ON-LINE MIXING RTM SIMULATION TREATING DUAL-SCALE FLOW

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Abstract
In the recent years, the interest for short cycle time Resin Transfer Molding (RTM) part production is growing especially in the automotive industry. In this process, a reactive resin is injected in a dry fibrous preform placed in the cavity of a mold. Impregnation being affected both by the architecture of the textile and the evolving viscosity of the fluid, experimental determination of the optimal injection strategy requires heavy and expensive trial-error campaigns. Thus, in order to reduce both the pre-industrialization phase and the part cycle time, an accurate simulation tool may be of great interest. In this context, the presented work, introduces a new flexible dual-scale simulation approach, to treat reactive injection cases. This technique simulates accurately both the complex flow pattern of the fluid in the channels and the tows of the preform and the thermo-chemo-rheological couplings induced by the polymerization. This technique proposes a flexible microscopic filling strategy that induces both a weak sensitivity to the mesh size and a high CPU-time efficiency.

1. Introduction

Resin Transfer Molding (RTM) has been identified as a promising process for mass production of composite structural parts. In this process, a preform made of fibrous material is placed in the closed cavity of a mold and a thermosetting or thermoplastic resin is injected in the cavity to fill the spaces between the fibers. The resin gives after curing or solidification the final shape to the part. Key points for the introduction of RTM in composite mass part production are both the reduction of the pre-industrialization phase through quick and cost-effective injection strategy definition so as the reduction of the cycle time. In this context, an accurate and efficient simulation tool may be of great interest to optimize the process and reduce significantly the heavy and expensive experimental trial-error campaigns. The development of an accurate simulation tool requires identifying the phenomena influencing significantly the RTM process. This accuracy must furthermore be coupled with computational efficiency to reduce the computational cost of the injection strategy optimization.

In the framework of this study, focus has been placed on RTM with on-line mixing, that enable high cadency production and reduce resin wastes due to off-line mixing. The components of the resin are mixed at the mold inlet prior to injection. Fast curing resins have a significant influence on the evolution of temperature (the curing reaction is exothermic) and on the viscosity (viscosity decreases with an increasing temperature but increases with the crosslinking of monomers) during injection, which needs to be taken into account in the simulation.

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Moreover, the architecture of the textile composing the preform affects much the resin flow pattern. Textiles referred as single-scale porous materials as mats are composed of gaps within the same scale and feature a well-defined flow front and no resin storage during impregnation. On the other hand, so called dual-scale porous materials, as uni, bi or tri-axial materials or fabrics, commonly used for structural applications, present two types of pores: macro-pores (channels) between the tows (in the range of the millimeter) and micro-pores inside the tows (in the range of some micrometers). This has two consequences on the flow pattern as observed experimentally [1] and presented in Fig. 1:

- An unsaturated region is generated behind the macroscopic flow front (Region II) and may constitute a poor mechanical region if it is located in the part at the end of injection
- Resin storage occurs inside the tows (Region I). Stored resin may cure prematurely and affect the temperature repartition in the part.

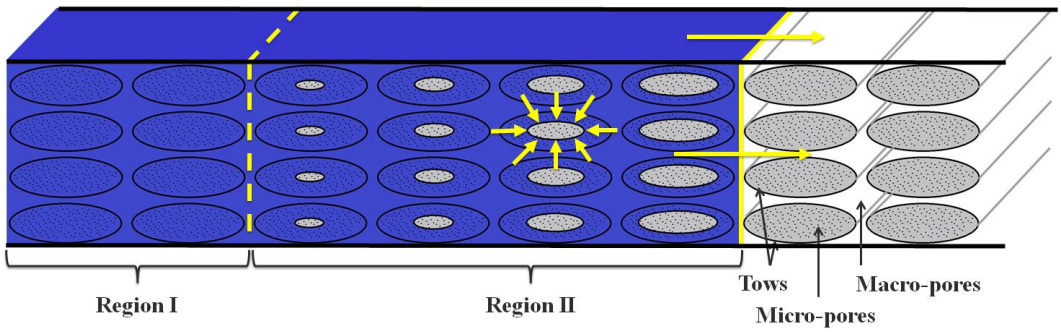

Figure 1. Dual-scale flow in a dual-scale porous material.

