Modeling and simulation of voids and saturation in liquid composite molding processes

Chung Hae Park\textsuperscript{a,\ast}, Aurélie Lebel\textsuperscript{a}, Abdelghani Souab\textsuperscript{a}, Joël Bréard\textsuperscript{a}, Woo Il Lee\textsuperscript{b}

\textsuperscript{a} Laboratoire d’Ondes et Milieux Complexes, FRE 3102 CNRS, University of Le Havre, 53 rue de Prony, BP 540, 76600 Le Havre, France
\textsuperscript{b} School of Mechanical and Aerospace Engineering, Seoul National University, Shinlim-dong, Kwanak-gu, 151-742 Seoul, Republic of Korea

\textbf{A R T I C L E   I N F O}

Article history:
Received 29 March 2010
Received in revised form 28 January 2011
Accepted 6 February 2011
Available online 5 March 2011

Keywords:
A. Polymer-matrix composites (PMCs)
B. Defects
C. Numerical analysis
E. Liquid composite molding (LCM)

\textbf{A B S T R A C T}

We propose modeling and simulation of the void formation and the tow saturation in liquid composite molding processes. The present model addresses the void formations in the macropore between fiber tows as well as in the micropore inside fiber tows. We also consider the bubble compression and tow saturation after voids are formed at the flow front. Finally, a void migration model is considered. The present models are validated by a comparison between simulation results and experimental data. The simulation results successfully represent important features of the void physics: the correlation of void formation at the flow front with capillary number, the advantage of vacuum application at air vents to reduce the void content inside tows, and the existence of partially saturated zone behind the global flow front. The representation of mold filling patterns by a degree of saturation shows the presence of a bubbly zone behind the flow front.

\section{1. Introduction}

Liquid composite molding (LCM) processes, such as the resin transfer molding (RTM) process and the vacuum assisted resin transfer molding (VARTM) process, are widely employed to fabricate large and complex parts in the aeronautic industry. Void type defects created during the manufacturing, however, have been important issues in this class of processing technologies, since they degenerate mechanical performances such as interlaminar shear strength, flexural strength and compressive strength \cite{33–44}. According to American aeronautics standard, final products with more than 2\% of void defects should be rejected. Hence, it is of great significance to analyze void generation physics and to optimize process conditions in order to improve the product quality.

There are many sources to create void type defects in composite manufacturing. However, the principal mechanism depends on the process type. Whereas the nucleation and the growth of void during cure are the main sources in the autoclave technique, the mechanical air entrapment is the main reason for the void creation in LCM processes \cite{2–5}. It has been known that a non-uniform flow is induced by a heterogeneous micro-structure of fiber preform and air is entrapped at the flow front during the mold filling process. Nowadays, textile reinforcements with high count fiber tows are frequently adopted as fiber preforms in the RTM process in order to improve the mechanical properties of composites. In the micro-structure of these textile fabrics, we can find two kinds of pores with remarkably different pore sizes: micropore (inside tow) which is a tiny space between individual fiber filaments, and macropore which is an open gap between tows (Fig. 1). In general, these fiber reinforcements with high count fiber tows are regarded as double scale porous media with a bi-modal distribution of pore size \cite{6}. In the macropore, viscous flow is dominant while capillary wicking is more important in the micropore since capillary pressure is inversely proportional to the pore size. Hence, it is assumed that the void formation mechanism in the RTM process is a competition between the viscous flow in the macropore and the capillary wicking in the micropore. It has been found, from experimental investigations, that the void formation at the flow front can be correlated with a dimensionless number called modified capillary number (\(Ca’\)) which is a ratio of viscous force and surface tension (e.g. Fig. 2a) \cite{6–9}.

\begin{equation}
Ca’ = \frac{\mu \cdot \dot{u}}{\gamma \cdot \cos \theta}
\end{equation}

where \(\mu\) is the resin viscosity, \(\dot{u}\) is the global resin velocity, \(\gamma\) is the surface tension of resin and \(\theta\) is the contact angle.

If the resin velocity is great (i.e. high capillary number), the resin flow in the macropore leads that in the micropore. As a result, air is entrapped in the micropore (Fig. 2c). On the contrary, air bubble is created in the macropore, if the resin velocity is small (i.e. low capillary number) and the capillary wicking inside the tow leads the viscous resin flow through the macropore (Fig. 2b). Images of these two different types of voids are shown in

\* Corresponding author.
E-mail address: chung-hae.park@univ-lehavre.fr (C.H. Park).
Fig. 2d–e. If the resin is injected under a constant pressure, voids are formed inside tows at the flow front near the injection ports where the flow front advancing velocity is great. On the other hand, voids are created between tows at the flow front far from the injection ports where the resin velocity is small.

