold cavity was designed with thickness of 4 mm, a width of 90 mm, and a length of 1,000 mm. A rubber seal ring and vacuum sealant were used to seal the edge of the cavity. The whole experiment was recorded using a digital camera; and experimental data was gathered by sensor which connected to a computer.
In this study, low-viscosity vegetable oil was used as mold filling liquid. Two different glass fiber fabrics were chosen as fiber preform. Sample 1 and 2 were triaxially stitched for 0°, ±45°; sample 3 was unidirectionally woven. These fiber fabrics were cut into 9 cm × 60 cm strips and layered in the mold cavity with certain ply. The experimental temperature and humidity were set 20 °C and 60%.

According to our previous studies, the inter-tow gap was impregnated quickly at early stage, and the intra-tow gap could be neglected due to relatively impregnation slow rate; this characteristic was attributed to distinctly different permeability through dual-scale fiber fabrics [9]. Base on this characteristic, the permeability between fiber tows \( k_{\text{gap}} \) could be tested by 1D constant flow experiment during this stage. In the same way, the porosity between fiber tows \( \varepsilon_{\text{gap}} \) (excluding porosity inside the fiber tow) and the porosity inside the fiber tow \( \varepsilon_{\text{tow}} \) could also be tested. During this experimental, a piston constant flow pump (purchased from Shanghai Hooyo Instrument and Equipment Corporation) and a constant air compressor (Jaguar ZB-0.10) were utilized to achieve constant injection. And the related experimental parameters are listed in Table 1.

| Sample | Material                  | Ply | Injection pressure (kPa) | Porosity | Viscosity (Pa·s) |
|--------|---------------------------|-----|--------------------------|----------|-----------------|
| 1      | Triaxially stitched       | 5   | 70                       | 0.51     | 0.059           |
| 2      | Triaxially stitched       | 5   | 100                      | 0.51     | 0.059           |
| 3      | Unidirectional woven      | 4   | 70                       | 0.5      | 0.059           |

2.2. Test method of sink function

From formula (2), the sink function \( S \) is a function related to the intra-tow saturated rate \( S_{\text{in}} \). The specific form of \( S \) can be obtained as long as the relational expression is determined. Therefore, we implemented dimensionless treatment of \( S_{\text{in}} \) by taking the characteristic time as the filling time \( t_{\text{in}} \). Then, the dimensionless form of intra-tow saturated rate can be expressed as follows:

\[
\frac{dS_{\text{in}}}{dr} = \left( \frac{dS_{\text{in}}}{dr} \right)_{t_{\text{in}}}
\]

(3)

In order to obtain the expression of saturated rate, an experiment under one-dimensional constant pressure was established. During this experiment, a constant air compressor was connected to a closed tank with mold filling liquid, and the output port of tank was connected to a flowmeter (made by NU.E.R.T. Company). Five pressure sensors were set from the injection port along the length of mold. This can be viewed in Figure 2.
Base on the characteristic of previous studies [9], the macro inter-tow gap was impregnated quickly at first; it was considered that there was only intra-tow flowing during this time. Hence, the time usage of fill time in micro intra-tow gap was \( t_{in} = t_2 - t_1 \) s. And the pressure at this point was recorded as the initial intra-tow pressure \( P_0 \). From Darcy’s law, a linear relationship was observed between pressure and the reciprocal of time by using constant pressure injection; otherwise, viscosity was proportional to filling time. Therefore, the relationship between \( t_{in} \) and \( P_0 \) could be expressed as follows:

\[
t_{in} = \frac{a \mu}{P_0}
\]

(4)

Where \( a \) is the impregnated coefficient and it can be fitted base on experimental data. By using the same method as above, the relationship for \( \frac{dS_{\text{inw}}}{d\tau} \) and \( S_{\text{inw}} \) could be expressed as follows:

\[
\frac{dS_{\text{inw}}}{d\tau} = b + cS_{\text{inw}} + dS^{2}_{\text{inw}} + eS^{3}_{\text{inw}}
\]

(5)

Integrating Equation (4) and (5) into Equation (3), the specific expression of the sink function can be expressed as follows:

\[
S = \varepsilon_{\text{inw}}(1 - \varepsilon_{\text{exp}}) \frac{P_0}{a \mu} \{ b + cS_{\text{inw}} + dS^{2}_{\text{inw}} + eS^{3}_{\text{inw}} \}
\]

(6)

where \( \varepsilon_{\text{inw}} \) and \( \varepsilon_{\text{exp}} \) are the intra-tow and inter-tow porosities, \( P_0 \) is the intra-tow initial pressure, \( S_{\text{inw}} \) is the saturation; and \( a, b, c, d, e \) are constant coefficients, which can be obtained through fitting the experimental data, as shown in Table 2.

Table 2. Coefficients of the sink function

| Sample | Injection pressure (kPa) | \( a \)  | \( b \)  | \( c \)  | \( d \)  | \( e \)  |
|--------|------------------------|--------|--------|--------|--------|--------|
| 1      | 70                     | 4,125,640 | 3.54   | -10.25 | 16.85  | -10.11 |
| 2      | 100                    | 4,358,640 | 4.45   | -11.38 | 17.33  | -10.40 |
| 3      | 70                     | 7,647,570 | 10.58  | -7.26  | 10.73  | -14.05 |

3. Simulation analyses

3.1. Comparison of unsaturated flow

The specific expression of the sink function used to solve control equation has been acquired previously. And the comparative analysis for this sink function was implemented by self-developed finite element solving programs. The commercial software ANSYS was used for preprocessing; a model was established according to the actual size of the mold cavity for the purpose of meshing and determining boundary conditions. Sample 1 was selected to verify accuracy of this calculation model; and the model adopted triangle unit discretion and included 540 discrete units and 310 nodes. Flow velocity was defined on the left node of the model, and the other side of mold was determined as the exit. The calculated results were inputted into the visual software Tecplot for post-processing. The pressure distribution along the flow front position under sample 1 is shown in Figure 3.

