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# Modeling of high speed RTM injection with highly reactive resin with on-line mixing

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Structural composite manufacturing in automotive industry tends towards short cycle times for being competitive with other material solutions. Development towards resin transfer molding process can be considered when highly reactive resin with short curing cycle is used. Mixing of the resin system components is then held at the mold inlet to reduce catalyzed resin life time. Cure kinetics and viscosity changes induced during filling are thus to be taken into account when injection process simulation is considered. In the case of on-line mixing of resin components, viscosity and degree of cure of the first injected resin droplets are not the same than for the following ones. This topic will be addressed here for mixed constant flow rate and pressure injection schemes. A solution that could be implemented in a RTM simulation package was developed and validated with an analytical solution and on a complex shape automotive part demonstrator.

## 1. Introduction

Due to their special features, such as high specific strength and rigidity, composite materials are increasingly being used to replace metallic components. They offer the potential to save weight, increase mechanical properties and shaping freedom, reduce the number of components in a part, and allow properties to be tailored to applications. For all of these reasons, composites are increasingly being used while also achieving a reduction in part cost. The transportation industry represents a large application area for fiber reinforced composites and is driven by numerous interacting requirements that depend on the specific sector considered. For example, aerospace and aeronautics have traditionally been driven by high performance, where longer cycle times and increased scrap levels are permitted. In the automotive industry where high volume applications are looked for, fast and highly automated techniques are required, with a strong emphasis on decreasing production and product costs. Thermoplastic-based composites are generally suited to lower cycle times and hence higher volume production due to the nature of the matrix, compared to thermoset matrices which require during processing time consuming cross-linking reaction. For polymer composites to compete with metallic parts, cost reductions in manufacturing cycles are necessary to balance the higher raw material cost. From a manufacturing point of view, it is desirable to process the part at the lowest possible pressures and temperatures and with the shortest

possible cycle times, but with an unavoidable incidence on part quality if this reduction does not result from a dedicated analysis. The challenge consists of making robust the production process for economic manufacture at high volume by an improved understanding of the material/process/property relationships.

Resin transfer molding is generally known as a long cycle process and reserved to low to medium volume manufacturing batch. In this process, a dry fibrous preform is placed in a closed mold, and then resin is forced through the preform during the injection step. Resin cures under the conjugated effect of heat and catalyst to form the final part that can be de-molded. The curing time usually represents 80% of the total cycle time, which places RTM among the medium series production processes. The automotive industry is however interested in that technique to develop structural composite parts. In order to render RTM competitive and highly productive, cycle times need to be reduced by increasing the injection speed and reducing cure cycle, which infers mold heating to reduce resin viscosity during filling and to catalyze polymerization kinetics. A beneficial effect for the injection is thus to have a fast resin cure right after mold filling.

Considering equipment, RTM injection processes are generally conducted at a constant injection speed with injection pumps in order to insure filling times and production rates, explaining why only few studies focused on constant pressure injection schemes. However, a pressure limit is fixed to avoid mold opening or fiber preform washing. Limited pressure level is also required when considering injection on a flexible material or on an inflatable bladder in order to avoid deformation of a foam core when producing sandwich structures or parts with hollow cores [1,2]. In those particular

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but not seldom cases, constant flow rate injection can transform to a constant pressure injection. Filling time and start of the curing kinetics then become an issue.

Generally, resin systems and molding conditions are chosen so as to allow the complete filling of the mold before the reaction kinetics is too much advanced. In order for RTM process to be competitive in the automotive industry, cycle times have to be short, so that the part can be removed from the mold cavity as early as possible. Resins used for this type of application are thus highly reactive, and cure kinetics may be started before the end of the filling stage. The objective is to have a part cured when the last resin droplet is injected. Solutions have been proposed where the ratio of catalyst evolves with time as the mold is being filled [3–6], the last resin droplets being more catalyzed than the first ones. The purpose of this solution was to have a homogeneous curing throughout the part. This solution requires knowing the effect of the amount of catalyst on resin kinetics and on the final degree of cure reached so as to insure good part quality. In the matter discussed here, a constant resin to catalyst ratio system is injected in a heated mold, the two components being mixed together right at the mold inlet. Resin kinetics thus starts as soon as the resin enters the mold, affecting the viscosity and thus the molding parameters, i.e. time and pressure.

Optimization of the process cycle then implies accurate prediction of the injection time to insure complete mold filling before gelling of the resin. During fast injection techniques such as in SRIM processes, viscosity changes are either considered non relevant during injection stage or mixing of the resin components is previously performed in a barrel [7,8]. However, before gelling of the resin, polymerization has been initiated, inducing a viscosity increase during mold filling which generally can be expressed in a generic constitutive equation with an exponential law [9–11].

Cure kinetics during composite manufacturing can be well described, taking into account the heat generated during the curing reaction, the part quality in terms of final degree of cure or residual stresses [12–20]. However, few developments consider the evolution of degree of cure or viscosity during mold filling in the case of on-line mixing [21]. In liquid molding processes, gelling of the resin starts after mold filling, whether the injection conditions are isothermal or non-isothermal. So resin viscosity is considered constant (isothermal case) or varying with time and temperature (non-isothermal case) during filling. The proposed article considers the isothermal filling with a highly reactive resin inducing a time and space variation of viscosity during filling of the mold as resin components are mixed directly at the injection head.

The process dealt with in this paper is placed between RIM process where reactive resin is injected at high speed in a mold but resin properties are considered constant, and non-isothermal mold filling where constant inlet conditions are kept but heat exchange due to a temperature difference between the mold and the resin and resin kinetics occur, influencing the resin viscosity level during infusion.