Once air bubbles are created at the flow front, their size and position change with time. As the resin pressure surrounding an air bubble increases, the air bubble is compressed. If the tow is not completed filled, the resin continues to impregnate the tow even after the flow front passes by. Furthermore, some bubbles can migrate along the resin flow. It should be noted that experimental investigations on the relation between void formation and capillary number have been performed by in situ visualization techniques [6–9]. Hence, a real distribution of void content in the final part may be different from a simple correlation of void content with capillary number. To better predict void content, subsequently, we should take into account all these physics: void formation, bubble compression, tow saturation and void transport (Fig. 3).

So far, many studies have been focusing on the modeling of micro-voids inside tows [10–17,45]. Even if voids are formed also in the macropore between fiber tows in practical processes, however, a very limited number of papers have addressed the modeling of voids in the macropore between fiber tows [18–20]. Moreover, few papers have been found in the literature on the modeling and simulation of void transport.

We present an integrated modeling on the formation, the compression and the transport of air voids. In particular, the void formation is modeled considering different tow orientations in directional mats. The current models will be validated by a comparison with the experimental result by a sensor system presented in Ref. [1]. A finite element method (FEM) code for mold filling simulations was developed based on the current models and we show some simulation results to investigate the influence of processing conditions. Mold filling patterns will be represented in terms of degree of saturation as well as fill factor. By contour plots of degree of saturation, we will show the existence of a partially saturated zone behind the global flow front, considering the voids in the macropore as well as in the micropore. As a parametric study, void content will be estimated for different air vent pressures under the same pressure differential which is a difference between injection.
pressure and air vent pressure. We will show that the void content is affected not only by the resin velocity as expected from the correlation with capillary number but also by the vacuum pressure at air vents.

2. Void modeling

2.1. Definition of fabric micro-structure

In the present work, we consider plain weave mats composed of warp and weft tows. However, the current configuration can be applied also to unidirectional mats or non-orthogonal fabrics by changing the properties of warp and weft tows.

Above all, the micro-structure of fabrics is assumed to be composed of a same unit cell in a repetitive way. In the unit cell, tow lengths are defined as illustrated in Fig. 4. In Fig. 4, the subscripts “wp” and “wt” represent warp and weft tows, respectively. For each tow (warp and weft), the longitudinal (//) and the transverse (⊥) lengths are defined in the unit cell of fabrics, assuming that all the fiber filaments in the tow are aligned in the parallel direction, i.e. the longitudinal direction.

Then, we define volumes of each tow (Fig. 5). \( v_{wp} \) and \( v_{wt} \) denote warp volume ratio and weft volume ratio in the unit cell, respectively. The tow volume consists of the volume of fiber filaments and the micropore between individual fibers. The macropore which is an open gap between tows is called “channel” as it forms a flow channel during the mold filling process. Then, we obtain the expressions of volume ratios of tows (warp and weft) and channel in the unit cell.

\[
 v_{wp} = \frac{\text{volume of warp}}{\text{volume of warp} + \text{weft} + \text{channel}} \quad (2)
\]

\[
 v_{wt} = \frac{\text{volume of weft}}{\text{volume of warp} + \text{weft} + \text{channel}} \quad (3)
\]

\[
 v_c = \frac{\text{volume of channel}}{\text{volume of warp} + \text{weft} + \text{channel}} = 1 - v_{wp} - v_{wt} \quad (4)
\]

The subscript “C” represents the channel whereas “wp” and “wt” denote the warp and weft tows, respectively.

The global fiber volume fraction of fabric \( \left( V_f \right) \) can be estimated from the fiber volume fractions of warp and weft tows \( \left( V_{f,wp} \text{ and } V_{f,wt} \right) \).

\[
 V_f = V_{f,wp} \cdot v_{wp} + V_{f,wt} \cdot v_{wt} \quad (5)
\]

The thicknesses of warp and weft tows in a single mat can be obtained from the micro-structure of the fabric in the mold. If the dimensions of warp and weft tows are the same, each tow thickness can be obtained as the following relations.

\[
 H_{wp} = \frac{H_{mold}}{N_f} \cdot \frac{v_{wp}}{v_{wp} + v_{wt}} \quad (6)
\]

\[
 H_{wt} = \frac{H_{mold}}{N_f} \cdot \frac{v_{wt}}{v_{wp} + v_{wt}} \quad (7)
\]

where \( H_{wp} \) and \( H_{wt} \) are the warp and weft thicknesses, respectively. \( H_{mold} \) is the mold height or the part thickness, and \( N_f \) is the number of fabric layers in the preform.

