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NUMERICAL SIMULATION OF RESIN TRANSFER MOLDING USING BEM AND LEVEL SET METHOD

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ABSTRACT: Resin Transfer Molding is widely used to produce fiber-reinforced materials. In the process, the resin enters a close mold containing the dry fiber preform. For mold designer, numerical simulation is a useful tool to optimize the mold filling, in particular to identify the best positions of the ports and the vents. An issue in mold filling simulation is the front tracking, because the shape of the resin front changes during the flow. In particular, topological changes can appear resulting from internal obstacles dividing the front or multi-injection. A previous approach [1] using the Boundary Element Method (BEM) in a moving mesh framework shows the capability of the method to compute accurately the front propagation at low CPU time. The present paper describes a method developed to handle complex shapes, using BEM together with a Level Set approach. Numerical results in two dimensions are presented, assuming a Newtonian non-reactive fluid, and an homogeneous and not-deformable reinforcement. The resin flow in the fibrous reinforcement is modeled using Darcy's law and mass conservation. The resulting equation reduces to Laplace's equation considering an isotropic equivalent mold. Laplace's equation is solved at each time step using a constant Boundary Element Method to compute the normal velocity at the flow front. It is extended to the fixed grid and next used to feed a Level Set solver computing the signed distance to the front. Our model includes a boundary element mesher and a Narrow Band method to speed up CPU time. The numerical model is compared with an analytical solution, a FEM/VOF-based simulation and experimental measurements for more realistic cases involving multiple injection ports and internal obstacles.

KEYWORDS: Resin Transfer Molding (RTM), Level Set, Boundary Element Method (BEM)

1 INTRODUCTION

Liquid Composite Molding (LCM) processes are widely used in industry. Among them, Resin Transfer Molding (RTM) is one of the most popular. It consists in injecting the liquid resin in the dry preform held in position in a mold.

Recent aerospace programmes focus on forming structural parts using LCM. As mechanical performances strongly depend on filling conditions, resin flow prediction is important in mold design. In particular gates' locations are adjusted so that the resin impregnates correctly the entire preform. In that task, numerical simulation can be useful. As the resin flows, a tracking technique is employed to follow the moving front. It can be performed using moving mesh methods [1–3], Volume Of Fluid methods [4, 5] or Level Set methods [6, 7]. The main advantage of the last one is that the front is accurately captured in an Eulerian

framework.

The present paper focus on a technique combining a Boundary Element Method(BEM) [1, 2, 7, 8] and a Level Set method. The first part of this paper considers the governing equations. The second part describes the implemented model. The last part covers some applications.

2 GOVERNING EQUATIONS

2.1 PRELIMINARY TRANSFORMATIONS

Our model assumes that the liquid resin is a Newtonian non-reactive fluid, flowing in isothermal conditions through an homogeneous and not deformable fibrous reinforcement. In the impregnated area Ω , the macroscopic resin motion is governed by the modified Darcy's law [9] and incompressibility equation

$$\begin{cases} \langle \vec{v} \rangle = -\frac{[K]}{\mu} \vec{\nabla} p' & (1) \\ \vec{\nabla} \cdot \langle \vec{v} \rangle = 0 & (2) \end{cases}$$

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where $\langle \vec{v} \rangle$ is the macroscopic velocity, $[K]$ the permeability tensor, μ the liquid resin viscosity and p' the acting pressure. That pressure given by $p' = p + \rho gz$ includes a gravity term, where ρ is the resin specific mass and g gravity. Combining the previous equations and transforming the coordinates in the isotropic equivalent domain Ω_e of permeability K_e , we obtain

$$\begin{cases} \vec{v} = -\frac{K_e}{\mu\epsilon} \vec{\nabla} p' & (3) \\ \Delta p' = 0 & (4) \end{cases}$$

where \vec{v} is the resin velocity, computed from the macroscopic velocity using ϵ (medium porosity), and K_e is the equivalent isotropic permeability. The isotropic equivalent transformation [1, 10] is

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix} = \sqrt{K_e} \begin{bmatrix} \frac{1}{\sqrt{K_1}} & 0 \\ 0 & \frac{1}{\sqrt{K_2}} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (5)$$

where K_1 and K_2 are the principal permeabilities of the reinforcement. The isotropic equivalent permeability, is given as $K_e = \sqrt{K_1 K_2}$.

