ANALYSIS OF THE UNSATURATED FLOW IN A DOUBLE SCALE POROUSITY PREFORM DURING LIQUID COMPOSITE PROCESS

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Abstract

We present an experimental investigation of unsaturated flow behavior during the liquid composite molding process. To investigate the unsaturated flow behavior and the influence of void generation, we measured transient liquid pressure at different positions in the mold during the unsaturated flow. Test liquid was injected under a constant flow rate at the liquid inlet to generate the same quantity of void at the flow front. We conducted pressure measurement with the same preform for different inlet flow rates and obtained different pressure profiles which were either linear or non-linear depending on the flow rate. Based on the experimental data, unsaturated and saturated permeability values were obtained for different flow rates. Finally, we suggest a model for the ratio of unsaturated permeability to saturated permeability in terms of void content, liquid properties and preform microstructure.

1. Introduction

Liquid composite molding (LCM) is a process which uses low viscosity resin(less than about 500cps) to be injected into the mold of which the preform is inside. LCM process is employed to large complex composite products such as air craft structure and wind turbine blades in cost effective way. During the LCM process, resin is impregnated into fibrous porous media made of glass, carbon, natural fibers, and so on. To enhance the productivity of the process and quality of the product, it is crucial to understand the behavior of the porous media flow during the impregnation.

In general, Darcy's law (equation (1)) has been used widely to analysis the porous media flow due to its effectiveness [1].

$$u_D = \frac{Q}{A} = -\frac{K}{\mu}\nabla P \qquad (1)$$

The volume average resin velocity is represented as u_D and Q is flow rate, A is the cross section of the flow path, K is the permeability of the porous media, μ is the resin viscosity, and P is the resin pressure. Darcy's law provided a general analysis of the flow inside the porous media but it left some controversies related to permeability. There are two experimental methods which are widely used for measuring the permeability of the certain porous media. One is the method for unsaturated method which can be measured by monitoring the flow front advancement with time in the transient flow. The other method is for saturated permeability which can be determined by measuring the pressure difference between inlet and outlet with the flow rate of the steady flow in a fully saturated flow. Since the permeability is a unique property of the porous media, it is determined by the microstructure of the porous media. Therefore the permeability of the porous media which appeared in the Darcy's law should have the identical value if the structure of the porous media remains unchanged. It has been reported, however, the permeability of the identical porous media may have the different value between the unsaturated and saturated flow [2, 3]. The explanation which is widely accepted by literatures is that the air void formed during the resin flow affects the flow behavior to bring about the difference between the unsaturated and saturated flow [4].

There are various structures of the preforms which are used for LCM process. Preforms such as random short fiber mat and glass fiber wool are homogeneous porous media while woven and bundled unidirectional glass fiber mats are heterogeneous. Heterogeneous microstructure of porous media can be characterized as double scale porosity which results in a non-uniform flow front during injection. The double scale porosity preform can be distinguished to two regions: dense area such as tow bundle area which has smaller scale, and area between the dense areas such as channel area between the bundles. When resin is injected and the flow front is developed by the resin, lead lag occurs between the tow and channel area due to the non-uniform flow front which induced by the velocity difference between the two areas. By this mechanism, air voids are formed in tow and channel areas depending on the flow conditions. Theses air voids may act as blockage of the flow and affect the global porous media flow [5, 6].

In this study, the pressure of the one-dimensional unsaturated flow of the double scale porous media is monitored continuously along the flow during the injection to observe the pressure profile depending on flow rate. Void content of each flow rate is measured to relate the effect of the air voids. Finally, modeling of the pressure gradient is suggested and compared with the experimental results to investigate the unsaturated flow behavior of the double scale porous media flow.

2. Experiment

2.1. Material

Two types of fluids are used in the experiments. Engine oil (Kixx PAO, GS Caltex) which has the viscosity of 0.2 Pa•s was used for pressure measurement because of easiness of handling. Epoxy resin (KFR130, hardener KFH140, Kukdo chemical) was used for composite manufacturing for void content measurement.

Unidirectional glass fiber mat was used as double scale porous media. Each tow bundle of the glass fiber mat is consisted of about 1000 single glass fiber filaments which has diameter of 16.5μm.

The dimension of the mold used for both pressure measurement and void content measurement was identical. The size of the mold was 500 x 55 x 3 mm. The upper mold for pressure measurement was made of 25 mm thick tempered glass in order to observe the flow during the flow. Other parts of the mold and composite manufacturing mold for void content measurement were made of SUS403 stainless steel.