It should be noted that all the parameters of fabric micro-structure are defined in the preform contained in the mold.

2.2. Void formation

As stated previously, the main source of void formation at the flow front is a non-uniform flow caused by a competition between the viscous flow in the macropore and the capillary suction in the micropore. Kang et al. proposed a void formation model considering two different flows in the macropore and the micropore [18]. In their approach, both the voids in the micropore and in the macropore were successfully modeled and the modeling result showed a good agreement in a qualitative way with an experimental correlation of void content with capillary number. However, some parameters should be decided by a curve fit of experimental results and the tow orientation was not considered. We improve this approach by considering the micro-architecture of fabrics.

Assuming that the global resin pressure gradient is identical both in the macropore (inter-bundle gap) and in the micropore (intra-bundle porous zone), time scales for the resin to traverse a single tow length are computed between tows and through a tow at the flow front, respectively (Fig. 6). In the macropore, the resin flow is a viscous flow. In this zone, the resin velocity is obtained using Darcy’s law with the unsaturated permeability of preform.

\[
 u_m = \frac{d l_c}{d t} = -\frac{K_{ unst}}{\mu} \frac{\partial P}{\partial n} \quad (8)
\]

In the micropore, capillary pressure should be considered to compute the resin advancing velocity through the tow (see the red solid line in Fig. 6a). Indeed, the resin pressure gradient in the micropore may be different from that in the macropore, because of the capillary pressure. However, the resin penetration distance inside the tow is so small compared with the global flow path and the time for the resin to travel by a single tow length is short. Hence, it is assumed that the resin pressure gradient in the micropore is identical with that in the macropore and kept unchanged while air is entrapped at the flow front.

\[
 u_m = \frac{d l_c}{d t} = -\frac{1}{V_{f,T}} \frac{K_{ unst}}{\mu} \left( \frac{\partial P}{\partial n} \frac{p_{ vac}}{l_f(t)} \right) \quad (9)
\]

where the subscript “T” represents “wp” for the warp tow or “wt” for the weft tow. \( l_c(t) \) and \( l_f(t) \) are the resin flow front positions with
time in the channel (macropore) and inside the tow (micropore), respectively. \( V_{fC} \) is the fiber volume fraction of tow, \( K_T \) is the permeability of tow and \( P_{\text{cap}} \) is the capillary pressure. Tow is regarded as a unidirectional composite. The tow permeabilities in the longitudinal and the transverse directions are obtained by Gebart’s model [21]. The fiber array in the tow is assumed to be a hexagonal array.

Capillary pressure in the unidirectional composites is obtained as the following relation [22].

\[
P_{\text{cap}} = \left( \frac{F}{D_f} \right) \frac{V_{fT}}{1 - V_{fT}} \cdot \cos \theta
\]  

where \( D_f \) is the fiber diameter and \( F \) is the shape factor (two for the transverse direction and four for the longitudinal direction).

Then, we compute time scales for the resin to travel by a single tow length in these two directions.

\[
I_C = \int_0^{\Delta t_C} u_M \, dt : \text{in the channel (macropore)}
\]  

\[
I_T = \int_0^{\Delta t_T} u_M \, dt : \text{inside the tow (micropore)}
\]

If the time scale inside tows (\( \Delta t_C \)) is greater than the time scale in the channel between tows (\( \Delta t_C \)), an air bubble is created in the micropore (Fig. 6b), and vice versa (Fig. 6c). If voids are formed inside the tow, the volume of unfilled portion of the tow is supposed to be proportional to the difference of these two time scales [18]. If the global resin flow direction does not coincide with the tow direction, the pressure gradient is decomposed into the longitudinal and transverse directions of tow. Then, the unfilled portion is obtained by a product of ratios of time scale differences in the longitudinal and transverse directions. The schematics of the flow angle and the unfilled portion in warp tows are depicted in Fig. 7.