2.2 BOUNDARY CONDITIONS

Let us consider Γ_e the isotropic equivalent front bounding Ω_e . Boundary conditions are assigned according to the location of the point $M \in \Gamma_e$ under consideration. Dirichlet conditions (imposed pressure) are prescribed on the gate $\Gamma_{e_{p_0}}$ and on the free edge $\Gamma_{e_{p_f}}$

$$p' = \begin{cases} p_0 + \rho gz_0 & \forall M \in \Gamma_{e_{p_0}} \\ p_f + \rho gz_f & \forall M \in \Gamma_{e_{p_f}} \end{cases} \quad (6)$$

and Neuman conditions (imposed normal pressure gradient) are prescribed on the mold wall $\Gamma_{e_{q_0}}$ for a non-penetration condition

$$\vec{\nabla} p' \cdot \vec{n} = 0 \quad \forall M \in \Gamma_{e_{q_0}} \quad (7)$$

where \vec{n} is the unit outwards vector at point M .

3 NUMERICAL METHOD

3.1 OUTLINE

Our program is implemented using Matlab environment. At the beginning, pre-processing imports a standard mesh file, performs the isotropic equivalent transformation, assigns material and processing data, and locates the injection ports. Next, the filling routine based on a Level Set formulation advances the front. At the end, the post-processing plots the results once the real domain is recovered.

The filling stage is divided into a finite number of quasi steady states. At each step time, governing equations are solved using a constant Boundary Element Method. More details can be found in section 3.2. The front is advanced

by feeding a Level Set solver with the BEM-computed velocities. How it is done is covered in section 3.3. It is repeated until the mold is completely filled.

3.2 BOUNDARY ELEMENT METHOD

For clarity, the subscript e referring to the isotropic equivalent domain is omitted by the next. As mentioned earlier, BEM confines the calculation on the front Γ which is a close curve bounding the calculation domain Ω . A known value of pressure p or normal pressure gradient q is prescribed on the edges Γ_p or Γ_q . Laplace's equation is multiplied by the Green function p^* . Integrated twice by parts over the calculation domain and using Green's theorem leads to Somigliana's equation [1, 11, 12]

$$c_i p_i + \int_{\Gamma} p q^* d\Gamma = \int_{\Gamma} p^* q d\Gamma \quad \text{with } c_i = \frac{\theta}{2\pi} \quad (8)$$

where p_i is the value of the pressure at a point M_i on the boundary, q^* the pressure gradient associated with p^* and θ the internal angle of the corner in radians. For a two-dimensional domain, p^* and q^* are given as

$$p^* = \frac{1}{2\pi} \ln \left(\frac{1}{r} \right) \quad \text{and} \quad q^* = \frac{1}{2\pi} \frac{-\vec{r} \cdot \vec{n}}{r^2} \quad (9)$$

where r is the distance from the point M_i of application of the Dirac delta function to any point under consideration. Meshing the boundary into N constant boundary elements and applying Equation 8 leads to

$$c_i p_i + \sum_{j=1}^N p_j \int_{\Gamma_j} q^* d\Gamma = \sum_{j=1}^N q_j \int_{\Gamma_j} p^* d\Gamma \quad (10)$$

Rewritten in a matrix form using H and G , Equation 10 is then transformed into

$$\sum_{j=1}^N p_j H_{ij} = \sum_{j=1}^N q_j G_{ij} \quad (11)$$

where $H_{ij} = \frac{1}{2} \delta_{ij} + \int_{\Gamma_j} q^* d\Gamma$ and $G_{ij} = \int_{\Gamma_j} p^* d\Gamma$ are N^2 matrix. Finally, the previous equation is reordered to take the form of a linear system $AX = F$, where X is a vector of N unknowns.