Non-isothermal injection modeling generally includes heat exchange between mold and the resin/fibrous medium structure and the heat of resin reaction. Resolution of heat and degree of cure advancement is linked to the constitutive equation through the viscosity term expressed as a function of heat only when cure kinetics are considered negligible in the injection time, as a function of the degree of conversion when heat increased is only due to cure kinetics [13,15,17,20,21].

Prior to describe the algorithm to be implemented in the simulation code for flow pattern prediction, an analytical solution is derived to predict for a 1D flow the transport of the degree of curing through the evolution of viscosity and meant to be compared with the numerical solution. The specific case of on-line mixing of resin components is addresses where viscosity and degree of cure of the

first injected resin droplets are not the same than for the following ones. This situation differs from the case where the full volume of resin components are mixed together prior to injection where all the resin droplets share the same initial curing condition.

Finally, the simulation code is used for filling time prediction of an automotive composite part produced in industrial conditions. Processes in the composite injection industry usually imply mixed injection scheme, generally a constant flow rate injection is conducted until inlet pressure reaches the maximum set level to avoid fiber washing or mold deflection, and then injection is switched to the constant pressure mode to complete the injection. Both schemes are addressed in the presented work.

## 2. Analytical approach

Fast injection for composite part manufacturing with a highly reactive resin in a heated mold is considered. The resin system is composed of two pre-heated components and mixing is conducted at the mold inlet, so that no reaction kinetics is involved prior to injection. The mold is heated and maintained at a constant temperature during the injection. Because resin system is pre-heated at the mold temperature, heat transfer effects at the mold inlet can be neglected. The simulation is thus considered isothermal. In that case, resin kinetics can be described through the evolution of resin viscosity with time at a desired temperature.

The parameters employed in this section are arbitrary and will only be used in the purpose of deriving a realistic analytical solution, although no resin systems may fulfill the properties employed.

Derivation of an analytical solution is performed according to the following assumptions:

- Resin viscosity change according to a given temperature, cure and time is known.
- Injection is conducted in isothermal conditions. Only viscosity change due to resin kinetics is considered.
- The mold is rectangular and is injected via a line gate, which allows a 1D representation of the macroscopic fluid flow velocity.

Filling of a mold containing a porous medium is modeled with Darcy's law that links the pressure gradient  $\nabla P$  in the mold to the volume averaged velocity  $\mathbf{v}$ , also known as Darcy's velocity:

$$\mathbf{v} = \frac{\mathbf{Q}}{A} = -\frac{\mathbf{K}}{\mu} \cdot \nabla P \quad (1)$$

where  $\mathbf{Q}$  is the flow rate across the cross section  $A$ ,  $\mu$  is the resin viscosity, and  $\mathbf{K}$  the fibrous preform permeability tensor. Neglecting the delay of saturation of fiber tows and density change, assuming fabrics are not deformed by the fluid flow, the mass conservation principle is expressed as:

$$\nabla \cdot \mathbf{v} = 0 \quad (2)$$

the governing equation for injection through fabrics viewed as a porous medium becomes:

$$\nabla \cdot \left( \frac{\mathbf{K}}{\mu} \cdot \nabla P \right) = 0 \quad (3)$$

In this analytical study,  $\mu$  is not constant, which leads to a more intricate expression of the filling time than usual. Let us assume that  $\mu$  depends on the polymerization time  $t_p$ , following the exponential form:

$$\mu = \mu_0 e^{\lambda t_p} \quad (4)$$

where  $\mu_0$  is the initial resin viscosity and  $\lambda$  is a constant. This expression gives a general representation of viscosity time history

under isothermal curing [9–11]. This assumption has the advantage to allow derivation of an analytical solution for the constant pressure injection scheme presented in Section 2.2. So the only purpose of this viscosity equation form is to allow the derivation of an analytical solution to validate the implementation of the simulation of an injection with space and time varying viscosity. The simulation code could then be used for any kind of viscosity time history profile.

In the case of a 1D plate filled linearly along the  $x$  direction (mold length), as presented in Fig. 1, the filling of the porous medium can be simply deduced from Eq. (1) as follows:

$$\frac{\partial P}{\partial x} = -\frac{\phi\mu}{K}v_r \quad (5)$$

where  $\phi$  is the preform porosity,  $K$  is the permeability of the preform in the flow direction ( $x$ ) and  $v_r$  is the resin interstitial velocity along the mold length defined by:

$$v_r = \frac{v}{\phi} \quad (6)$$

Then the mass conservation equation, taking in account the above-cited assumptions, simply writes:

$$\frac{\partial v_r}{\partial x} = 0 \quad (7)$$

which allows to express the uniform velocity easier as follows:

$$v_r = \frac{dl}{dt} \quad (8)$$

thus only involving the position  $l$  of the flow front.

From this process description, two boundary condition cases will be addressed separately, the constant flow rate injection and the constant pressure injection strategies.

### 2.1. Constant flow rate injection

For a constant flow rate injection, resin velocity is constant and time is directly linked to the flow extent via the resin velocity. Injection time will not be affected by the resin viscosity increase during filling, however pressure field along the mold will be greatly modified. This pressure profile is derived from Eq. (5) that can be written as:

$$\frac{\partial P}{\partial x} = -\frac{\phi v_r}{K}\mu_0 \exp\left(\lambda \frac{x}{v_r}\right) \quad (9)$$

Due to the constant resin velocity, the polymerization time here is simply related to the position of the given resin fluid particle. At each location, resin viscosity will remain constant until the mold is completely filled and resin front is stopped. The pressure field along the mold length is obtained by integrating Eq. (9) from the mold inlet to the resin flow front located at a distance  $x = l$  where an atmospheric pressure condition is assumed, thus obtaining:

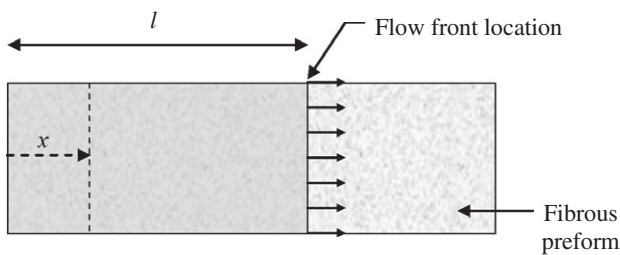


Fig. 1. 1D flow representation.

$$P(x) = \frac{\phi l^2}{t^2 \lambda K} \mu_0 \left( \exp(\lambda t) - \exp\left(\lambda \frac{x}{v_r}\right) \right) \quad (10)$$

or

$$P(x) = -\frac{\phi v_r^2}{\lambda K} \mu_0 \exp\left(\lambda \frac{x}{v_r}\right) \quad (11)$$

where  $v_r = \frac{L}{t_{inj}}$  is the constant resin velocity and  $t_{inj}$  the total filling time of the total mold length  $L$ .

### 2.2. Constant pressure injection

Next consideration is for processes involving constant pressure injection schemes. When the viscosity  $\mu$  remains constant during the process, even in the case of a prescribed constant pressure  $P_{inj}$ , the filling time is obtained by a straightforward integration over the total length of the mold  $L$  and can be expressed as:

$$t_{inj} = \frac{1}{2} \frac{\phi \mu}{K P_{inj}} L^2 \quad (12)$$

Let us now consider the case where viscosity change must be taken into account. First, the current position  $x$  of a resin droplet along the 1D flow direction, at time  $t$ , can be related to the corresponding polymerization time:

$$x = \int_{t-t_p}^t v_r dt = l(t) - l(t-t_p) \quad (13)$$

In other words, it means that the particle considered at time  $t$  has polymerized from the mold inlet to its current position  $x$ , what corresponds to a duration of  $t_p$ . As the resin velocity is uniform (it only depends on time), the traveled distance corresponds to the flow front advance between  $t - t_p$  and the current time  $t$ .

By differentiating Eq. (13) with respect to  $t_p$ , it gives:

$$dx = -dl(t-t_p) = v_r(t-t_p) dt_p \quad (14)$$

By integrating Eq. (5), it leads to the nominal prescribed pressure:

$$P_{nom} = -\int_0^l \frac{\partial P}{\partial x} dx = \frac{\phi}{K} v_r \int_0^l \mu dx \quad (15)$$

Using Eq. (14), we get the following integro-differential equation, only involving the time-dependent velocity:

$$\int_0^t \mu(t_p) v_r(t-t_p) dt_p = \frac{K P_{inj}}{\phi v_r(t)} \quad (16)$$

Let us note  $\psi(t)$  the left-hand side of Eq. (16). Thanks to the viscosity definition (Eq. (4)):

$$\dot{\psi}(t) = \mu_0 v_r(t) + \lambda \psi(t) \quad (17)$$

where the dot superscript denotes a time derivative.

Finally,  $v_r$  is solution of the ordinary differential equation:

$$\dot{v}_r + \lambda v_r + \frac{\mu_0 \phi}{K P_{inj}} v_r^3 = 0 \quad (18)$$

and takes the following general expression:

$$v_r = \frac{1}{\sqrt{\alpha e^{2\lambda t} - \frac{\mu_0 \phi}{\lambda K P_{inj}}}} \quad (19)$$

where  $\alpha$  is a constant of integration such that the velocity tends to infinity at initial instant  $t = 0$ :

$$\alpha = \frac{\mu_0 \phi}{\lambda K P_{inj}} \quad (20)$$

Then, the flow front position can be deduced, by integrating Eq. (19):

$$l = \sqrt{\frac{KP_{inj}}{\lambda\mu_0\phi}} \arctan(\sqrt{e^{2\lambda t} - 1}) \quad (21)$$

with a null constant of integration in order to ensure  $l(0) = 0$ .

The analytical prediction of the filling time of the total length  $L$  of the mold is then straightforward:

$$t_{inj} = \frac{1}{2\lambda} \ln \left[ 1 + \tan^2 \left( L \sqrt{\frac{\lambda\mu_0\phi}{KP_{inj}}} \right) \right] \quad (22)$$

The exponential expression presented in Eq. (4) to represent the evolution of viscosity with time has the advantage of offering an easily derived analytical solution. However, caution should be taken with the expression obtained. According to the analytical solution, there is a mathematical singularity without physical meaning for which no solution can be derived and it occurs when the tangent term goes to infinity, namely when the expression  $L \sqrt{\frac{\lambda\mu_0\phi}{KP_{inj}}}$  equals an odd multiple of  $\frac{\pi}{2}$ . This first occurs when:

$$\lambda = \frac{\pi^2}{4L^2} \frac{KP_{inj}}{\mu_0\phi} \quad (23)$$

Coefficient  $\lambda$  is thus chosen with care for implementation of the analytical solution for validation of the numerical study.

### 3. Numerical approach

The main issue is the implementation of space and time varying viscosity variation during injection. Actually, the first resin droplet injected will remain in the mold longer than the last resin droplet. The part will then cure first close to the mold outlet and then at the mold inlet, which also implies that resin viscosity at the mold inlet and that at the mold outlet are not the same. The aim of the algorithm is thus to consider the elapsed time spent in the mold for each resin droplet to be able to evaluate the resin viscosity at any time and location in the mold. The algorithm described here can be implemented in any simulation code without changing the fundamental equations. An open source code was used for development of the method [22].

Two cases are presented separately, the constant flow rate injection scheme and the constant pressure injection scheme.