2.2. Experimental setup

2.2.1 Pressure gradient measurement

The UD glass fiber mat was placed in the mold with the volume fraction of about 40%. The direction of the glass fibers was perpendicular with the flow direction. Engine oil was injected with the flow rates of 50, 100, 200, and 400 mm^3/s. Seven pressure transducers were installed at the bottom of the mold to record the pressure continuously. The distance between the transducers was 60 mm and the first transducer was installed 100 mm from the inlet. The experimental setting is in the figure 1.

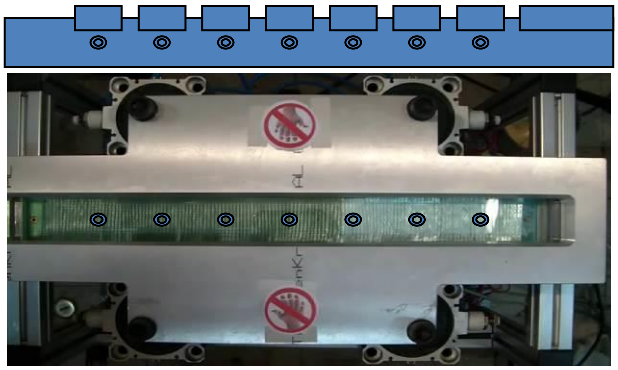

Figure 1. Experimental setup for pressure profile measurement

2.2.2. Void content measurement

Void content of each flow rate case was investigated with the composite specimen made with epoxy resin. The flow condition of the void content experiment was identical with the pressure measurement experiment. It is ideal to observe the void content inside the flow to consider the effect of the void on flow behavior. It is difficult, however, to measure the void during the impregnation. Therefore, the void content of each flow rate was measured after saturation. Composite specimens were prepared for 50, 100, 200, and 400 mm^3/s flow rate cases and different locations of the composite plate were examined. The voids in the cross sections of the composite plates were measured by image analysis. Mechanical properties such as flexural strength and inter laminar strength were conducted to be compared with the void content result.

3. Result

3.1. Pressure profiles of unsaturated flow

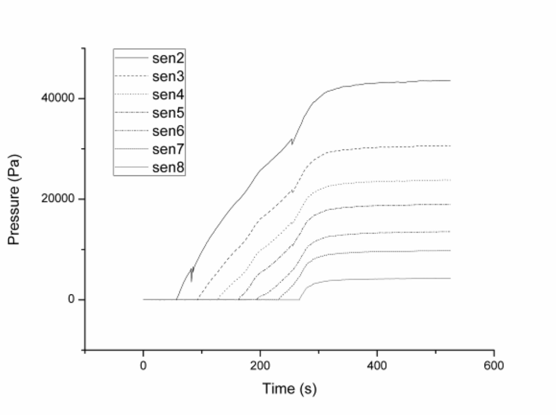

Figure 2. Raw data of the pressure profile measurement

Data of the pressure change of each transducer are shown in figure 2. When the flow front reaches the first pressure transducer, the pressure starts to rise until flow reaches outlet. Other transducers act the same way as the first transducer to display the pressure change. In figure 3, pressure change of each transducer's position depending on time is shown.