These phenomena affect the process and may lead to defects in the final part. For these reasons, simulation tools require to deal both with the reactive and dual-scale aspects of the injection to optimize the injection strategy. The aim of the new approach is to propose a computation technique for dual-scale flow simulations that features both CPU time efficiency and a fine degree of precision in the unsaturated area to treat reactive dual-scale problems. Final objective is the implementation of these developments in PAM-RTM from ESI's PAM-COMPOSITES commercial simulation tool.

In the following, physics and published numerical works dealing with dual-scale simulation of the reactive RTM process will be introduced. The second section will focus on the developed numerical approach and especially on the proposed novelties. And in the last section, results of simulations highlighting the flexibility of the method and the need for using dual-scale simulations to treat reactive RTM injections will be presented.

2. Previous work

2.1 Governing equations

Flow of a Newtonian fluid in porous materials has been widely investigated in the past. The commonly used equation to characterize the flow is Darcy's law (Eq. 1) [2]:

$$\bar{v} = \frac{-\bar{\bar{K}}}{\mu}\bar{\nabla}P \tag{1}$$

Where, $\bar{v}$ is the Darcy velocity of the fluid and P is the pressure in the fluid. $\bar{\bar{K}}$ is a tensor containing permeability values. μ is the viscosity of the fluid. The other governing equation for a single-scale fluid flow is the equation of mass balance, expressed for an incompressible fluid as Eq. 2:

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$$\nabla \cdot \bar{v} = 0 \tag{2}$$

In the case of a dual-scale porous material, a sink term q is introduced in the equation of mass balance (Eq. 2) leading to equation Eq. 3.

$$\nabla \cdot \bar{v} = S_I \tag{3}$$

The sink term S_I introduces in the mass balance the piece of information that a certain amount of fluid is removed from the macroscopic channels to be stored in the tows. Its value is non-zero in the unsaturated area and equal to zero in the saturated area. Furthermore, advection equation Eq. 4 describes the transport of the saturation I.

$$\frac{\partial I}{\partial t} + \bar{v} \cdot \bar{\nabla} I = S_I \tag{4}$$

I evolves between 0 (when the considered region is empty) and 1 (when the region is saturated with fluid). Moreover, the quantities of interest, temperature (T) and degree of cure (α), follow advection equations in the form of equation Eq. 5. The generic letter J is used for one or the other of these quantities. S_J is a generic expression for sink or source term(s) relative to the considered quantity of interest and $S_I J_c$ treats the absorption of fluid with a certain temperature or degree of cure in the tows.

$$\frac{\partial J}{\partial t} + \bar{v} \cdot \bar{\nabla} J = S_J - S_I J \tag{5}$$

Finally, the viscosity depends commonly on the temperature and the degree of cure and may be described using one of the numerous thermo-chemo-rheological laws proposed in the literature [3, 4].

2.2 Numerical approaches

The Finite Element Method/Control volumes (FEM/CV) is classically used to treat numerically Liquid Composite Molding problems [5, 6]. The nodes of the mesh are used to compute the pressure field in the impregnated area. Control Volumes associated either to the nodes or elements of the mesh allow dealing with the fluid filling. In the case of single-scale simulations, there is one single level of control volumes and no unsaturated area can be observed as volumes of channels and tows are counted together within an element [5, 6]. However, in the case of dual-scale simulations, to each macroscopic element (treating the flow in the channels) is associated a microstructure (treating the flow in the tows). These microstructures may be single fiber tows [7] or a crossing of tows[8, 9] and are treated using analytical expressions or 1D, 2D or 3D FEM/CV methods. Despite their high level of precision, these dual-scale simulation techniques present significant drawbacks: meshing parameters are constrained by the dimensions of the unit-cells used for the microscale simulations. Furthermore, unit-cells are often in the range of some mm² which imposes a very dense mesh inducing a high computational cost. Furthermore, the more complex is the microstructure, the more expensive the computations will be. In order to address the highlighted drawbacks, a new approach has been developed and will be presented in section 3. Furthermore, the Volume of Fluid (VOF) Method used by Abisset-Chavanne in [10] has been selected and adapted to treat the reactive aspects of the simulation. This method has been preferred to the Flux Corrected Transport technique [11] because it avoids iterative matrix inversions and appears more CPU time efficient.

3. Numerical Developments

The aim of the developed numerical technique is to track finely the filling kinetic of the tows and the evolution of the quantities of interest at both scales with a reduced computational cost.

