

## **THREE DIMENSIONAL, NONISOTHERMAL ANALYSIS OF RTM AND VARTM PROCESSES USING hp-ADAPTIVE FINITE ELEMENT METHOD**

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### **Abstract**

A highly accurate numerical technique for the simulation of resin infusion in composite preforms using a transient, 3-D, non-isothermal, two-phase analysis is presented. An adaptive finite element method is used to solve the equations. The uniqueness of the present approach is that resin infusion is modeled as a weakly compressible, two-phase flow in a porous media. VARTM processes can be solved by accurately specifying air properties based on the vacuum conditions. The results presented indicate the usefulness of the model.

### **1. Introduction**

#### **1.1 Background**

Resin Transfer Molding and its variants, such as, Vacuum Assisted RTM, are used to produce resin infused thick and thin fiber reinforced composites. These methods offer excellent alternatives for large scale manufacturing of composites in the military, aerospace, and the automotive industries. However, to succeed commercially, RTM and its variants have to establish themselves as a reliable technique for manufacturing defect free composites with short cycle times. An accurate numerical simulation of these processes can help to achieve the above mentioned goal.

The manufacture of polymeric composites using RTM is achieved by infusing a liquid polymer in a porous preform. The preform of the part to be filled is placed in a mold and the resin is infused through inlet gates. The design of inlet gates and vent locations is crucial for successful filling of the part. A poor design will result in resin breaking through the vent without completely filling the part. The curing and flow properties of the resin should be maintained optimum by controlling the temperature of the resin. Some of the common defects in RTM processes are: dry patches, fiber washout, and air entrapment. A thorough understanding of the sensitivity of the process to the control parameters such as location of gates and vents, temperature, and injection pressure are required to optimize the manufacturing process.

#### **1.2 RTM Simulation: Review of previous work**

A recent literature review of RTM simulation is presented in reference [1]. In this section, relevant

developments, especially in the nonisothermal modeling of the process, are presented. Some of the chief issues pertaining to nonisothermal modeling are: (a) the definition of local equilibrium temperature (b) the computation of effective properties, (c) the inclusion of dispersion and dissipation terms, and (d) the numerical issues related to the advection terms. The first issue is well addressed by Tucker and Dessenberger [2]. There are two distinct approaches followed in the literature for simulating nonisothermal filling. The energy equation can be solved independently in the preform and the resin by defining a distinct local equilibrium temperature in them and link the equations via coupling heat transfer terms [2,3]. An alternative approach would be to define a single local equilibrium temperature in the continua and solve a single energy equation with averaged properties. The latter is often used due to its simplicity and the accuracy of the former method heavily relies on the modeling of the coupling terms and it is required only when the temperatures of the solid and the liquid phases change rapidly [2]. In this work, the latter approach is followed.

The definition used for the volume averaged properties of the porous continua is a modeling issue. In the references [2] and [4], the conduction terms of the preform and the resin are modeled as resistors connected in parallel. On the contrary, the expression used by Young [5] implies that they act as if they are connected in series, and this does not depict the heat transfer dynamics accurately. In the present work, in addition to the interaction between the preform and the resin, we have a three-phase interaction of the preform, resin, and air. A parallel resistance model between the preform and the fluids, and a series model between the fluids is assumed. Importance of the dispersion terms is well discussed in the references [2] & [4]. The inertial dispersion terms become significant when the flow becomes turbulent and they are not important in most RTM processes. The significance of different modes of heat transfer are analyzed in the references [4] and [6]. The effect of natural convection is dominant in geophysical flows in porous media [7], and it can become significant in a RTM process when the filling is slow. Another important aspect of the heat transfer in the dynamics of the RTM is the temperature dependence of the properties. In addition to the density and the viscosity, material properties such as the permeability of the preform also vary with temperature [8].

## 2. Proposed Method

The infusion of resin in a porous preform is modeled as a transient, three dimensional, nonisothermal, weakly compressible, two-phase flow of a resin and air in a porous media. This model accurately describes the physics of the process. In this section we describe, governing equations, boundary conditions, and the numerical method.

### 2.1 Governing Equations

Conservation of Mass: The mass conservation equation for the resin and air are given in equation (1). The suffixes 1, 2, and 3, indicate properties of the resin, air, and the preform, respectively. The flow domain  $\Omega \subset \mathbf{R}^3$  is three dimensional and its boundary is denoted by  $\Gamma \subset \mathbf{R}^2$ .

$$\partial(\phi S_i)/\partial t = -\nabla \cdot (\rho_i \mathbf{v}_i) \quad i = 1, 2 \text{ in } \Omega \quad (1)$$

where  $\phi$  denotes the porosity,  $\rho_i$ ,  $S_i$ , and  $\mathbf{v}_i$  are the density of the fluid, the phase saturation, and the phase velocity vector, respectively. Since,  $S_1 + S_2 = 1$ , it is suffice to compute the saturation of resin.

