Introduction
With the increasing use of composite materials in the aerospace industry, composite parts suppliers show a growing interest about process simulation. Among the industrial processes used in the production phase, resin infusion appears more and more as an economical alternative for manufacturing large parts with an important fiber fraction (wind turbine blade, aircraft wing…). However, the lack of control on the final properties of the part, implying long and expensive process tuning, significantly reduces the above-mentioned advantages. So, a full model coupling fluid/solid/porous mechanics is proposed to simulate the liquid resin infusion (LRI) process, in order to anticipate the potential problems numerically.

Liquid Resin Infusion descriptions
Liquid Resin Infusion (LRI) consists in creating a liquid film of resin on the top of a dry preform stacking thanks to a very permeable material, the distribution medium. Then, the pressure differential between the vent (0 bar) and the injection line (atmospheric pressure) induces the infusion of the resin across the thickness direction (Fig. 1. (a)). Finally, a pressure and temperature cycle is applied to the system to bring the resin into a solid state. The flexibility of the vacuum bag does not allow maintaining a constant thickness during the whole process, while its good control is mandatory to ensure geometrical and mechanical properties of the final part.

The geometry evolution implies change in permeability and may results in post-infusion flows due to the non-zero final pressure gradient inside the piece. Those phenomena need to be integrated into simulation tools in order to anticipate properly the final fiber volume fraction, the final thickness and the infusion time.

Modeling and numerical aspects
Referring to the description of the process, one can note the presence of two different media, the distribution medium and the reinforcements, partially impregnated by a fluid, the resin. Thus, P. Celle proposed to divide the domain into three zones [1] (figure 1 (b)) whose boundaries will evolve over time:

- Stokes zone: fast flow zone constituted of the distribution medium and the resin,
- Darcy zone: incompressible flow of the resin in the preforms submitted to finite deformations,
- Dry preforms zone: zone constituted of non-impregnated preforms submitted to finite strains.

In addition, four time periods corresponding to change in boundary conditions or physical problem can be identified:

- Pre-filling: initial compaction of the preforms due to the vacuuming of the system,
- Filling,
- Post-filling: re-compaction or “rest period” ending by the mechanical equilibrium mandatory to the dimensional quality of the final part,
- Curing (not studied here).
Based on this division, we now strive to present the physical models and numerical methods implemented to simulate this process.

3.1 Initial compression

Initially, there is no resin in the system, only the dry fabrics are considered. When the vacuum is pulled out, the preform is subject to atmospheric pressure (1 bar) and deforms. The stresses and strains thus induced are the source of permeability variations to consider during the filling phase. Neglecting the effects of inertia, we can write the momentum conservation as follows:

\[ \text{div} \, \bar{\sigma}(\bar{u}) = f_v \]  \hspace{1cm} (1)

where \( \bar{\sigma} \) is the Cauchy stress tensor, \( \bar{u} \) is the displacement and \( f_v \) the volume forces. In addition, the porous medium is represented by an equivalent orthotropic homogeneous medium composed of rigid fibers, so that each macroscopic strain is reflected by fiber rearrangements at the microscopic scale. Therefore we can directly compute porosity from solid mechanics strains, with no need to use semi-empirical laws expressing porosity as a function of interstitial pressure, as currently proposed in the literature \([3-4]\). Thus, porosity is updated according to the following equation:

\[ J(\bar{x}, t + \Delta t)(1 - \phi(\bar{x}, t + \Delta t)) = J(\bar{x}, t)(1 - \phi(\bar{x}, t)) \]  \hspace{1cm} (2)

where \( J \) is the Jacobian of the transformation and \( \phi \) is the porosity of the equivalent homogeneous medium.