For the convenience, the warp orientation is assumed to be identical with \( x \) axis (Fig. 7a). If the time scale inside warp tows is greater than in the channel zone (\( \Delta t_{Cwp} > \Delta t_{Cwp} \)), for example, the unfilled portion in warp tows is obtained as (Fig. 7b):

\[
\Delta t_{Cwp} = \min[\Delta t_{Cwp}, \Delta t_{Twp}]
\]  

\[
\Delta t_{Cwp} = \min[\Delta t_{Cwp}, \Delta t_{Twp}]
\]

Fig. 6. Schematic of resin impregnation in the macropore and the micropore. (a) Two different flows in the macro-pore and the micro-pore. (b) Air entrapped inside tow (\( \Delta t_C > \Delta t_C \); void in the micropore). (c) Air entrapped between tows (\( \Delta t_C < \Delta t_C \); void in the macropore). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Schematic of resin impregnation when the flow direction and the tow direction are not identical. (a) Angle between global resin flow and tow orientation. (b) Schematic of resin impregnation in tow and in channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
For example, we need about $10^6$ elements for the computations, since the tow size is so small and very tiny elements are reshaped to need heavy computations with a huge number of elements. Meanwhile, the increase of air pressure yields a flow resistance to reduced and the air pressure is increased if the air mass is conserved. As the pore size is so tiny inside the tow, the air volume entrapped inside the tow is reduced into the tow. As the resin is infiltrated into the tow, the air volume fraction in the channel region at each instant can be updated as a function of resin pressure.

Applying the ideal gas law assuming the resin temperature is constant, the air volume fraction in the channel region at each instant can be updated as a function of resin pressure.

$$V_{ac}(t + \Delta t, x, y) = \frac{P(t, x, y)}{P(t + \Delta t, x, y)} \cdot V_{ac}(t, x, y) \quad (20)$$

The air bubbles inside tows are compressed as the resin is permeated into the tow. As the pore size is so tiny inside the tow, the capillary pressure induced by the surface tension effect has a significant influence on the resin flow at the liquid–air interface. Consequently, the resin flow inside the tow is driven by the overall effect of the resin pressure, the air pressure inside the air bubble and the capillary pressure at the flow front. As the resin is infiltrated into the tow, the air volume entrapped inside the tow is reduced and the air pressure is increased if the air mass is conserved. Meanwhile, the increase of air pressure yields a flow resistance to the tow saturation accordingly.

In fact, numerical simulation of resin flow in the complex shaped tow need heavy computations with a huge number of elements, since the tow size is so small and very tiny elements are required [23]. For example, we need about $10^6$ elements for the simulation of a unit cell with dimensions of 1 cm × 1 cm × 1 cm if we adopt a mesh size of 100 μm. Instead, the tow geometry is simplified as a rectangular plate or a cylinder where analytical solution or fast calculation can be found, in most practical modeling approaches [10–17,45]. The cross section of an actual fiber tow is close to an ellipsoid with large upper and bottom surfaces. Hence, it is assumed that the resin flow into tows in the thickness direction is more important than in the planar directions, once the tow is surrounded by the resin and the air is entrapped inside the tow [15].

At each instant, transverse flow into the tow is estimated by Darcy’s law using a pressure difference between the resin outside the tow and the air inside the tow.

$$q_i = \frac{K_i}{\mu} \frac{P_{resin} - P_{air} + P_{cap}}{H_i - h_{air}} \quad i = wp, wt \quad (21)$$

where $H_i$ is the half height of the tow contained in the mold and $h_{air}$ is the average half height of air bubble inside the tow. Capillary pressure at the air–liquid interface is obtained by Eq. (10).

Then, at each instant, the unfilled portion is updated as

$$\phi_{T_i}(t + \Delta t) = \phi_{T_i}(t) - \frac{1}{(1 - V_{air})} \cdot \frac{2 \cdot q_i \cdot A_e \cdot \Delta t}{(l_{l_i} \cdot l_{l_i} \cdot H_i)} \quad i = wp, wt \quad (22)$$

where $A_e$ is the effective area of wetting zone inside the tow.