Conservation of Momentum: Darcy's law describes the momentum dynamics in a porous media completely saturated with a fluid. In the case of a two phase flow model, Darcy's law is modified using the relative permeability function [9] to account for the presence of two fluids. The modified Darcy's model is given by  $\mathbf{v}_i = \mathbf{m}_i \nabla p_i - \rho_i \mathbf{g} \nabla D$ , where  $D$  denotes the depth and  $\mathbf{m}_i$  denotes the mobility of the phase  $i$  and it is given by the expression  $(\mathbf{m}_i = \mathbf{k} \mathbf{k}_{ri} / \mu_i)$ . Here,  $\mathbf{k}$  is the absolute permeability tensor for the fiber preform,  $k_{ri}$  is the relative permeability of the phase  $i$ , and  $\mu_i$  is the dynamic viscosity of phase  $i$ .

Model equations for average Pressure and Saturation: The above equations can be rearranged into a parabolic equation describing the average pressure and an hyperbolic equation describing the saturation of the resin. The average pressure,  $P$  is the average of the phase pressures and it is given by,  $P = (P_1 + P_2)/2$  and the capillary pressure,  $P_c$  is given by the difference,  $P_c = P_2 - P_1$ . To close the system of equations, the capillary pressure is empirically specified.

$$\phi C_t (\partial P / \partial t) = \tilde{\mathbf{N}} \cdot ((\mathbf{m}_1 + \mathbf{m}_2) \cdot \tilde{\mathbf{N}} P) + 1/2 \tilde{\mathbf{N}} \cdot ((\mathbf{m}_2 - \mathbf{m}_1) \cdot \tilde{\mathbf{N}} P) - \mathbf{g} \tilde{\mathbf{N}} \cdot ((\mathbf{m}_1 \rho_1 + \mathbf{m}_2 \rho_2) \cdot \tilde{\mathbf{N}} D) \quad (2)$$

$$\mathbf{v}_t = \mathbf{v}_1 + \mathbf{v}_2 \quad (3)$$

$$\phi (\partial S_1 / \partial t) = \tilde{\mathbf{N}} \cdot (\mathbf{h}_1 \cdot \tilde{\mathbf{N}} S_1) - \tilde{\mathbf{N}} \cdot (f_1 \mathbf{v}_t) - \tilde{\mathbf{N}} \cdot (\mathbf{G}_1 \cdot \tilde{\mathbf{N}} D) \quad (4)$$

where  $\mathbf{v}_t$  is the total velocity vector, the fractional flow coefficient  $f_1 = \mathbf{m}_1 / (\mathbf{m}_1 + \mathbf{m}_2)$ , the capillary term

$\mathbf{h}_1 = -\mathbf{m}_2 f_1 (d p_c / d S_1)$  and the gravity term  $\mathbf{G}_1 = f_1 (\rho_1 + \rho_g) \mathbf{g} \mathbf{m}_2$ . The total compressibility,  $C_t$  is the sum of the individual compressibilities of the resin, air, and the preform.

Law of Conservation of Energy A local equilibrium temperature  $T$  is defined and the heat transfer in the domain is studied using a single energy equation. The thermal conductivity is assumed be in parallel between the preform and the fluids, and in sequential mode between the fluids. Hence the equivalent thermal conductivity  $\kappa$  is given by the expression  $\kappa = (1 - \phi) \kappa_3 + \phi \kappa_1 \kappa_2 / (\kappa_1 S_1 + \kappa_2 S_2)$ .

Equation (5) describes the energy equation. The terms  $\alpha$  and  $\beta$  denote the averaged capacitance coefficients and are given by  $\alpha = (\rho C_p)_1 S_1 + (\rho C_p)_2 S_2$  and  $\beta = (\rho C_p)_3 (1 - \phi) + \alpha$ , respectively.

$$\beta (\partial T / \partial t) + \alpha \mathbf{v}_t \cdot \tilde{\mathbf{N}} T = \tilde{\mathbf{N}} \cdot (\mathbf{k} \cdot \tilde{\mathbf{N}} T) \quad (5)$$

### 2.2 Boundary and Initial Conditions

The boundary of the domain consists of the inlet gates, the exit vents, the solid walls of the mold, and the symmetry planes. For the pressure equation, either the pressure or the fluxes should be specified on all boundaries, as this equation is elliptic in space and parabolic in time. The saturation equation is hyperbolic, hence it is only necessary to specify the value of saturation of resin (which is 1) at the inlet boundaries. The velocities are post computed using the pressure distribution, hence, an accurate specification of boundary conditions for the pressure equation is suffice for the velocity equations. Energy equation is also parabolic in time and elliptic in space, hence, either temperature or the heat flux must be specified on all boundaries. Initial conditions for the pressure, saturation, and the temperature should be specified through out the domain  $\Omega$ .