3.2 Filling simulation

3.2.1 The resin flow: Stokes-Darcy coupling

As described above, the resin flows in the distribution medium and then in the preforms under the action of the vacuum. In the so called Stokes domain, the high permeability of the distribution medium, relatively to the preform permeability, allows us to consider, as a first approximation, an incompressible flow governed by Stokes equations (3),

\[ \text{div} \left( \mu \bar{D}(\bar{v}) \right) - \bar{v} p = 0 \]  \hspace{1cm} (3)

\[ \text{div} \bar{v} = 0 \]

with \( \mu \) is the resin viscosity, \( \bar{v} \) the resin velocity, \( p \) the resin pressure and \( \bar{D}(\bar{v}) = \frac{1}{2} \left( \bar{v} \bar{v} + \bar{v}^T \bar{v} \right) \) the Eulerian strain rate tensor associated with the velocity field. While in Darcy zone, we consider an incompressible Newtonian fluid flowing through a low permeability (down to \( 10^{-15} m^2 \)) porous medium governed by the Darcy law (4),

\[ \bar{v} = -\frac{1}{\mu} \bar{K} \bar{v} p \]  \hspace{1cm} (4)

\[ \text{div} \, \bar{v} = 0 \]

with \( \bar{v} \) the Darcy velocity or the relative average resin velocity with respect to the fabrics, \( \bar{K} \) the permeability tensor and \( p \) the interstitial pressure. The two domains are separated by an interface through which the conservation of mass and the continuity of the normal stress must be respected. Furthermore, we choose to control the tangent velocity on the interface using the Beavers-Joseph-Saffman condition \([2]\). Darcy’s law involving \( \bar{a} = p_D \bar{I} \) the continuity of the normal stress is equivalent to a Dirichlet condition on hydrostatic pressure when using the primal mixed velocity-pressure formulation, leading to the following system of conditions:

\[ \bar{v}_S \cdot \bar{n} = \bar{v}_D \cdot \bar{n} \]  \hspace{1cm} (5)

\[ 2 \bar{n} \cdot \bar{D}(\bar{v}_S) \cdot \bar{t}_i = -\frac{\bar{a}}{\sqrt{\bar{K}}} \bar{v}_S \cdot \bar{t}_i \]

\[ p_D = p_S \]

where \( \bar{n} = \bar{n}_S = -\bar{n}_D \) is the outward normal vector to Stokes/Darcy interface and \( \bar{t}_i \) are the unit tangent vectors to the interface. In practice, normal velocity taken form Darcy domain is prescribed by a penalty method into the Stokes equations, and hydrostatic pressure taken from Stokes domain is imposed into Darcy equations. The Stokes-Darcy coupling algorithm is summarized on figure 2.

From a numerical point of view, even if Darcy equation form allow to solve separately for pressure and velocity fields, in order to be consistent with the Stokes problem due to the coupling, we chose to solve a mixed velocity/pressure formulation with the finite element method stabilized by the mini element
P1+/P1 [3]. The mini element P1+/P1 stand on the enrichment of the velocity field approximation by the introduction of an extra node in the center of the element (figure 2). Since the velocity field degree of interpolation is higher than the pressure one, the Brezzi-Babuska condition is fulfilled avoiding pressure parasite modes [3].

3.2.2 Fluid-solid coupling: principle of Terzaghi

The fluid/structure coupling is treated in a quasi-static approach, by a strong iterative coupling. Indeed, the Stokes/Darcy coupled fluid problem is solved on a fixed grid (i.e. for rigid preforms). The influence of the resin on the fibers is taken into account through the hydrostatic pressure through Terzaghi’s law (6),

\[ \bar{\sigma}_{\text{overall}}(\varepsilon) = \bar{\sigma}_{\text{fib}}(\varepsilon) + p I \]  

(6)

with \( \bar{\sigma}_{\text{overall}}(\varepsilon) \) the overall stress applied to the system, \( \bar{\sigma}_{\text{fib}}(\varepsilon) \) the effective stress in the preforms and \( I \) the unit tensor. The non-linear finite strain problem is then solved for a given pressure field (and therefore for an equivalent Terzaghi’s behavior), the influence of deformations being taken into account through porosity variations which affects the permeability of the medium. The permeability can be computed with any porosity dependent measurement or model. Here, for the example, the Carman-Kozeny’s law (7) can be considered:

\[ \bar{K} = \frac{d_f^2}{16h_k} \zeta^3 (1-\phi)^2 \]  

(7)

with \( d_f \) the average fiber diameter, \( h_k \) Kozeny constants and \( \phi \) the porosity. Finally, the convergence is checked by a calculation of relative error on the fields of pressure, speed and deformation between two iterations. The fluid-solid coupling algorithm is presented on figure 3.