This scheme is illustrated in Fig. 9. $h_{air}$ and $A_e$ are approximated as a function of unfilled portion.

$$h_{air} = H_i \cdot \phi_{T_i} \quad i = wp, wt \quad (23)$$

$$A_e = l_{l_i} \cdot l_{l_i} \cdot \phi_{T_i} \quad i = wp, wt \quad (24)$$

The change of air pressure at each instant is obtained by the ideal gas law.

$$P_{air}(t + \Delta t) = \frac{\phi_{T_i}(t)}{\phi_{T_i}(t + \Delta t)} \cdot P_{air}(t) \quad i = wp, wt \quad (25)$$

2.4. Void transport

In LCM processes, there are two principal paths for void migration: inside a tow (Fig. 10a) and along a channel which is an open gap between tows (Fig. 10b).
Inside the tow, air bubbles are stationary only decreasing their sizes due to the progressive tow saturation if the air pressure in the air bubbles is smaller than the sum of the resin pressure outside the air bubbles and the capillary pressure. Otherwise, the air bubbles begin to move. It is assumed that the relative velocity of air bubble which is the difference of the bubble velocity and the resin velocity, is close to zero, as the size of pore inside the tow is so small (i.e. the order of micrometer) and the surface tension effect is great. Hence, the air void is supposed to be displaced at the same velocity of the resin flow in the micropore inside the tow. If the pressure gradient in the micropore is the same as that in the macropore, we can obtain the bubble migration velocity in the micropore \( \left( u_{\text{air},r} \right) \) that equals to the resin velocity in the micropore as the following relation.

\[
u_{\text{air},r} = \frac{K_{\text{air}}}{K_{\text{insat}}} u_{\text{resin}} \quad i = x, y
\]  

As air voids continue to be displaced, they will escape, eventually, from the tow and join the air bubbles that already exist in the channel. We can derive a void convection equation from the conservation law.

\[rac{\partial \phi C}{\partial t} + \nabla \cdot \left( \phi C \cdot \mathbf{V} \right) = \dot{S}_0
\]  

where \( \phi C \) is the void migration velocity in the macropore and \( \dot{S}_0 \) is the source term for air volume in the channel zone such as air volume rate added from the tow to the channel. If a thermostet resin is injected, the initial air content in the resin coming from the resin pot and the evaporation of chemical volatile gas can be considered in this source term.

For the migration velocity of air bubbles in the channel zone, we adopt a phenomenological model (Fig. 11) \[24,25\]. From experimental observations, it has been found that there exists a critical resin velocity. Below this value, voids do not move at all or move at a very low speed. Above this value, voids move faster than the resin and the slant of the resin velocity and the void velocity approaches an asymptotic value as the resin velocity increases further.

\[
u_{\text{air},C} = F_u \cdot u_{\text{resin}}
\]  

\[
u_{\text{resin}} = \begin{cases} \frac{A}{2} \left( 1 - \frac{1}{k} \theta_{\text{resin}} - \theta_{\text{resin}} \right), & u_{\text{resin}} \geq u_{\text{crit}} \\ \frac{A}{2} \theta_{\text{resin}} - \theta_{\text{resin}}, & u_{\text{resin}} < u_{\text{crit}} \end{cases}
\]

where \( F_u \) is the void slip factor. \( A \) and \( k \) are model constants which can be obtained by curve fitting of experimental data. Model constants are presented in Table 3.

### 3. Results and discussion

#### 3.1. Rectilinear injection simulation

We integrated the present models into the FEM code for RTM mold filling simulations \[26\].

Simulations of rectilinear mold filling were performed to obtain air void content. As a preform, a bi-directional woven mat was considered. The material properties and the micro-structure parameters are provided in Tables 1 and 2. The injection pressure was maintained as a constant value of 2.7 bar and the air vent pressure was the atmospheric pressure (1 bar). Hence, the pressure differential was 1.7 bar. The air volume fractions inside warp and weft tows and in channel zones between tows were obtained as a function of the distance from the injection gate. Then, the air volume fraction was also plotted against modified capillary number.