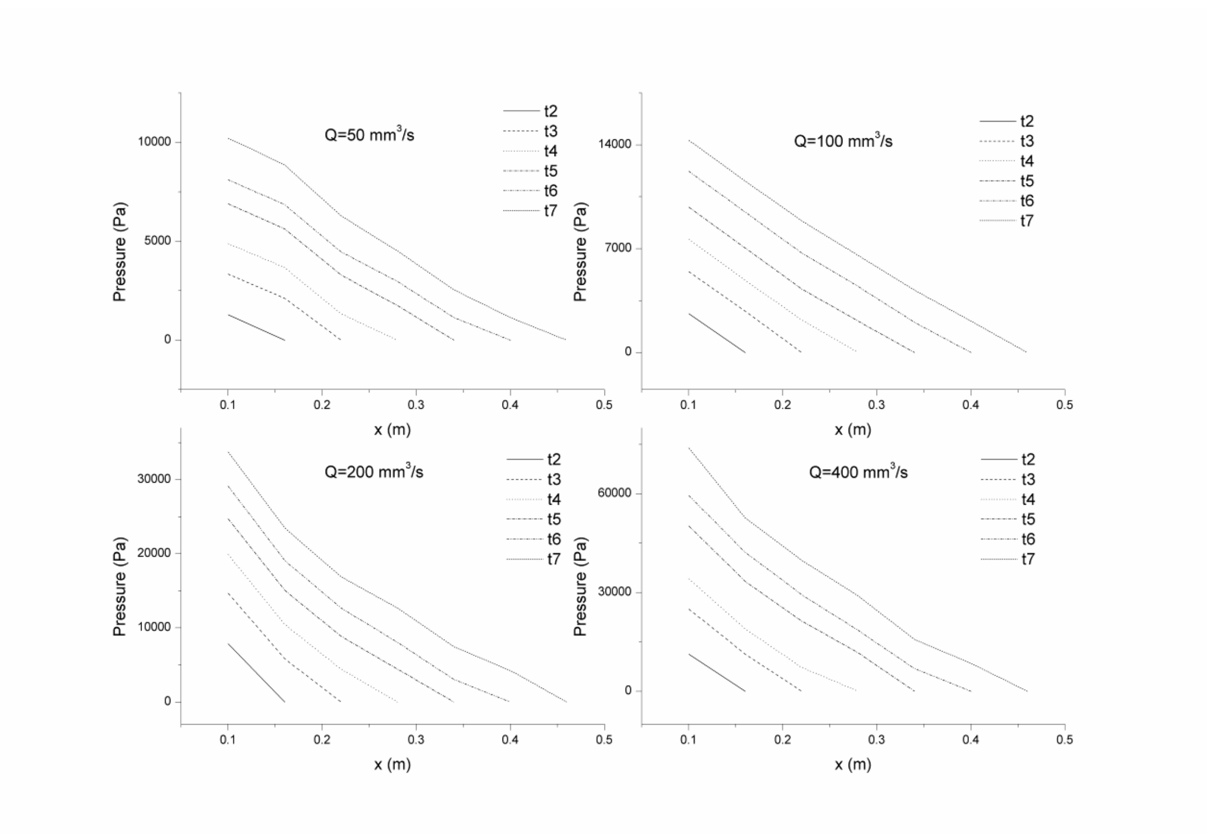

Figure 3. Pressure profiles of each flow rate depending on distance from the inlet

To observe the pressure gradient along the flow, it is necessary to observe the pressure depending on distance from the inlet. In figure 3, pressure data of the time when flow front reaches the transducers is collected to show the pressure profile depending on distance from the inlet for every flow rate cases. Among the four cases, pressure profile of 100mm^3/s shows high linearity while others are not. It can be seen that pressure gradient is steeper near the inlet of the 400 and 200 mm^3/s cases while the gradient near the inlet of 50 mm^3/s case is rather gentle and getting steeper near the outlet. Observing the results by time wise for each flow rate case, it can be found that the pressure gradient of 100 mm^3/s case remains still regardless of time while the pressure gradient changes to become gentler in the case of 200 and 400 mm^3/s. If the porous media used in this experiment is homogeneous, the pressure gradient will be linear regardless of location and time regardless of flow rate. Except the 100 mm^3/s case which has linear pressure gradient, other results can be considered to be affected by voids formed in flow front. Therefore it is necessary to observe the void content of each flow rate.

3.2. Void content measurement

The void content measurement was conducted to find the effect of void on pressure profile. In figure 4, the void content result and inter-laminar shear and flexural strength are shown for each flow rate.

