Simulation and experimental study of resin flow in fibre fabrics

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Abstract. Liquid Composite Moulding (LCM) is gradually becoming the most competitive manufacturing technology for producing large composite parts with complex geometry with high quality and low cost. These parts include those for airplanes, wind turbine blades and automobile components. Fibre fabrics in liquid composite moulding can be considered as dual-scale porous media. In different gap scales, an unsaturated flow is produced during the mould filling process. This particular flow behaviour deviates from the traditional Darcy’s law, which is used to calculate the filling pressure and will cause errors. According to sink theory, the unsaturated flow characteristics of this dual-scale porous media were studied in this paper, and a FEM solution program was developed. The results showed that the pressure curves against the position which simulated by sink functions were departure from the position of traditional theory. In addition, the simulation results of partially-saturated region were consistent with the experimental data.

1. Introduction
Fiber fabrics in LCM is often woven or stitched by fibre tow. The gap between fiber tows is at the millimeter level, and the gap inside the fiber tow is at the micron level. Once resin is impregnated into the dual-scale fiber preform, the gap between the fiber tow was impregnated fast at first, and the gap inside the fiber tow was impregnated subsequently. The unsaturated flow would be generated due to the different impregnation rates, thus making existing theory misestimate mold filling pressure and fail to predict mold filling time accurately [1-3].

Several scholars proposed the "sink model" to analyze the unsaturated flow behavior of resin in dual-scale porous fibre preform [4, 5]. This hypothesis would lead to inaccuracy results. For example, the overestimate inlet pressure induced excess in stiffness design of mould, thus increased cost significantly. Failure to simulate the partially-saturated region would ignore the impregnated time inside the fiber tows, so as to underestimate the filling time which cause quality problem of product.

Recently, more and more scholars recognize that the unsaturated flow and its effect on simulated results. Dai Fuhong, Lu Shouzhou and Du Shanyi have established flow control equations that include sink function, and get the distribution of partial saturation by solving the equation. Zhang Yuhua, Chen Xiaojiang and Yan Shilin using Matlab to do study of the pressure curves against the position and the flow front, but its algorithm has some defect and lack of experimental verification [6, 7]. Base on sink theory, the unsaturated flow characteristics of this dual-scale porous media were studied in this
paper, and a FEM solution program was developed by our team. In addition, the simulation results of partially-saturated region would be validated.

2. Basic Theory

2.1. Sink Model

To simulate the resin flow behavior, the traditional theory considered the gap between and inside the fibre tows as uniform distribution, when the resin impregnated the preform, the gap would be filled simultaneously. While the sink model considered the different gap between and inside the fibre tows as two independent systems. The resin would impregnate the preform with different rate [8-10]. The volume change rate of resin in fibre tow is not zero and the intra-tow gap is not filled completely. From the mass conservation equation, the following expression can be derived:

\[ \nabla \cdot V = S_g \]  

(1)

Where \( V \) is the average velocity and \( S_g \) is the sink function. Combined with the Darcy’s law, the control equation of unsaturated flow in fibre fabrics can be derived as follow:

\[ \nabla \cdot (\frac{K}{\mu} \nabla P) = S_g \]  

(2)

Where \( \nabla P \) is the pressure gradient, \( \mu \) is the liquid viscosity, \( K \) is the permeability tensor, \( S_g \) is the function of saturation.

2.2. Unsaturated Flow Representation

Due to the characteristics of dual-scale fibre fabrics, the region when resin impregnated was partially saturated, shown in fig. 1(a). The width of partially-saturated region \( L_{ps} \) represented the distance for saturated flow front and unsaturated flow front. As the fill process continued, partially-saturated region moved along, this phenomenon can be reviewed during experiment.

![Figure 1](image_url)

**Figure 1.** (a) Unsaturated characteristics of resin flow. (b) Distribution of filling factor. (c) Distribution of tow-saturation.
In order to simulate the unsaturated flow, we have to get the flow process during the preform and intra-tow gap. Base on the control volume finite element method (FEM/CV), filling factor \( f \) and saturation \( s \) is represented the different behavior separately. The control volume is a unit that around the mesh node in FEM. It’s a quadrangle which connects by the centroid and each midpoint of the unit. For example, the quadrangles that divide by dash line during in fig. 1 are control volume units. For each control volume unit, it can use filling factor \( f \) to represent the filling degree. The relation of filling factor and flow front is shown in fig. 1(b). And the saturation \( s \) represents the filling degree at intra-tow gap during partially-saturated region, which is shown in fig. 1(c).