3.3 Flow front tracking

There are several methods for tracking the flow front, such that the level-set method and the FE-CV method. As part of this work, we did not study these methods but have used the filling algorithm already present in PAM-RTM™. This algorithm is based on a division of the transient phenomenon in a series of quasi-static states. Elements newly filled between two time steps are determined from the flow rate calculated at the last known time step. A filling factor varying from 0 to 1 is associated with each element. In the case of flow in deformable porous medium, porosity changes over time. Because the time increment is determined before the calculation, it is necessary to correct it so that the total amount of resin present inside the system corresponds to the volume of saturated pore. The following correction is proposed:

\[ \Delta t = \frac{\Delta t_{\text{algo}}}{v_t} \frac{v_{t+\Delta t}}{v_t} \]  

(8)

where \( \Delta t \) is the corrected time increment, \( \Delta t_{\text{algo}} \) is the time increment given by the filling algorithm, \( V_t \) is the volume of resin that would have been injected in the system during the time step with no deformation and \( V_{t+\Delta t} \) is the actual injected volume of resin during the time step.

3.4 “Post-filling” flows

At the end of the filling, the system is not balanced; the pressure gradient between vent and injection induces flows which are called “post-filling” flows. These flows, little studied in the literature, have a great influence on the final properties of the infused part. Indeed, the final pressure gradient, combined with the flexibility of the vacuum bag, involves inhomogeneous thickness [4] and resin distribution. Therefore, the resin will migrate slowly from the areas with small fiber fraction to the one with small resin fraction until mechanical balance.

The simulation of this phase is driven by the same physical problems that the filling phase and is based on the same kind of coupling. However, successive quasi-static states are more difficult to determine, because the part is completely filled and therefore there is no more a resin front to transport. Thus, we propose to determine the new resin volume fraction (\( \Phi \)) from a mass balance on each finite element, as follows:

\[ \phi_{i+1} = \frac{V_{i+1}^* + \Delta t \sum S_i^* n_i}{V_i^* + \Delta t \sum S_i^* n_i} = \phi_i + \Delta t \sum S_i^* n_i \]  

(6)

where \( V_{i+1}^* \) is the volume of the element at time \( t+\Delta t \), \( S_i^* n_i \) is the flow rate passing through the ith
face of the element at time $t$. Knowing the new resin distribution in the medium, we can deduced the jacobian ($j$) of the transformation at time $t + \Delta t$ from equation (2). The volume variation of the element being a consequence of the variation of resin volume contained by the element, we assume that the associated deformation is a consequence of the intersticial pressure variation. Therefore, the deformation increment is considered hydrostatic.

This hypothesis allows us to compute an equivalent deformation increment ($\Delta \varepsilon_i$) from equation (9) that’s permits to deduce the pressure increment associated with the resin migration inside the part.

$$
\prod (1 + \varepsilon_i + \Delta \varepsilon_i) = J_{t+\Delta t}
$$

(9)

where $\varepsilon_i$ is a current deformation (known). Finally, applying Darcy’s law (4), the new resin velocity can be computed. This procedure is repeated until resin stops to migrate inside the part ($\vec{v} \approx \vec{0}$).