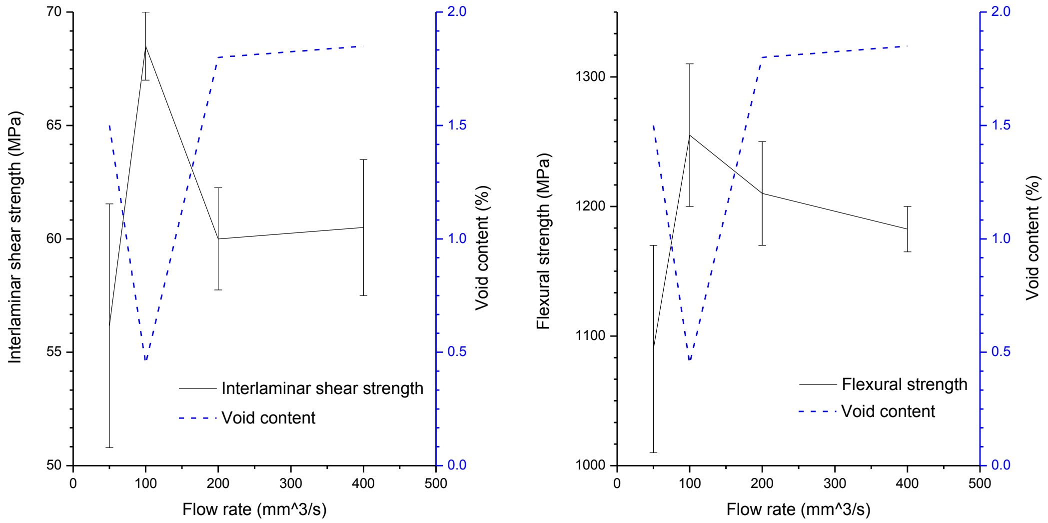

Figure 4. Void content and inter-laminar and flexural strength of the composite plate made by LCM process for each flow rate

As we can see in figure 4, the void content of the 100mm^3/s is under 0.5%, so the effect of the void will be smaller than other flow rate cases. This result is well matching with the pressure profile measurement result of which the pressure gradient of the 100mm^3/s shows high linearity. In 50, 200, and 400 mm^3/s cases, void contents are significantly higher than that of 100mm^3/s case, thus the influence of the voids on the pressure profile need to be considered.

4. Modeling and Discussion

The formation of the voids can be categorized to two ways. In case of high flow velocity such as flow in the beginning of the constant pressure flow, the flow velocity of the channel area is faster than that of tow area so that tow void is formed by outrun of the channel area. When the velocity of the flow is slow such as the flow when the flow front is near the outlet of constant pressure case, the velocity of the tow area is faster than channel area due to the capillary effect, so channel voids are formed by outrun in the tow area [7, 8, 9]. Therefore, the 50

mm^3/s case can be regarded as low velocity flow so that most of the voids inside are channel voids, while 200 and 400 mm^3/s cases are high velocity flows which has tow voids, and 100 mm^3/s case has similar velocities in tow and channel area so there are few voids inside.

Pressure measurement results from the 100 mm^3/s case are measured with few voids, so the permeability calculated from the pressure profile of the 100 mm^3/s case by Darcy's law can be regarded as permeability which are not affected by the voids viz. the property of the structure of porous media only. In other cases, however, the permeability is not same and it changes by the time in the same flow rate nevertheless, the porous media which was used was identical.

To explain the nonlinear profiles of the high flow cases such as 200 and 400 mm^3/s, tow voids needs to be considered. After the tow voids are formed in the flow front by the outrun in the channel area, the global flow keep flowing through the mold and new tow voids are continuously formed in the flow front at every moment. Therefore, it can be considered that there are voids in the tow along the flow from the inlet to the flow front. Once the tow voids are formed, it begins to shrink due to the pressure gradient along the radius of the tow and capillary pressure driven flow. This can be analyzed by combining the continuous equation and Darcy's law.

$$-\frac{\partial u}{\partial x} = -\frac{\partial}{\partial x}\left(-\frac{K}{\mu}\frac{\partial P}{\partial x}\right) = q_T \quad (2)$$

The continuous equation with the sink term q_T for 1-dimension can be written as equation (2). The velocity of the global flow is u which can be expressed with permeability, viscosity, and pressure gradient. The permeability calculated from the experimental result in pressure profile of 100mm^3/s case is used for the equation, because the permeability is least affected by the voids.

The sink term q_T can be rewritten as equation (3).

$$q_T = V_T u_T \frac{p_a}{A_T} = V_T\left(\frac{K_T}{\mu}\frac{P_{cap,T}}{r_{ave}}\right)\frac{p_a}{A_T} \quad (3)$$

Where,

$$A_T = a_T b_T\,,\;\; p_a = a_T \phi_{T,a}\,,\;\; r_{ave} = \frac{b_T}{2}\left(1-\phi_{T,a}\right) \quad (4)$$

In equations (4), P_a is the perimeter of the void which can be simplified with horizontal length of the bundle, a_T and void content, Φ_T, a, regarding the model is based on 1-dimensional flow and void content is constant along the x axis.

Appling the void content measured from the experiment, pressure profile of the tow void cases such as 200 and 400 mm^3/s can be suggested. The comparison between the experiment and modeling is shown in figure 5.