The dotted line represented the simulated results of ideal saturated flow; and the accompanying curve represented the simulated results of unsaturated flow. Each curve represented the pressure distribution when flow front reached test points 1 to 5. Figure 3 shows that the pressure distribution curves of unsaturated flow deviated from the left of ideal results. Firstly, this shows an obviously unsaturated flow behavior during the filling process. Due to the unsaturated flow characteristics, the unsaturated flow front was farther away from the saturated flow front; that means the resistance for fluid was smaller than ideal saturated flow, thus made the constant pressure gradient deviated towards the left side.
Figure 3. Pressure distribution when the saturated flow front reaches points 1 to 5.

The unsaturated region, unsaturated flow front for simulation and experiment are shown in figure 4, it shows that the unsaturated flow front would arrive at the end of mould more quickly than experiment. Because the model in this study both ignore the surface tension between fibers and the effects of capillary pressure, thus extend the unsaturated flowing during simulation. When \( t = 4 \) s, the value of relative error was bigger than any other time spot, and it reached at a highest value for 29.2%. During the first stage of filling process, the inlet pressure couldn’t increase to the set value in transient and it delayed for a few seconds; therefore, the results would slightly less than simulated value, which was shown in Figure 9. With the filling process continued, this difference would offset gradually. When \( t = 66 \) s and \( t = 100 \) s, the simulation results were all below 10%. It shows this sink function has high accuracy with experimental data.

Position of flow front

Flow front position of sample 1 when \( t = 66 \) s

Unsaturated region

Simulated results for sample 1 when \( t = 4.3 \) s

Flow front position of sample 1 when \( t = 120 \) s

Figure 4. Unsaturated flow front for simulation and experiment at different time spot.

3.2. Two-dimensional flow simulation

Sink function \( S \) represents the rate of unit volume change when resin impregnates fiber tow. It’s an independent variation which has no relationship with dimensions. This sink function could also be applied in two-dimensional flow. Base on this sink function, a finite element module was established
to investigate the influence factors for two-dimensional unsaturated flow. We have selected 1,000 kPa as the injected condition and the relative parameters, such as porosity, viscosity and etc, could be obtained from sample 1.

Figure 5 were the flow front both for unsaturated flow and saturated flow during same conditions. Scale of $f_{ai}$ is the filling factor, which represents the degree of impregnation. When $t = 4.5$ s, unsaturated flow front was shorter than saturated flow. Compared to simulated results, we found the filling time for saturated flow was just 7.7 s. The time usage for unsaturated flow front arrived at the edge of plane was 23 s, and the fully injected time for saturation flow was 31.5 s. The filling time for unsaturated flow during dual-scale fiber preform was much longer than saturated flow.

![Saturated flow and Unsaturated flow](image)

**Figure 5.** Flow front for unsaturated flow and saturated flow at same point.

Figure 6 shows the distribution for pressure and saturation when filling time was at 4.5 s. The ordinate represents pressure, and abscissa represents saturation. The color of scale means the impregnation degree for fiber bundle. The red color means fully impregnation, while the blue color means none impregnation. From Figure 6 we could observe an unsaturated region below the flow front significantly. During the process of simulation, we assumed the permeability value of x direction was equal to y direction, which caused pressure to distribute uniform against the injection point. Finally, the unsaturated region shows a circular ring in view.

![Distribution for pressure and saturation at 4.5 s](image)

**Figure 6.** Distribution for pressure and saturation at 4.5 s.

Increasing the injected pressure to tenfold level, we can get the results as follows. Figure 7(a) shows the flow front arrived at 40 cm under 1,000 kPa, the time usage was 14.9 s. Figure 7(b) shows the flow front arrived at 40 cm under 10,000 kPa, the time usage was 1.5 s. Firstly, the shape of unsaturated region for Figure 7(a) and 7(b) were almost same; as the injected pressure increased tenfold, the fill time decreased tenfold. The decrement of filling time has a fixed relation with the increasing amount of injected pressure. When pressure increased tenfold, the time usage for flow front arrived at the edge of plane was 4.5 s, it decreased for about 5 folds. Because the edge of the plane was considered as a closed surface; when flow front arrived at this area, it would stop flowing and the flow rate was changed to zero. The FEM program needed more time step to verify the convergence, which caused the filling process become slower relatively.
4. Conclusions
From the experiment and analysis, this study established the specific expression of sink function and derives the following conclusions:

(1) The flow front position during mold filling was consistent with experimental result, which could be used to predict the mold filling process accurately. Establishing the sink function based on experiment would be helpful for designing products, controlling product quality and raising economic benefits.

(2) The simulated flow during early stage was different from the experimental result because pressure increased slowly in first few seconds of the filling process. As mold filling continued, the simulated data agree well with experiment results. The pressure distribution curves against position for unsaturated flow all deviated left from saturated results.

(3) The filling time for unsaturated flow in two-dimensional constant pressure injection was much longer than saturated flow.

Acknowledgments
This work was supported by the National Science Foundation of P.R. China, Grant No. 51073125.

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