4 Experimental validation and industrial application

4.1 Experimental validation: infusion of a plate

This innovative model has been validated through a comparison to an infusion experiment made by P. Wang [4]. The test involved a $335 \times 335 \text{mm}^2$ plate made of 24 plies $[90_6, 0_6]_3$ of quasi-unidirectional fabrics (G1157, Hexcel Reinforcements) for a total thickness before compression of 9.8 mm and 40% of fiber content. The permeability is considered as isotropic and driven by Carman-Kozeny’s law as follows:

$$
K = 1.5635 \cdot 10^{-13} \frac{(1 - \nu_f)^3}{\nu_f^2}
$$

(10)

with $\nu_f$ the fiber content. The resin is the RTM6 also provided by Hexcel Reinforcement. The experiment was monitored through a fringe pattern projection method coupled with three in-situ thermocouples located between ply number 21 and 22. The fringe pattern projection method permits to follow the change in the thickness during the whole infusion process. Table 1 and figure 3 shows the results that are in very good agreement with experiment.

Figure 4 permits to compare the evolution of the thickness simulated with the one observed during the experiment. This comparison validates the model used to simulate the evolution of the thickness over time. In fact, the curve corresponding to the simulation lies in the tendency of the experimental curves. However, the three stages (impregnation without swelling, sudden swelling and moderated swelling) observed experimentally are not clearly identifiable on the simulation. This can be explained by several reasons. Firstly, we can notice that the simulated thickness variation evolves by steps, that seems unrealistic. These numerical artifacts could come from the filling algorithm that advance element-by-element. On the other hand, the conditions of the experimental infusion did not correspond to standard conditions used for the simulation. Indeed, to use the fringe pattern projection, the oven was opened during the experiment resulting in a not constant and not controlled temperature. This had an influence on the viscosity of the resin, which has directly impacted its flow and therefore has probably influence the mode of impregnation of the preform.

Even if work remains to achieve optimal experimental validation (monitoring thickness and flow front while controlling infusion parameters), these results demonstrate the interest and the relevance of the approach presented in this work.

4.2 Industrial application: Panel reinforced by a stiffening «T»

To demonstrate the capability of the code developed in this work, to deal with industrial cases, we propose to simulate the full infusion of a plate reinforced by a “T” stringer, which geometry has been proposed by Daher-Socata within the European INFUCOMP project. This part consists of a plate $380 \times 280 \times 3 \text{ mm}^3$ stiffened by a «T», itself made up of two “L” preforms 3 mm thick, as described in figure 5.

Conditions of infusion are presented in figure 6. A distribution medium is placed under the part in contact with the mold and a second one is positioned above the “T”. Resin injection is located in the center of the plate under the mold while the vent is located in the center of the second distribution medium above the “T”.
The preforms used are made of carbon fabrics provided by Hexcel Reinforcements (reference 48302 made of T700 12 k carbon fibers). The orthotropic permeability of the reinforcement measured by Hexcel is:

\[
\begin{align*}
K_p &= 9.76 \times 10^{-12} \text{ m}^2 \text{ in plane} \\
K_t &= 6.75 \times 10^{-9.8\nu} \text{ m}^2 \text{ through thickness}
\end{align*}
\]

with \(\nu\) the fiber volume fraction. The resin used for the infusion is RTM6. Due to the symmetry of the problem, we simulate only one quarter of the geometry as described in figure 7 (a). The mesh used is composed of 8,100 triangles and 1,884 nodes. The distribution medium at the bottom of the preform is represented by a pure resin flow (Stokes area) and is 1 mm thick. It is considered non-deformable. The preform is considered as an equivalent porous homogeneous medium (Darcy area), whose constitutive law has not been studied. Here, for the example we will assume that it obeys to the same behavior as the one measured by P. Wang [4]. However, we are aware that the behavior of a stack of quasi-unidirectional fabrics not preformed is much more flexible than a classic industrial preform held in shape by an epoxy powder. Injection is represented by a boundary condition in pressure of 1 bar and the vent by a pressure boundary condition of 0 bar. Finally, the other boundary conditions are impervious wall (\(\vec{v} \cdot \vec{n} = 0\)). The boundary conditions are summarized in figures 7 (b) and 7 (c).