3. Simulation Case

Base on FEM/CV, a solution program was developed by using FORTRAN in order to simulate the unsaturated flow.

In this case, we have study on unsaturated flow at constant injection. The fibre preform is rectangle, which was 90-mm width and 570-mm length. By using triangle unit to discrete, we could get the FEM mesh shown in fig. 2. Where the node number was 204, unit number was 330. The viscosity of resin was 0.059 Pa s, and the permeability of fibre fabrics was \( 7.85 \times 10^{-10} \) m², the porosity between fibre tow was 0.3872 and the porosity inside fibre tow was 0.1. The left side was inlet boundary, using line injection. And the flow rate was \( 1.6 \times 10^{-2} \) m/s. The right side was out boundary.

**Figure 2.** Discrete finite element mesh.  
**Figure 3.** Pressure distribution of different time.

The nonlinear distribution of pressure was indirect exposition of the partially-saturated region. The impregnated degree could be calculated by the saturation of sink model. And the variations of partially-saturated region could get by calculating the saturation of each steady sub step during simulated process. Fig. 4 was the distribution of partially-saturated region when flow front arrived at different locations. For convenient observing, distinct gray scale was represented the difference of saturation. The saturation value between 0 and 1 was represented partially-saturated. From fig. 4 we could find the partially-saturated region moved along the flow front during constant injection. At the first stage, the width of partially-saturated region increased gradually, until the rate of saturated flow and unsaturated flow became sameness. At the second stage, the width of partially-saturated region kept stable and moved along the flow front. At the final stage, the flow front arrived at the end of preform, and the width of partially-saturated region decreased gradually until disappeared.
4. Experimental Research

In order to study further on unsaturated flow characteristics of this dual-scale porous media, an experimental device of constant flow rate was established. This system mainly consisted of a mould, constant flow pump, pressure sensor, data and acquisition terminal. The cavity was designed with 4-mm thickness, 90-mm width and 1000-mm length. It used 7075-T651 aluminium alloy with excellent performance for the mould. To enable observation of the flow process, the upper mould had a 1000 mm × 150 mm × 10 mm transparent organic glass (PMMA) attached to the aluminium alloy frame. The fibre fabrics are both triaxially stitched, and the viscosity of resin was 0.059Pa s. The inlet point was at left side of mould, the flow rate of resin was $1.6 \times 10^{-2}$m/s, at the right side of mould there was an exhaust port, shown at fig. 5.

The inlet injection was a point, so it hard to achieve the line injection during simulation. The edge effect would lead to the shape of flow front become arc, but after the flow front there was still a uniform arc-shaped partially-saturated region, shown at fig. 6. In order to investigate the variation of partially-saturated region, the distance between arcs was considered as width of partially-saturated region.

Figure 4. Simulation result of variation tendency of the partially-saturated region. 

Figure 5. Device of constant injection rate experiment.

Figure 6. Experimental result of variation tendency of the partially-saturated region.
During the filling process, the variation of partially-saturated region against time could be observed, as shown in fig. 6. Fibre tows between the partially-saturated region still showed white color, and the gap inside fibre tows were fully impregnated. The partially-saturated region could get by this feature. The distance between two arcs in fig. 6 represented the width of partially-saturated region. At the early stage of filling process, the width of partially-saturated region increased gradually, and then kept stable. When the flow front arrived at the end of preform, it decreased gradually. These variations were in full accord with simulation results.

5. Conclusion
Aiming at the characteristics of this dual-scale porous media, a method of introducing saturation was developed on response of unsaturated flow during LCM. A FEM solution program was compiled by our team. The results showed that the pressure curves against the position of the saturated region which far from the flow front varying linearly. Before the flow front, pressure curves for partially-saturated region were deviated from linear trend which predicted by traditional theory. According to the simulation results, the partially-saturated region were increased at first and then remained stable. At the end of filling process, it decreased gradually. These results were consistent with the experimental data. It explains the program has good reliability and can provide good references for optimizing the process parameters or controlling the product quality.

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