#### 3.1. Constant flow rate case

Viscosity changes are first applied to mesh properties. In the case of LIMS software, resin viscosity is a global input for the entire mesh. Viscosity variations are thus introduced through the permeability defined for each mesh element. The ratio  $\frac{k}{\mu}$  appearing in Darcy's law (Eq. (1)) is thus considered as a whole. Change in viscosity is transferred to a change in permeability values without affecting the computed solution. In this section, only simple parts, defined as parts that will induce a constant local velocity at all locations in the mold, are considered. When a change of resin velocity is possible, the numerical approach should be conducted as for a constant pressure injection scheme, described in the next paragraph.

In the case of a constant flow rate injection, viscosity only depends on the spatial location. At each location, the time taken for a resin droplet to flow from the inlet to the considered location will be the same for the first droplet or any following droplet. The time-dependent viscosity can then be transferred to a spatially dependent viscosity. The only output value required is thus the wetting time at every node location in the mesh. The general algorithm developed is schematized in Fig. 2. At each calculation step, the

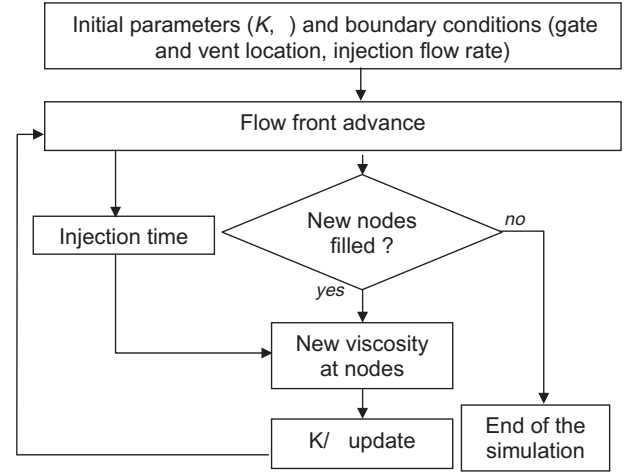


Fig. 2. Constant flow rate injection with on-line resin components mixing algorithm.

flow front advances in the mold. A time step is calculated and the filling status of the nodes is updated. The algorithm will run a test on the nodes to see if their status has changed during the calculation step. If they are newly filled, the elapsed time since the beginning of the injection is taken to calculate the new viscosity such as expressed in Eq. (4) and is updated on the mesh properties.

#### 3.2. Constant pressure case

Imposing a constant pressure at the injection gate implies that resin velocity is not constant during mold filling, or more exactly that the travel time for a resin droplet from the injection gate to a considered location increases. As for the constant flow rate injection case, spatial viscosity variations are considered, but for a constant pressure injection the time increase to travel a given length needs to be taken into account.

The algorithm for viscosity calculation for a constant pressure injection is thus based on the calculation of the travel time for each resin droplet. Due to on-line mixing of the resin components, each resin droplet has a different initial curing condition. In order to avoid particle tracking, the algorithm will consider the evolution of the travel time for a resin droplet to reach a specific position in the mold. A first injection simulation is performed in order to record the volume injected before each node is filled. During a second injection simulation, for each calculation step and for each node that is filled, comparison of the injected volume with the volume recorded during the first injection allows to define the viscosity change by considering the time taken to inject the considered volume from the viscosity equation expressed as a function of time. Fig. 3 highlights the main steps of that algorithm. The important parameter retrieved from the first injection is the volume injected to reach a particular node. During the effective simulation, at each flow front advance, the time step and the volume injected during that time step are recorded. For each filled node, a sum on the latest injected volumes and a sum on the corresponding time steps are conducted until the injected volume defined from the first injection is reached. Time is then retrieved and is used to calculate the new local viscosity at the considered node.

#### 3.3. Validation

The numerical algorithm developed is tested on a plate, the objective being to compare numerical and analytical results in terms of flow front advancement during filling so as to validate the implementation scheme of the spatial and time dependence