3.3 LEVEL SET METHOD

The moving front is captured using the signed-distance function ϕ , defined so that the zero level set corresponds to the interface [6, 13]

$$\Gamma(t) = \{(x, y) \in \mathbb{R}^2 / \phi(x, y, t) = 0\} \quad (12)$$

For each point under consideration, distance is signed negative if located in the impregnated area and positive otherwise. We consider two meshes : a fixed grid made of unstructured triangle elements and a moving mesh made of beam elements.

Level Set equations [6, 13] govern the evolution of the signed-distance function. To combine with BEM, we use

a formulation involving a propagating interface with a velocity in its normal direction, given as follows

$$\begin{cases} \frac{\partial \phi}{\partial t} + F|\vec{\nabla} \phi| = 0 & (13) \\ \phi(x, y, t = 0) = \phi_0 & (14) \end{cases}$$

where F is the extended normal velocity, built to coincide with the velocity of the front (it is extrapolated outside without physical meaning). The filling stage is initialized by choosing ϕ_0 as the signed-distance to the inlet gates. Next, values for each points are updated using an Euler scheme

$$\phi(x, y, t + \Delta t) = \phi(x, y, t) - F|\vec{\nabla} \phi|\Delta t \quad (15)$$

where Δt is the time step, adjusted to match its upper limit (CFL conditions).

For the sake of efficiency, ϕ is not updated on the entire grid, but only on few nodes around the front in a “narrow band” [6]. Next, front is rebuilt using a boundary element mesher, based on interpolating the zero level set on the grid.

The method directly handles topological changes, involving merging or dividing fronts, but does not ensure that the resin remains inside the mold. Contact with mold is implemented using a fixed level set describing the mold walls. It acts by correcting ϕ as follows

$$\phi = \max(\phi, \phi_{\text{mold}}) \quad (16)$$

where ϕ_{mold} is the signed-distance to the mold.

4 APPLICATIONS

4.1 ISOTROPIC RADIAL INJECTION

We consider here the standard case of an isotropic radial injection, for a 0.25 m^2 square plate. The resin enters the part from the center and flows through the preform describing circular patterns. Four vents located on the corners ensure the complete filling. Material and processing parameters are summarized in Tables 1 and 2.

Table 1: Material data

$K[\text{m}^2]$	$\mu[\text{Pa}\cdot\text{s}^{-1}]$	$\rho[\text{kg}\cdot\text{m}^{-3}]$	$\epsilon[-]$
1.10^{-9}	0.1	1150	0.5

Table 2: Processing data

$p_0[\text{Pa}]$	$p_f[\text{Pa}]$	$r_0[\text{m}]$	$g[\text{m}\cdot\text{s}^{-2}]$
2.10^5	1.10^5	$2.5\cdot 10^{-3}$	9.81

In the first case, gravity is neglected for a comparison with an analytical solution [1, 10]. It is given as

$$\left[\frac{r_f}{r_0}\right]^2 \cdot \left[2 \ln\left(\frac{r_f}{r_0}\right) - 1\right] + 1 = \frac{4K(p_0 - p_f)t}{\epsilon\mu r_0^2} \quad (17)$$

where r_f and r_0 are the radii of the moving front and the inlet gate, p_0 and p_f the inlet and outlet pressures. The mold is meshed using 2500 triangle elements. CPU time is around 20 s on a 2.26 GHz / 1.93 Go of RAM laptop. The predicted filling time is 98 s. Our model is assessed by fitting the numerical fronts using the analytically predicted circles. Figure 1 shows the comparison between our numerical results (left) and the analytical results (right). Analytical results (in bold lines) are overlaid on our results, for 10.7 s and 63.3 s elapsed time. Using L1 norm leads to the relative error of 2.1%, which shows the accuracy of our numerical model.