Figures 8 and 9 show the filling ratio at times \(t = 1\) s, \(t = 69\) s, \(t = 273\) s and \(t = 550\) s. The results reflect a quick filling of the distribution medium (1 s), then a transverse infusion of the plate. When the resin starts to infuse the plate, beginning of the swelling can be identified (see figure 10). After about one minute, the plate is completely filled, the pressure is balanced in its extremities and the preform swells back to its initial thickness (see figure 9 at \(t = 69\) s). Then, the resin begins to migrate in the base of the T, first in the transverse direction, and then, when it reaches the curvature, in the plan of the plies (see figure 8 at \(t = 273\) s). Finally, resin finishes impregnating the upper part of the “T” and the filling ends after 549 seconds. One can notice a bad impregnation at the base of the “T” (see figure 8 at \(t = 549\) s). This result has been observed on certain infusions made during the project INFUCOMP.

Figure 10 shows the variation of the thickness during the infusion. It may be noted that the areas of the part that have been impregnated in the in-plane direction (curvature and upper part of the T) presents a linear swelling along time, while the plate and the base of the T, which have been impregnated transversely, have three distinct phases. Indeed, one can observe a first phase of filling with a small swelling. Then when resin reaches the vacuum bag, a sharp increase of thickness occurs. Finally, it continues to swell linearly during the end of the infusion.

5 Conclusion

We have presented an innovative model for the simulation of composite parts processing by resin infusion. The originality of the proposed method is that it remains robust and accurate even for real severe physical parameters such as low permeability values, thin pure fluid layer, large deformations and complex geometries which are often discarded in recent publications but more relevant with respect to industrial applications. To do that, we coupled Stokes and Darcy equation with finite strain solid mechanics. The specific coupling conditions allowing taking into account actual physical parameters have been presented and validated on an experimental test cases. Finally, an application on a complex case in three dimensions demonstrated the ability of this approach to deal with industrial infusion cases.

However, to fully meet the industrial needs, improvements must be developed. Thus, Thermo-chemical coupling must be introduced to simulate non isothermal processes. Mechanisms governing the formation and the transport of micro porosities should be studied, in order, to take it into account in our simulations.

Acknowledgements

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References


Table 1. Comparison between simulation and experimental results

<table>
<thead>
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<th></th>
<th>Simulation</th>
<th>Experiment</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness after compression</td>
<td>6,2</td>
<td>6±0,5</td>
<td>3,3%</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swelling (μm)</td>
<td>645</td>
<td>656</td>
<td>1,7%</td>
</tr>
<tr>
<td>Fiber fraction</td>
<td>56%</td>
<td>56%</td>
<td>-</td>
</tr>
<tr>
<td>Resin mass (g)</td>
<td>369</td>
<td>350</td>
<td>5,4%</td>
</tr>
<tr>
<td>Infusion time (s)</td>
<td>507</td>
<td>500</td>
<td>1,4%</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Principle of the liquid resin infusion process (LRI). (b) proposed model [1]

Fig. 2. Stokes/Darcy coupling algorithm
Fig. 3. Fluid-Solid coupling algorithm

Stokes-Darcy coupling:
Permeability update through porosity
Coupled fluid problem solved for $v(t), p(t)$

Solid mechanics computation:
Internal load update (Terzaghi’s law)
Non-linear mechanical problem solved for $\mathbf{u}(t_0)$

$\text{no}$

Is convergence reached $(v(t), p(t), \mathbf{u}(t))$?

$\text{yes}$

End

Fig. 4. Simulated thickness variation against experiment in the case of the experiment of P. Wang [4] $\left(\frac{\Delta h}{h_0} = f\left(\frac{t}{t_{final}}\right)\right)$
Fig. 5. Geometry of the “T” stiffener (Daher-Socata)

Fig. 6. Description of the conditions of infusion of self-stiffened Panel

Fig. 7. Infusion of “T” stiffener: (a) geometry of the problem with in blue the mesh used (quarter of the problem), (b) fluid boundary conditions, (c) solid boundary conditions
Fig. 8. Filling ratio obtained in the case of the infusion of self-stiffened panel

Fig. 9. Filling ratio viewed from the side with the initial geometry drawn in black in the case of the infusion of self-stiffened panel
Fig. 10. Variation of the thickness during the infusion of the "T" stiffener.