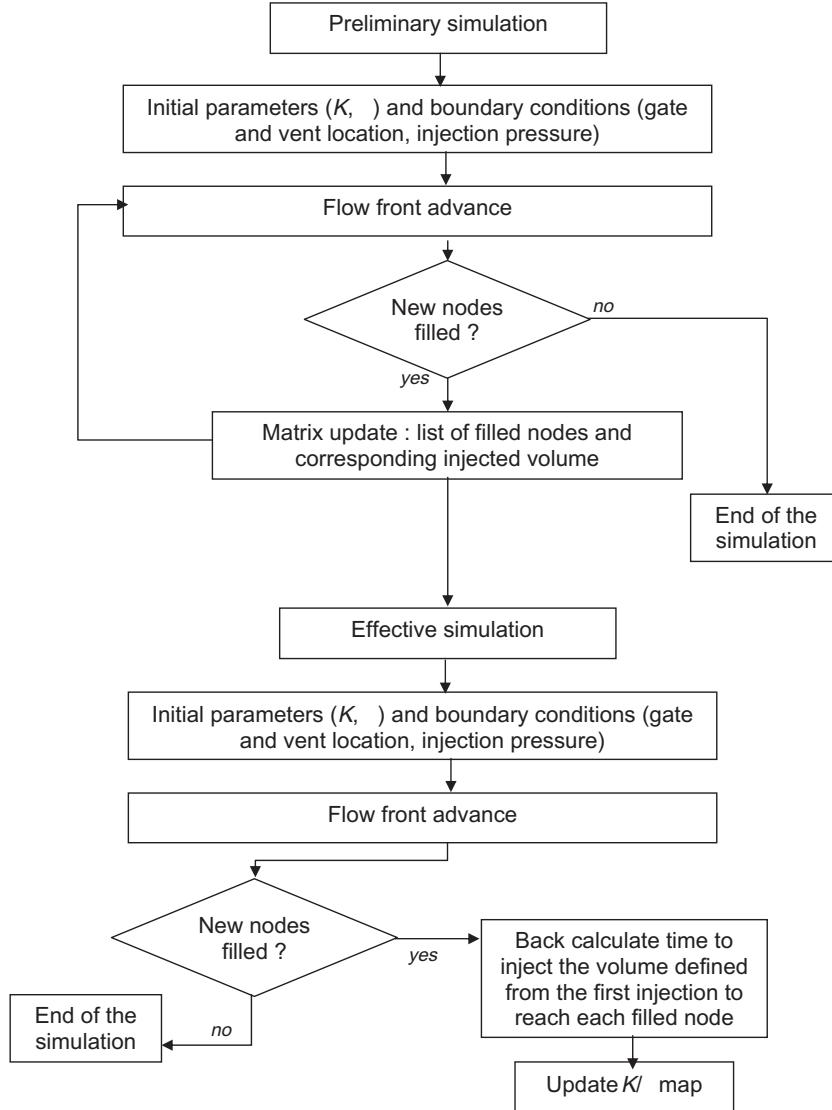


Fig. 3. Constant pressure injection scheme with on-line resin components mixing algorithm.

of viscosity through the evaluation of the length of the path followed by resin.

A line injection is considered to derive an analytical solution. The part is 0.5 m long, 0.2 m wide, and 2 mm thick. Preform permeability and fiber volume fraction are set to  $1 \times 10^{-8} \text{ m}^2$  and 45% respectively. A constant 0.5 MPa injection pressure is applied. The viscosity change with time considered is represented by Eq. (4) with  $\mu_0 = 0.1 \text{ Pa s}$  and for two cases, where  $\lambda$  is equal to 5 and 8. Filling profiles for both cases are presented in Fig. 4, through the representation of the flow front location along the mold length with time derived from the analytical solution (Eq. (22)) and from the numerical study. A perfect match between analytical solution and the implemented code is obtained. The constant viscosity case is also considered using a 0.1 Pa s viscosity, equivalent to  $\mu_0$ . For  $\lambda = 5$ , the highest viscosity in the mold is of 0.27 Pa s inducing an increase in the filling time of 25% compared to the constant viscosity injection case. For  $\lambda = 8$ , the highest viscosity in the mold is 1.70 Pa s, the final injection time in that case is 144% longer than for the constant viscosity case. In both cases, perfect match is obtained between the analytical and the numerical injection profile, as shown in Fig. 4.

The numerical code is thus validated and can be applied on an industrial part, with the effective injection parameters used during

the trial and according to the resin viscosity evolution with time characterization.

#### 4. Study on an automotive industrial part

Implementation of the algorithm for constant pressure injection was used on a demonstrator representing a low B-pillar part using an industrial high-speed RTM process. Injection was performed in an aluminum mold heated at 80 °C. The final part presented in Fig. 5 is manufactured with two preforms with an overlap section with a 3 mm thick cavity in the overlap zone and 1.5 mm thick cavity elsewhere. Permeabilities used were characterized in [2]. The permeabilities used for given fiber volume fractions  $V_f$  are reported in Table 1. Materials were shown to be in-plane isotropic. No significant shear was induced as no draping was done directly on the mold. Moreover, the part is composed of two preforms with simple deformation (simple curvature and short drawing effect), limiting in-plane shear of the fabric. On the contrary, local thickness variations and race tracking channels had to be taken into account. Changes in thicknesses were considered with a proportional law on fiber volume fraction. The equivalent permeability  $K_c$  of the race tracking channel of height  $h$  is evaluated by:



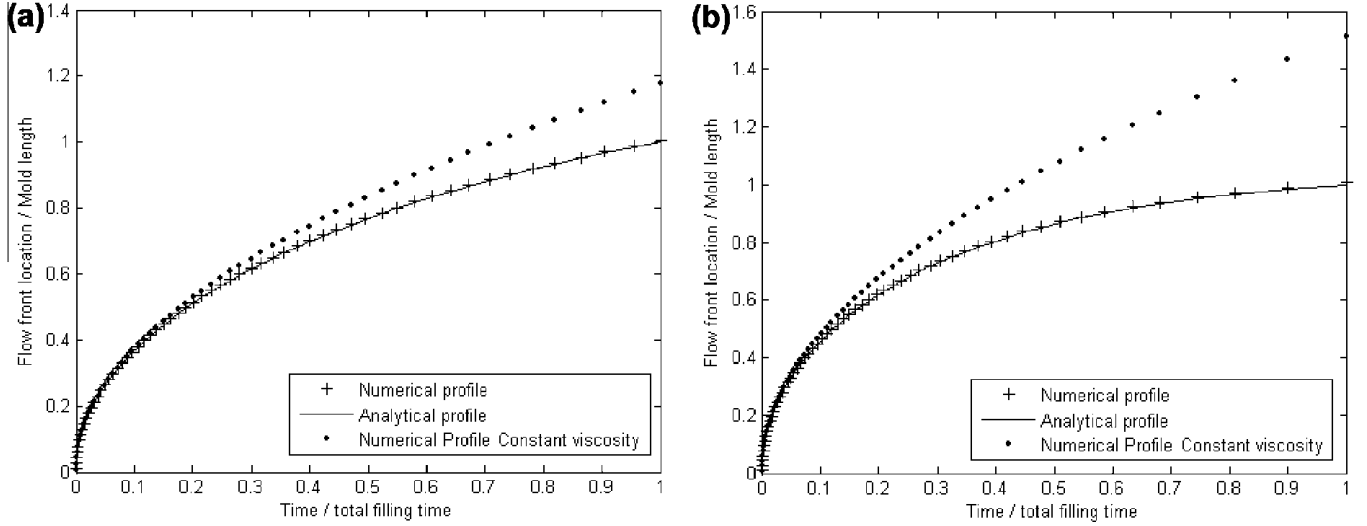


Fig. 4. Numerical validation of the code: (a) with  $\lambda = 5$ ; (b) with  $\lambda = 8$ .