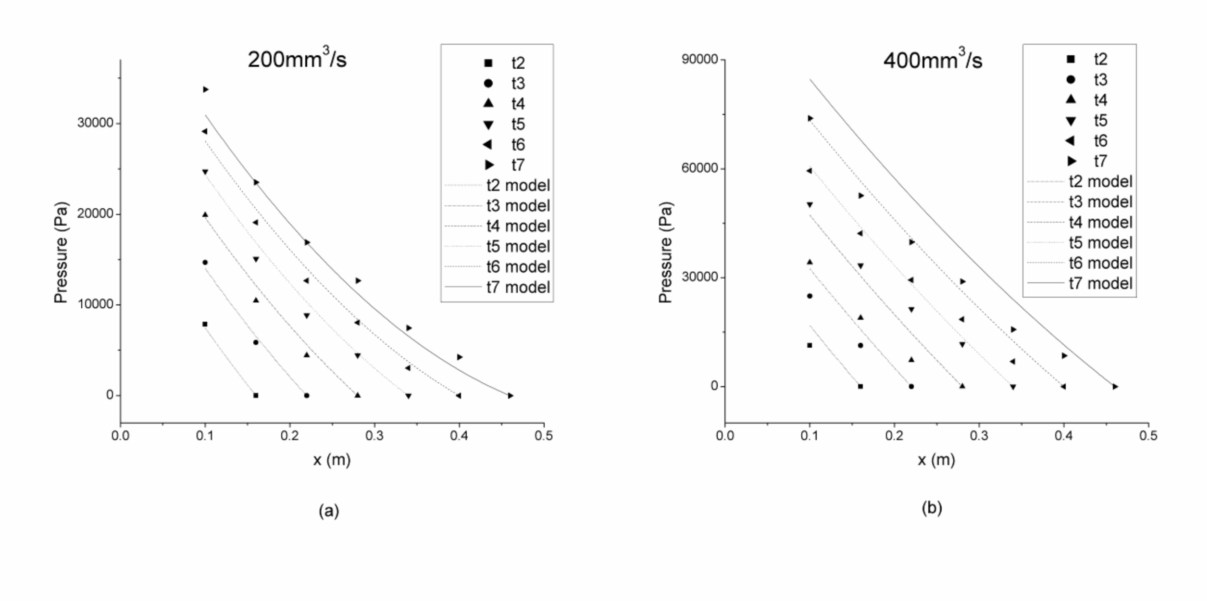

Figure 5. The comparison between experimental results and model of 200 and 400 mm3/s cases

In figure 5, it can be seen that the experimental results and modeling matches well. In the beginning of the injection, there are less non-linearity because the effect of the sink term is small. As the flow advances, the sink effect along the flow affects to the global flow to lose its total amount into the tow. The amount of the flow absorbed into the tow by sink effect accumulates from inlet to the outlet so that the non-linearity of the pressure profile appears at the flow front. When we compare the results of 200 and 400 mm^3/s cases, tendency of the results are identical but the result of $400mm^3/s$ is not well matching as $200mm^3/s$ result. This might be explained by the void migration. The void formed in the tow during the flow can be migrated by the flow so that the void content of the saturated flow can be different compared to the unsaturated flow. It can be considered that due to its velocity, the void of the $400mm^3/s$ case is migrated by the flow so that the non-linearity of the pressure profile decreases. To earn the result which better matches with the model, the voids content of the unsaturated flow needs to be measured.

5. Conclusion

In this study, pressure profiles of unsaturated flow in LCM process depending on flow rates were investigated. The linearity of the pressure profile varied with the flow rate, and the formation of the voids was considered to explain the phenomenon. During the flow, voids were formed inside the flow and the global flow behavior was affected by the voids. In order to find the influence of the void on flow behavior, the void content of the saturated flow for each flow rate was measured. The case of the 100 mm^3/s case had the smallest void content so that it can be regarded that the velocity of the tow area and channel area is similar. Higher flow rates such as 200 and 400 mm^3/s have higher velocity of channel area than that of tow area which results in tow void. The voids in the tow act as sinks in the flow. Assuming that the voids are distributed in the flow constantly, the sink effect of the void leads to the non-linear pressure profile of the 200 and 400 mm^3/s cases. The modeling of the 200 and 400 mm^3/s cases were suggested and compared with the experiment result. The result of modeling for 200 mm^3/s case well matched with the experimental result, while modeling of the 400 mm^3/s case was under estimated. It seems that the void content of the unsaturated flow needs to be provided to evaluate the model for high flow rates.

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