### 2.3 Finite Element Model

The equations presented was solved using an  $hp$ -adaptive finite element method. The RTM code was developed on a  $hp$ -finite element kernel called ProPHLEX [10]. This library offers a variety of methods for the estimation of error in the computed solution and can perform dynamic mesh adaptivity based on such estimates. These techniques enable the code developed to provide an accurate solution at an optimal cost.

## 3. Results and Discussion

The results of the numerical simulation of three test cases are presented in this section. The first test problem, resin infusion of a 1-D preform, is studied to validate the nonisothermal model. The results are compared with the analytical solution. RTM of a boat hull

preform is presented as the second example. The analysis of a VARTM infusion of a thin door panel is discussed as the third test case. This example clearly demonstrates the need for three dimensional modeling even for thin parts and also the ability of the model to use the actual vacuum conditions.

### 3.1 1-D Preform Filling: Analytical Comparison

For a one-dimensional problem, in the absence of the advection and the transient terms in the energy equation, a closed form analytical solution can be derived for the equation (5). If the saturation front is at a distance  $x$  from the inlet gate, then the temperature at the front can be obtained from the expression,  $T = (\kappa_{13} (L-x) T_{inlet} + \kappa_{23} x T_{vent}) / (\kappa_{13} (L-x) + \kappa_{23} x)$ , where  $\kappa_{13}$  and  $\kappa_{23}$  are the effective thermal conductivity of the resin filled portion of the preform and the unfilled preform, respectively. Figure 1 shows the mesh used for the analysis and it has 80 linear elements. The comparison between the predicted temperature distribution and the closed form solution is shown in the figure 2. The saturation and the pressure distributions corresponding to this time step is shown in figure 3. Table 1 shows the comparison of the temperature at different front positions. Figure 5 shows the fill factor plot, the percentage of preform filled is shown as a function of time. The results of the model developed compare well with the analytical solution.

### 3.2 Filling a boat hull preform

The resin infusion of a symmetric boat hull preform is analyzed using the model developed. Figure 5 shows the distribution of saturation in the domain. The mesh used for the problem has 900 quadratic (hex 27) elements. Due to the symmetry conditions, only one fourth of the domain is studied. The preform is made of two different mats, the skin veil has a higher permeability and porosity than the inner core. Due to the placement of the vent and the inlet gate on the inner core side, the filling is initially slow, but once the resin reaches the veil, the filling process is accelerated by the rapid filling of the veil due to the race tracking like effect. This is clearly seen from the fill factor plot in figure 6.

### 3.3 VARTM of a door panel

In a VARTM processes, there is no vent in the system. In such cases, the preform in the mold is subjected to vacuum conditions, then the resin is infused in the preform. The advantage of the technique is, loss of resin due early break through to the vent can be avoided in cases where optimum design of the gate and the vent locations are not possible. Air properties are pressure dependent and based on the vacuum pressure, the compressibility and the density can be prescribed. The weakly compressible, two-phase flow model implemented enables the simulation of such problems. The properties at vacuum pressure are

determined based on the ideal gas thermodynamics. Figures 6 and 7 shows the pressure and the saturation distributions. Due to the symmetry of the panel, only one fourth of it is modeled. The resin is infused through the center of the panel. And the panel is made of mats with varying permeability data. From the saturation distribution one can see the race tracking effect. In a normal RTM process, such a situation will pose difficulty in the placement of vents and will also lead to the loss of the resin. However, this is avoided with VARTM. Even though the panel analyzed is thin (figures are magnified 10 times in Z direction), three-dimensional effects are important due to the varying material properties.

## 4. Conclusions

The model presented in this paper is highly accurate very useful to simulate numerically RTM and VARTM processes. The comparison of predictions with analytical results validate the model. More examples demonstrating dynamic mesh adaptivity, coupled heat and momentum transfer, and additional validation using experimental results will be presented in the conference.