Firstly, only the void formation model was considered whereas neither the bubble compression/tow saturation nor the void transport was considered. Simulation results are presented in Fig. 12. At the vicinity of the injection gate, the velocity of flow front progress was great. Hence, the viscous flow between tows was more important than the capillary wicking inside tows. Subsequently, air bubbles were entrapped inside tows. It is noteworthy that the air bubble content in weft tows are greater than in warp tows (Fig. 12a). In fact, the tow permeabilities and the capillary pressures in each tow are different according to the tow orientation. Consequently, this leads to a difference in the resin impregnation.
velocity inside each tow. Far from the injection port, the resin velocity was small and the capillary suction inside tows was more important than the viscous flow. As a result, air bubbles were formed in open gaps between tows. Many experimental results obtained by in situ monitoring of void formation have shown that the void content can be correlated with modified capillary number as shown in Fig. 2a [6–9]. It has been observed that there exists an optimal capillary number that minimizes the void formation. This implies that the void formation can be suppressed by optimizing the resin velocity at the flow front. For many fiber reinforcements used in the RTM process, this optimal capillary number is about of an order of $10^{−3}$ [6]. In Fig. 12b, we can see the presence of optimal capillary number which is of the same order. It should be noted that the minimal void content at the optimal capillary number does not drop to zero. In the case of unidirectional mats (Fig. 2a, [8]), the resin flows between tows and inside tow are synchronized at the optimal capillary number. Eventually, the void formation is virtually suppressed. If there are multiple tows in different orientations in the same fabric (e.g. bi-directional mats), it is no more possible to match all the resin velocities in channel zones and in each tow. Hence, the minimal void content is not suppressed to zero (Fig. 12b). This corresponds to the results with woven mats inRefs. [17,27].

### Table 2

Fabric micro-structure parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp length (longitudinal)</td>
<td>$l_{wp,l}$ = 5.5 mm</td>
</tr>
<tr>
<td>Warp length (transverse)</td>
<td>$l_{wp,t}$ = 4.5 mm</td>
</tr>
<tr>
<td>Weft length (longitudinal)</td>
<td>$l_{wt,l}$ = 5.5 mm</td>
</tr>
<tr>
<td>Weft length (transverse)</td>
<td>$l_{wt,t}$ = 4.5 mm</td>
</tr>
<tr>
<td>Warp height</td>
<td>$2H_{wp}$ = 1.0 mm</td>
</tr>
<tr>
<td>Weft height</td>
<td>$2H_{wt}$ = 1.0 mm</td>
</tr>
<tr>
<td>Warp volume fraction</td>
<td>$V_{wp}$ = 0.453</td>
</tr>
<tr>
<td>Weft volume fraction</td>
<td>$V_{wt}$ = 0.453</td>
</tr>
<tr>
<td>Fiber volume fraction of warp</td>
<td>$V_{fwp}$ = 0.64</td>
</tr>
<tr>
<td>Fiber volume fraction of weft</td>
<td>$V_{fwt}$ = 0.64</td>
</tr>
<tr>
<td>Fiber volume fraction of fabric</td>
<td>$V_f$ = 0.58</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td>$D_f$ = 14 $\mu$m</td>
</tr>
<tr>
<td>Shape factor of bubble inside warp</td>
<td>$h_{V,T,wp}$ = 0.53</td>
</tr>
<tr>
<td>Shape factor of bubble inside weft</td>
<td>$h_{V,T,wt}$ = 0.53</td>
</tr>
<tr>
<td>Shape factor of bubble in the channel</td>
<td>$h_{V,C,wp}$ = $h_{V,C,wt}$ = 0.53</td>
</tr>
</tbody>
</table>

### Table 3

Void migration model constants (Eq. (29)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>12.203</td>
</tr>
<tr>
<td>$k$</td>
<td>18,240</td>
</tr>
<tr>
<td>$u_{crit}$</td>
<td>0.00028 m/s</td>
</tr>
</tbody>
</table>

![Fig. 12. Simulation results of void formation (without bubble compression/tow saturation nor void transport). (a) Void content vs. position. (b) Void content vs. modified capillary number. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image1)

![Fig. 13. Simulation results of void formation and bubble compression/tow saturation (without void transport). (a) Void content vs. position. (b) Void content vs. modified capillary number. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image2)
Then, the void formation and the bubble compression/tow saturation were considered whereas the void transport was not taken into account (Fig. 13). Compared with the results without the bubble compression/tow saturation (Fig. 12), the maximal void contents (voids inside tows near the injection gate and voids between tows far from the injection gate) were greatly reduced. In particular, this reduction was more significant near the injection gate (i.e. air voids inside tows at higher capillary number), since the rise in resin pressure was more significant and the bubble compression/tow saturation was greater.

In real practices, most of voids are concentrated in a region close to the air vent, in the final part [28]. This is a strong evidence of void migration. Moreover, air voids are expanded as the voids are transported into the downstream where the resin pressure surrounding the voids is low. The void migration phenomenon implies that the void distribution in the finished part can be different from the simple correlation of void content with capillary number. Fig. 14 presents simulation results obtained by considering the void transport as well as the void formation and the bubble compression/tow saturation. We can see that the void content near the injection gate has been significantly reduced. This shows that some air voids near the injection gate have been swept away along the resin flow. There still remained some residual air voids inside tows (particularly weft tows) near the injection gate, however, since the void transport velocity inside tows was very low (see Eq. (26)). This corresponds to the experimental observation reported in the literature: it is hard to remove voids entrapped inside tows [6].