3.1 Macroscopic and microscopic volume repartition

In the developed approach, the macroscopic mesh made of triangular elements covering the whole part allows dealing with the flow in the channels of the material while a fitted geometrically representative

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microstructure is associated to each macroscopic element to deal with the flow in the tows. As presented in Fig. 2, to each macroscopic element is associated a number of tows n_1 and n_2 with average lengths L_1 and L_2 that represent the equivalent number and lengths of tows oriented in the two directions of the fabric. This association is based on purely geometrical considerations (size and shape of the element, tows width, spaces between the tows). The filling of one tow in each direction is then used as reference to compute the saturation of the microstructure. Thus, the complex microstructure is reduced to two tow filling problems in each element.

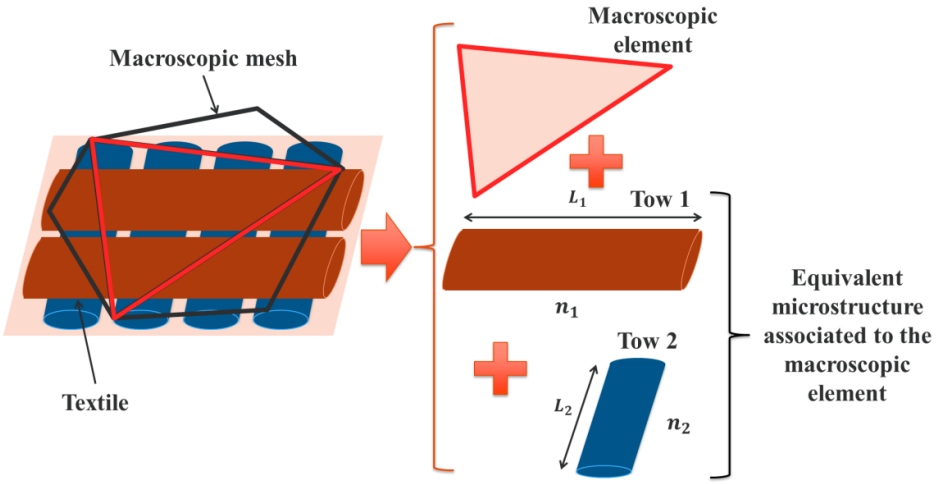

Figure 2. Equivalent tows are associated to each macroscopic element depending on its size and shape

3.2 Microscopic tow discretization

The classical FEM/CV approach is used to compute the pressure and the filling at the microscale. Two assumptions are made regarding tow filling which helps defining the microscopic tow meshing:

- The ratio of tow impregnated surface to the overall tow surface is assumed equal to the ratio of volume of fluid contained to the overall volume V_{macro} (Fig. 3).

I_c is the ratio of impregnated (blue) volume V_{imp} to the volume of the macroscopic element V_{macro}. It is also equal to the ratio of tow impregnated surface S_{imp} to the total tow surface S_{tot} and also to the impregnated length $L_{imp}$to the total length of the tow L.

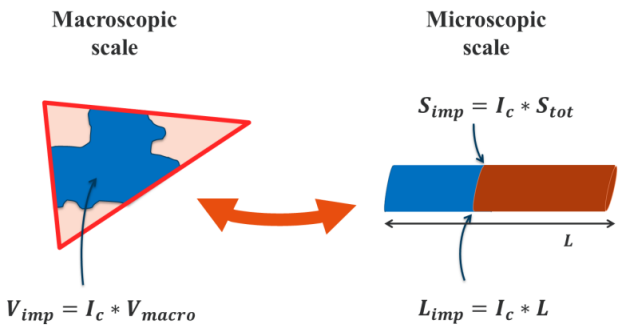

Figure 3. Ratio equivalence between impregnated to overall volumes, surfaces and lengths.

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- Tow filling is assumed to occur exclusively transversely in the tows

Fig. 4 presents the tow discretization principle. The discretization of the tow is made both in the transverse (A) and the longitudinal (B) directions. The mesh in the transverse direction is fixed and used for the FEM computation of the pressure field. To each element in the thickness is associated one single value of temperature, degree of cure (and therefore of viscosity). Furthermore, a longitudinal mesh is built along the filling of the macroscopic element (Fig. 4B) using a numerical method presented in section 3.4. This longitudinal mesh defines "columns" that will be treated as separated 1D filling problems. These "columns" allow representing finely the unsaturated area even in elements bigger than the unsaturated area itself. This approach allows reducing the filling of the tows to a sum of 1D filling problems which is more CPU time efficient than complex 2D or 3D. Moreover, with larger elements, less nodes are required for the same part and the computational cost is reduced.