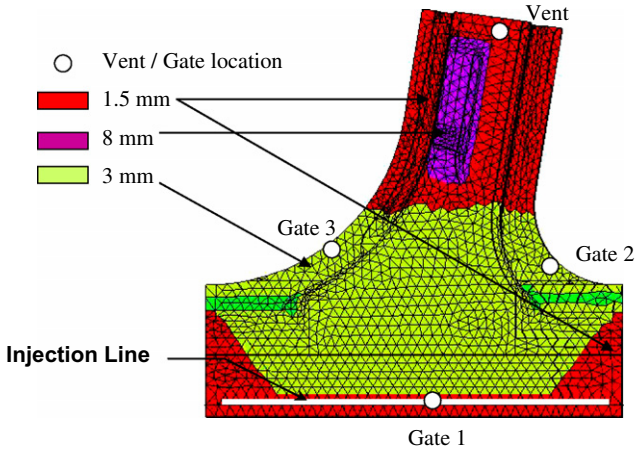


Fig. 5. Meshed part and zones of different thickness.

$$K_c = \frac{h^2}{12} \quad (24)$$

For this demonstrator, preforms were not fully adapted to the mold geometry and a small gap created between the preform and the mold wall edges had to be taken into account for flow simulation. Resin will flow faster in those race tracking channels, disturbing the flow front shape. This consideration is fully handled by the code by evaluating the size of the race tracking channel and evaluating an equivalent permeability [23].

A two components epoxy resin, pre-heated to 60 °C, is considered. Mixing of the two components is performed at the mold inlet, thus no polymerization reaction takes place before injection. Mold is kept at the constant temperature of 80 °C. As the part thickness can be considered small compared to the in-plane characteristic length of the part, resin temperature is considered constant at the mold temperature after entering the mold. Afterwards, when temperature increase generated by the heat reaction occurs, the heat is assumed to be dissipated through the metallic mold walls and it will not affect resin viscosity. Thus, only resin viscosity change with time at a given temperature can be considered [24].

Resin viscosity evolution versus time during polymerization at 80 °C was characterized, and reported in Fig. 6. Resin viscosity is stable and close to 1 Pa s during 20 s and then starts rising slowly up to 1.25 Pa s at 36 s before resin kinetics is clearly initiated. Gel

Table 1  
Preform characteristics.

Preform	1.5 mm		3 mm	
	$V_f$ (%)	Permeability ( $m^2$ )	$V_f$ (%)	Permeability ( $m^2$ )
Preform #1 glass biaxial stitched fabric	38	$1.6 \times 10^{-9}$	41	$2.5 \times 10^{-10}$
Preform #2 hybrid preform (glass and carbon biaxial stitched fabric)	50	$4.6 \times 10^{-11}$	53	$3.8 \times 10^{-11}$

time of the resin is then set at 67 s. The resin viscosity was tested with Brookfield viscosity measurement apparatus at constant temperature fixed to be 80 °C, temperature of the mold during injection. Viscosity measurement was held until resin gel time. Epoxy resin was considered Newtonian, as it is generally observed for epoxy resin [25].

Best fit of the viscosity time history curve was obtained with two polynomial curves:

$$\text{For } t < 50 \text{ s} \quad \mu = 3 \times 10^{-4}t^2 - 0.0024t + 0.93 \quad (25)$$

$$\text{For } t > 50 \text{ s} \quad \mu = 247.5t^2 - 2176t + 4.3 \times 10^5 \quad (26)$$

The injection unit is controlled for a constant flow rate injection but switches to a constant pressure injection scheme when it reaches a specified pressure value. This value is set to 1 MPa. During injection, pressure increase at the inlet is recorded over time and is

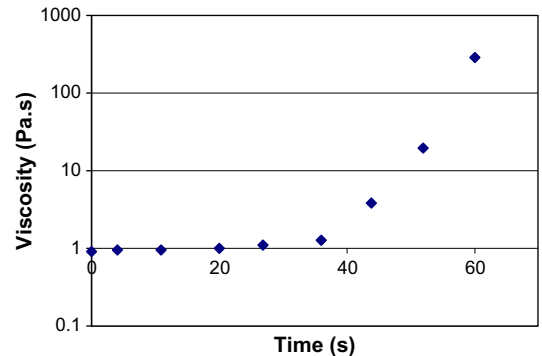


Fig. 6. Viscosity versus time at 80 °C.