We presented another simulation result with a lower air vent pressure but the same pressure differential (Fig. 14b). Under the same pressure difference between the injection gate and the air vent, the resin velocity and the corresponding modified capillary number are identical. If the air vent pressure is reduced by a vacuum application, however, the initial air pressure at the moment of void formation is also low. Hence, this favors the bubble compression and tow saturation. In Fig. 14b, we can see that void content inside tows was greatly decreased with the reduced air vent pressure. This shows an advantage of vacuum application in order to decrease the void content in real processes.

3.2. Comparison with experimental data

To validate the proposed modeling approaches, we compared simulation results with experimental data. We presented simulation results in terms of degree of saturation ($S_w$) which was a ratio...
of liquid volume fraction ($V_l$) to pore volume fraction in the control volume (Fig. 15).

$$S_w = \frac{V_l}{1 - V_l} = \frac{1 - V_f - (V_{AC} + V_{AWP} + V_{AWE})}{1 - V_f}$$

In Fig. 15a, solid lines are the curves of degree of saturation obtained by the experimental technique presented in Ref. [1]. Dashed lines represent the simulation results. The experimental results showed that there still remained residual air voids near the injection gate: about 3% of air volume fraction which correspond to 0.92 of degree of saturation. We can see that the degree of saturation has been significantly increased with a reduced air vent pressure, even if the same pressure differential was employed, in Fig. 15b.

3.3. Simulation of complex geometry

In conventional mold filling simulations, the mold filling pattern is represented in terms of fill factor as defined in the volume of fluid (VOF) method [29]. In this method, a sharp flow front divides an unfilled zone and a filled zone and the variation of fill factor is confined to only a single mesh (element or control volume) distance. In practical mold filling processes, however, there exists a partially saturated zone covering a significant distance behind the flow front. Hence, the degree of saturation is a better representation parameter to interpret mold filling patterns considering void content. We presented mold filling simulation results of a half body of automotive front panel in two different ways (Fig. 16). At same instants, the mold filling pattern was represented in terms of fill factor (left figures), and in terms of degree of saturation (right figures). The mold filling pattern plots represented by degree of saturation showed the presence of partially saturated zone behind the global flow front which could not be shown in the contour plot of fill factor.

Finally, to better show the void convection effect, the total void content which was the sum of air volume fractions inside warp and weft tows and in channel zones, was plotted (Fig. 17). At an early stage of mold filling process (Fig. 17a), voids were formed near the injection port. As the flow front advanced, however, the voids were migrated along the resin flow and most of air voids were concentrated in a narrow zone just behind the flow front, as reported in the literature [28]. It was also observed in the simulation result that the length of this bubbly zone remained almost constant through the mold filling process.

4. Conclusions

We proposed the models on the formation, the compression and the transport of voids in LCM processes. The present models were
integrated in the computer code for mold filling simulations. One-dimensional mold filling simulations were conducted and simulation results successfully represented some important features of the void physics: the correlation of void formations inside tows and between tows with modified capillary number, the influence of vacuum application at the air vent on the tow saturation and bubble compression. The void migration was also modeled to represent a partially saturated zone of high bubble content near the flow front. The simulation result was compared with the experimental data in terms of total sum of voids in the channel and in the tows (warp and weft). The simulation code represents mold filling patterns in terms of not only fill factor but also degree of saturation. The representation of a partially saturated zone suggests need for a bleeding process where residual air voids are swept away, while maintaining an injection pressure high and air vents open, even after the global resin front reaches air vents.

In the current work, we investigated the influence of the global resin flow upon the void formation. However, it has been reported that the existence of voids may alter the global resin flow pattern: injection pressure drooping in the case of constant flow rate injection and non-linear pressure profile in the partially saturated zone [30–32]. In future works, we will address these phenomena by modeling unsaturated permeability in terms of void content and resin volume change caused by air void volume change.

Acknowledgements

This work has been performed in collaboration with SAFRAN/Aircelle under the research program of “RTM Structural”. The authors also would like to acknowledge the financial support from the French Ministry of Economy, Finance and Industry.
References