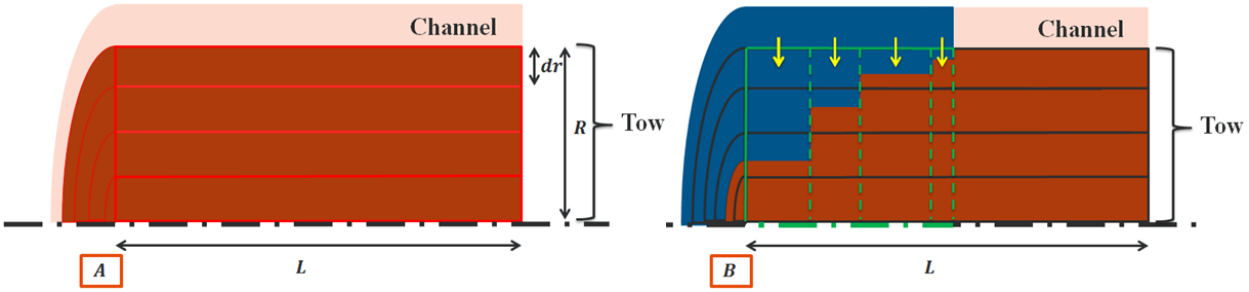

Figure 4. Meshing of the microstructure: example of a cylindrical tow with radius R and element thickness dr. (A) Red : fixed transverse meshing. (B) Green : longitudinal meshing ("columns") build along the macroscopic elements filling.

3.4 General algorithm

The pressure field and the macroscopic (channel) flow velocity are computed using a classical FEM/CV technique. This velocity enables to compute the amount of fluid that will enter each macroscopic element of the impregnated area. In the elements where the microstructure is not saturated, this volume needs to be spread between the channels and the tows. The microscopic pressure field is obtained from a FEM method applied in the transverse direction of the tow, and Darcy's equation allows computing the depth reached in the tow by the resin within a time step. Using the equation of mass balance, the width of the new column is determined (a position of equilibrium exists that satisfies these two equations). The depth reached, and the width of the column, are saved for the computation of the next time step. These macroscopic and microscopic techniques enable the determination of the flows in the channels and in the tows. The first order explicit approximation of Eq. 5 is then used to transport and update the quantities of interest (temperature and degree of cure) at both scales in the part. More details on the technique can be obtained in [12].

4. Numerical Results

4.1 Flexibility of the method regarding mesh size

One of the claims of the developed technique is its ability to treat dual-scale flow with the same degree of precision with various element sizes. Therefore, isothermal 1D filling simulations of a rectangular plate with constant inlet pressure have been conducted using meshes with element size from 2 mm to 20 mm. The textile considered in the frame of the simulation is a biaxial material with tows considered cylindrical. The characteristics of the textile and the processing conditions are described in Table 1.

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Table 1. Parameters for the isothermal injection at constant injection pressure.

Material Parameters	Value	Injection Parameters	Value
Length of the cavity (cm)	20	Injection pressure (Pa)	10^5
Radius of the tows (mm)	0.812	Injection viscosity (Pa.s)	$8.2 * 10^{-3}$
Average porosity	0.64		
Channel isotropic permeability (m²)	10^{-10}		
Tow radial permeability (m²)	$5 * 10^{-13}$		

The length of the unsaturated area has been measured in the simulations conducted with the different mesh sizes. It has been estimated to 6 mm with the 2 mm mesh and 5.7 mm within the elements of the 20 mm mesh. These values are very close even if for the 20 mm mesh, the elements are 3 times bigger than the unsaturated area. This highlights the capacity for the model to track accurately the unsaturated area even with large elements.

Furthermore, tracking the pressure evolution and the macroscopic flow front arrival at specific positions in the cavity enables to determine if the resin is spread in the same way between macro and micro-scales with a small or a large mesh. Table 2 presents the flow front arrival time at 10 cm from the injection line for the different mesh sizes. These arrival times are compared to the one obtained from the most refined 2 mm mesh and the relative errors are presented.

Table 2. Comparison of several parameters and results of the simulations with various element sizes.