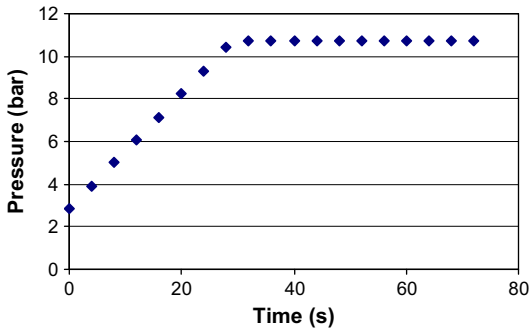
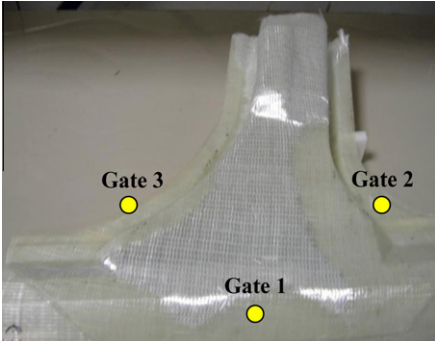
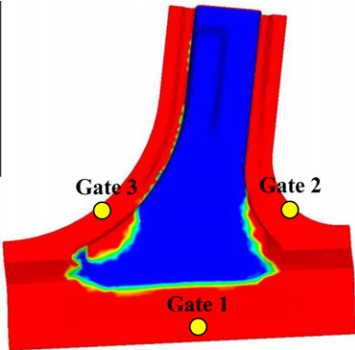
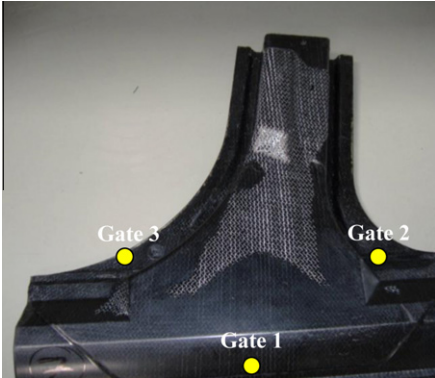
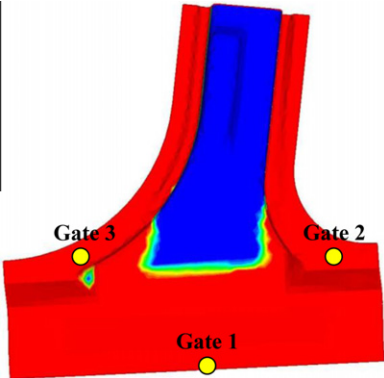
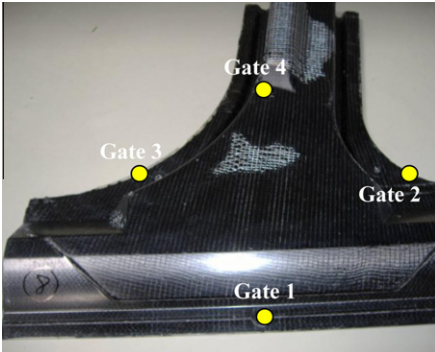
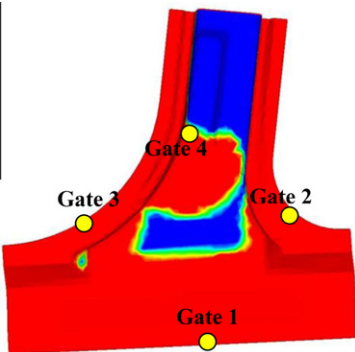


Fig. 7. Recorded inlet pressure profile versus time and used as boundary condition in numerical simulations.

implemented as a boundary condition in the numerical code. This actual inlet pressure profile is represented in Fig. 7. Simulations are then run using the constant pressure implementation scheme and compared with the injection time and/or profiles obtained on the injected parts.

Multipoint injection offers the possibility to reduce mold pressure, run faster injections or inject larger parts. Several scenarios were tested among isochronal and sequential strategies. The injection gates are the one located on a line-injection channel at the bottom of the part (Gate 1) and the two pin gates while a point vent is located at the top. Two families of injection were conducted, one until complete filling of the part whenever process conditions make it possible and the second one is stopped after 30s (short shot) in order to compare the observed flow front pattern at that time with the one obtained from the simulation. The part obtained for preform #1 is shown in Table 2 along with the

Table 2  
Comparison between simulated and injected flow patterns.

Produced parts	Simulated flow patterns
Preform 1 – time $t = 30$ s 3 Injection points: Gate 1 opened at time $t = 0$ ; Gate 2 at $t = 6$ s and Gate 3 at $t = 12$ s 	
Preform 2/case 1 – time $t = 67$ s 3 Injection points: Gate 1, 2 and 3 opened at time $t = 0$ 	
Preform 2/case 2 – time $t = 67$ s 3 Injection points: Gate 1, 2, 3 and 4 opened at time $t = 0$ 	



simulated flow profile after 30 s. The flow front shape shows good agreement with the simulation. Complete filling of the glass fiber part made with preform #1 was obtained after 57 s during trial, while simulation gives a total filling time of 58 s. The same injection conducted with a constant viscosity of 1 Pa s, corresponding to the initial resin viscosity, gives an injection time of 50 s, 13% less time than with the varying viscosity model.

Injection of the hybrid glass/carbon fiber preform #2 was conducted using the line injection and the two secondary injection gates (case 1 in Table 2). Because of the low permeability of this preform, injection velocity is slower in this case than in the glass fiber preform case. For preform #2 in Table 2, flow stopped after 67 s due to the resin polymerization and the viscosity increase (Fig. 6). The injection pressure at that level is not sufficient to induce a flow front advance. The part obtained is shown in Table 2 along with the simulated flow profile after 67 s. Again, the flow front shape predicted by the simulation is in reasonable agreement with the one obtained during the real process. Finally a fourth inlet gate is added in case 2 to impregnate preform #2, however it has been shown that the hybrid preform #2 with lower permeabilities could not be fully impregnated with the current gating system. The filling patterns reported in Table 2 show a good agreement between the predicted and the real injection flow front patterns. The numerical flow advancements correlate well with experimental profiles. The difference between experimental and numerical flow profiles are due to the non regularity of the preform cut and the positioning of the preform in the mold that is made by hand and is not accurate. This results in pinching the preform in some places, inducing a local increase in fiber volume fraction and by consequence a decrease in local permeability. The experimental flow front is thus disturbed whereas a regular flow is numerically obtained.

## 5. Conclusion

Simulation of the injection of a highly reactive resin leads to additional complexity when considering an on-line mixing injection head and constant pressure driven mode. This unusual injection scheme is motivated by the specific requirements of high speed and robust manufacturing of structural composite parts in automotive industry. Viscosity changes are not spatially homogeneous any longer and should be considered when resin kinetics is involved during the injection phase. A methodology for prediction of flow pattern and pressure field is proposed in this paper. Digital simulation software is used in combination with the proposed algorithm by considering viscosity as a function of time for each location in the mould. Although development was performed for two injection cases, constant flow rate and constant pressure injections, mixed injection scheme can also be considered by combining the two algorithms. The implementation algorithm thus presented could be adapted to other commercial codes dedicated to the numerical simulation of RTM process.