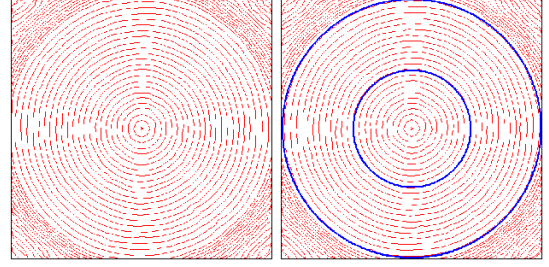


Figure 1: Comparison with analytical solution

The second case takes into account gravity effects. On Figure 2 we compare our results (left) with a FEM/VOF-based code (PAM-RTMTM) (right) using the same mesh. As expected, the flow is slightly deformed in the lower part of the plate. The predicted filling time is 101 s for our simulation and 89 s for PAM-RTMTM, which shows a good qualitative accordance. The difference is due to the contact implementation which is different in Level Set (see Equation 16) and VOF. Further developments will improve the contact accuracy by refining the mesh on the mold wall.

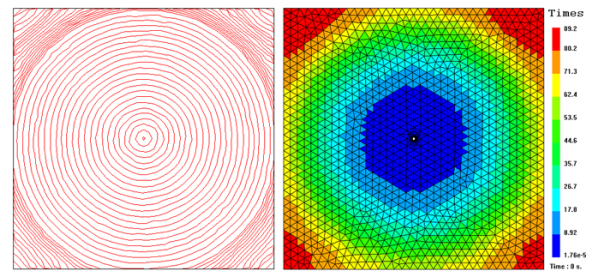


Figure 2: Comparison with FEM/VOF (PAM-RTMTM)

4.2 ANISOTROPIC INJECTION INVOLVING COMPLEX SHAPES

We compared our numerical results with experimental data, performing an infusion experiment involving a more realistic case. It consisted in impregnating an anisotropic knitted glass preform (1x1 rib knit fabric manufactured by *Textile Aero Tarn*) using a canola oil. The reinforcement (one layer) was placed under a transparent flexi-

ble bag and filled using two inlet gates and two vacuum lines (on the upper and lower sides). The dimensions of the mold are 0.3 m per 0.35 m. Some internal obstacles were placed to simulate contacts with mold walls. Material data (see reference [14] for measurement procedure) and processing parameters are given in Tables 3 and 4. CPU time is around 200 s for a model involving 3693 elements. Figure 3 shows the comparison between our results (at the top) and experimental data (at the bottom) at different times. The agreement is fair at any time. In particular, fronts merging (at 3 s) and dividing on the obstacles (at 7 s) are accurately predicted.

Table 3: Material data

$K_1[m^2]$	$K_2[m^2]$	$\mu[Pa.s^{-1}]$	ϵ
$1.50.10^{-9}$	$7.75.10^{-10}$	0.067	0.705

Table 4: Processing data

$p_0[Pa]$	$p_f[Pa]$	$r_0[m]$
$1.03.10^5$	120	5.10^{-3}

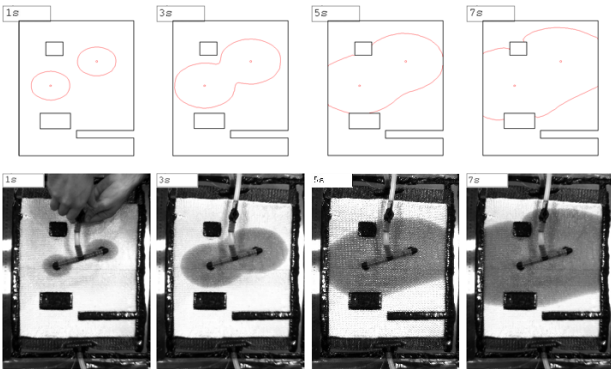


Figure 3: Comparison with infusion experiment

5 CONCLUSION

We developed a software to predict a two-dimensional resin impregnation for both isotropic and anisotropic cases. Results were compared with an analytical solution, a FEM/VOF-based simulation and experimental data, with a fair agreement. The implemented model includes a gravity term, but it can easily be modified to take into account other body forces. Further developments will include a 3D approach (technique remains unchanged), and a high permeability layer to simulate infusion process.

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