Distance from injection 10 cm	Mesh size			
	2 mm	5 mm	10 mm	20 mm
Time of flow front arrival (s)	2.49	2.53	2.60	2.71
Error to the 2 mm mesh (%)		1.61	4.42	8.84
Number of elements in the model	2000	800	400	200
Ratio of computation time compared to the 2 mm mesh calculation	1/1	1/6.5	1/30	1/124

It can be noticed from Table 2 that with increasing mesh size, the error on the macroscopic flow front arrival is increasing. However, even when dividing the number of macroscopic elements in the model by a factor 10, this error remains under 10%. Furthermore, the method remains accurate in a range of 10% for elements more than three times bigger than the unsaturated area. This demonstrates the flexibility of the proposed model and its ability to treat accurately an isothermal injection case for several element sizes. Finally, the advantages of the new numerical method in terms of CPU time reduction can be noticed. In the case of the 10 mm mesh, the computation time is reduced by a factor 30 while the error on the time of flow front arrival stays smaller than 5% compared to the 2 mm mesh.

4.2. Dual-scale reactive simulation

A single scale reactive simulation using parameters of Table 3 has shown that the resin reaches the outlet after 95 s and prior to gelling. A dual-scale simulation is conducted using the same material and injection parameters. Results of both simulations are presented in Fig. 5.

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Table 3. Parameters used for the reactive 1D filling simulation.

Material parameters	Value	Injection parameters	Value
Dimensions of the cavity (cm^3)	74x10x0.34	Injection flow rate ($m^3.s^{-1}$)	$1.46 * 10^{-6}$
Tow geometry	Cylindrical	Injection viscosity (Pa.s)	$8.2 * 10^{-3}$
Tows 1: diameter (mm)	1.5	Injection and mold temperature	140
Tows 2: diameter (mm)	0.2	Injection duration (s)	95
Intra-tow porosity	0.4		
Channel porosity	1		
Average porosity*	0.529		
Channel permeability** (m^2)	$2 * 10^{-10}$		
Tow radial permeability (m^2)	$1 * 10^{-13}$		

*Porosity used for the single-scale simulation
**Permeability used for the single-scale and the channels of the dual-scale simulation

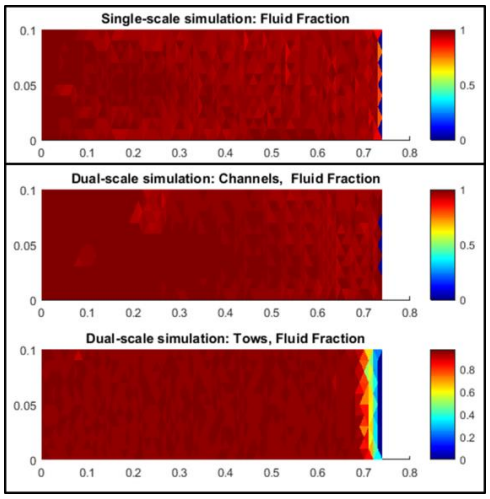

Figure 5. Fluid fraction in the part after 95 s of injection in single and dual-scale simulations

Fig. 5 presents the mapping of the fluid fraction after 95 s of injection. It can be noticed that the predictions of the single-scale simulation state that the part is fully filled with the resin (100 % of the part is filled). However, in the dual-scale simulation, it can be observed that the tows are not saturated at the end of the cavity (over the whole part, saturation reaches 100% in the channels but only 95.3% in the tows). Moreover, the reactive computation reveals the imminent resin solidification in the tows next to the vents, making impossible a further tow filling even with a longer injection time. Thus the dual-scale reactive simulation demonstrates that the injection parameters determined with a classical single-scale simulation do not allow filling the part properly.

5. Conclusions

In this work, a new numerical strategy has been proposed to simulate in an efficient way the flow of a reactive resin in a dual-scale porous material. The novelty of the approach consists in reducing the microscopic filling problem to a sum of 1D tow transverse fillings. The number and average length of tow in each macroscopic element is determined prior to the injection simulation. Thus, the microstructure associated to each element depends on its geometry. The representative tows are then discretized both in the longitudinal and transverse directions to track accurately the unsaturated areas

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in elements smaller or larger than the unsaturated area itself. These features make thus the approach more efficient in term of calculation time and more flexible in term of meshing.

Numerical simulations have been conducted to highlight the flexibility of the method. It has been demonstrated on a simple 1D filling simulation that increasing the size of the elements by a factor 10 reduced by more than 100 time the computation time and only led to errors smaller than 10 % on the flow front time arrival. Furthermore, single and dual-scale simulations of a reactive injection have been compared and the necessity of using a dual-scale simulation has been demonstrated.

Finally, the developed approach has demonstrated its ability to treat dual-scale injection cases. The next step will be to validate the approach by confronting the numerical with experimental results before industrial implementation in PAM-RTM from ESI's PAM-COMPOSITES simulation suite.

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