This article presents resin kinetics as a function of time, when constant temperature can be considered. For thick parts, temperature variation due to the exothermic reaction of cure needs to be considered and the use of a non-isothermal model is needed along with resin characterization. In that case, special care is required for characterization of the resin and fabric. Non-isothermal modeling of the on-line mixing high speed RTM process is also required for thick preforms where the heat generated during polymerization due to mass effect is not negligible. In addition, this algorithm is based on the assumption that the resin travel path does not deviate during mold filling. Evolution of algorithm would be needed to

take into account changes in the flow front path that can occur for complex part shape manufacturing when the flow is split due to presence of inserts or non homogeneous filling for a radial injection when a vent is closed before others.

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## References

- [1] Binetruy C, Advani SG. Foam core deformation during liquid molding of sandwich structures: modeling and experimental analysis. *J Sandwich Struct Mater* 2003;5(4):351–76.
- [2] Deleglise M, Binetruy C, Krawczak P. Simulation of LCM processes involving induced or forced deformations. *Composites: Part A* 2006;37(6):874–80.
- [3] Comas-Cardona S, Ziaee S, Advani SG. Spatially homogeneous gelation in liquid composite molding. *Polym Eng Sci* 2002;42:1667–73.
- [4] Devillard M, Laut A, Advani SG. On-line mixing during injection and simultaneous curing in liquid composite molding processes. *Polym Compos* 2005;26(1):74–83.
- [5] Shojaei A, Farrahinia H, Pishvaei SMR. Effect of system of initiators on the process cycle of nonisothermal resin transfer molding-numerical investigation. *Composites Part A: Appl Sci Manuf* 2010;41(1):138–45.
- [6] Kim SK, Kim DH, Daniel IM. Optimal control of accelerator concentration for resin transfer molding process. *Int J Heat Mass Transfer* 2003;46:3747–54.
- [7] Polushkin EY, Polushkina OM, Malkin AYA, Kulichikhin VG, Michaeli W, Kleba I, et al. Modeling of structural reaction injection molding. Part II: Comparison with experimental data. *Polym Eng Sci* 2002;42(4):846–58.
- [8] Kuznetsov V, Malkin AYA, Michaeli W, Kleba I, Blaurock J. Modeling of structural reaction injection molding. Part I: Mathematical model. *Polym Eng Sci* 2001;41:850.
- [9] Stolin AM, Merzhanov AG, Ya A. Non-isothermal phenomena in polymer engineering and science: a review. Part II: Non-isothermal phenomena in polymer deformation. *Polym Eng Sci* 1979;19(5):1074–80.
- [10] Polushkin EY, Polushkina OM, Malkin AYA, Michaeli W, Kleba I, Blaurock J. The rheokinetics of a fast-curing polyurethane. *Int J Appl Mech Eng* 1999;4:85–90.
- [11] Chick JP, Rudd CD, Van Leeuwen PA, Frenay TL. Material characterization for flow modeling in structural reaction injection molding. *Polym Compos* 1996;17(1):124–35.
- [12] Ngo ND, Tamma KK. Non-isothermal 2D flow/3D thermal developments encompassing process modelling of composites: flow/thermal/cure formulations and validations. *Int J Numer Methods Eng* 2001;50:1559–85.
- [13] Fei Shi, Xianghai Dong. 3D numerical simulation of filling and curing processes in non-isothermal RTM process cycle. *Finite Elem Anal Des* 2011;47:764–70.
- [14] Shojaei A, Ghaffarian SR. Modeling and simulation approaches in the resin transfer molding process: a review. *Polym Compos* 2003;4(4):525–44.
- [15] Lin R, Lee LJ, Liou M. Non-isothermal mold filling and curing simulation in thin cavities with preplaced fiber mats. *Int Polym Process* 1991;VI:356–69.
- [16] Mal, Couston, Dupret. Non-isothermal simulation of the resin transfer moulding process. *Composites Part A: Appl Sci Manuf* 1998;29:189–98.
- [17] Farina, Preziosi, Summerscales. Non-isothermal injection molding with resin cure and preform deformability. *Composites Part A: Appl Sci Manuf* 2000;31:1355–72.
- [18] Ledru Y, Bernhart G, Piquet R, Schmidt F, Michel L. Coupled visco-mechanical and diffusion void growth modelling during composite curing. *Compos Sci Technol* 2010;70(15):2139–45.
- [19] Brusckhe M, Advani SG. A finite element/control volume approach to mold filling in anisotropic porous media. *Polym Compos* 1990;11:398–405.
- [20] Kendall KN, Rudd CD, Owen MJ, Middleton. Characterisation of the resin transfer moulding process. *Compos Manuf* 1992;3(4):235–42.
- [21] Markus H, Breyer C, Niedermeier M, Ermanni P. A new kinetic and viscosity model for liquid composite molding simulations in an industrial environment. *Polym Compos* 2004;25(3):255–69.
- [22] Simacek P, Advani SG. A numerical model to predict fiber tow saturation during liquid composite molding. *Compos Sci Technol* 2003;63:1725–36.
- [23] Bickerton S, Advani SG. Characterization and modeling of race-tracking in liquid composite molding processes. *Compos Sci Technol* 1999;59:2215–29.
- [24] Trochu F, Ruiz E, Achim V, Soukane S. Advanced numerical simulation of liquid composite molding for process analysis and optimization. *Composites: Part A* 2006;37:890–902.
- [25] Advani SG, Sozer EM. *Process modeling in composites manufacturing*. New York: Marcel Dekker; 2003.