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## Keywords

Resin transfer molding, two-phase flow, finite elements, and nonisothermal

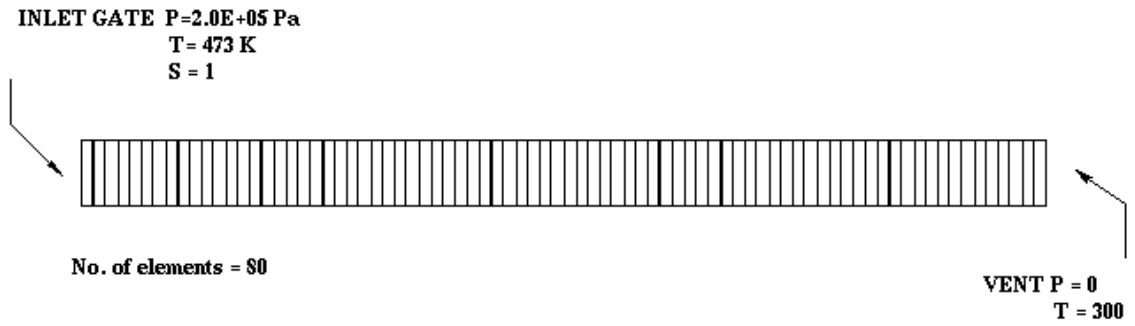


Figure 1: The finite element mesh used for the 1-D preform.

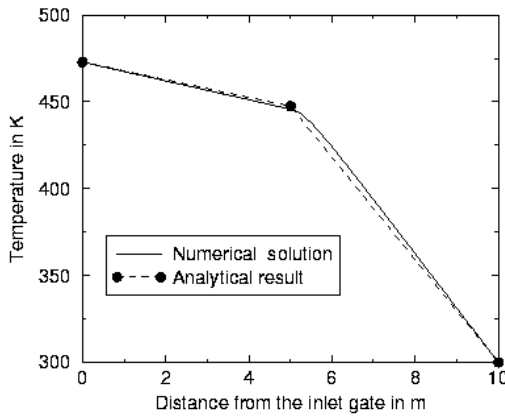


Figure 2. Comparison of the predicted temperature with the analytical result when the saturation front is at 5.0m

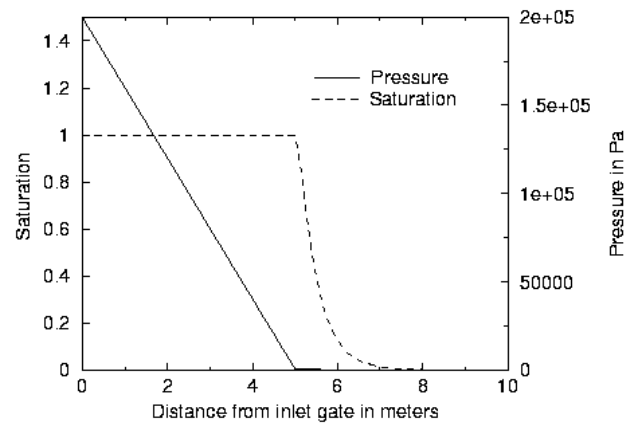


Figure 3: Distribution of the saturation and the pressure in the 1-D preform. Front location is at 5 meters from the inlet.

Front Location	Analytical	Numerical
2.25 m	464.71 K	464.27 K
3.25 m	459.67 K	459.05 K
3.90 m	455.73 K	454.80 K
5.00 m	447.43 K	445.87 K
5.25 m	445.72 K	442.31 K
6.00 m	437.28 K	435.15 K
6.50 m	430.85 K	428.46 K
7.25 m	418.71 K	415.37 K

Table 1: The comparison of the temperature at the flow front. The error is less than 1.0%

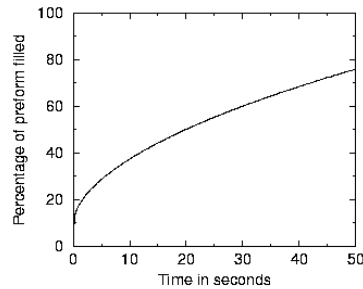


Figure 4. Percentage of preform filled with the resin.

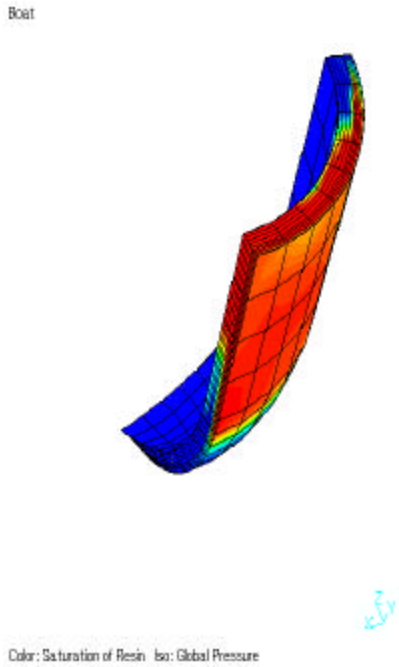


Figure 5. The saturation distribution in the boat hull.

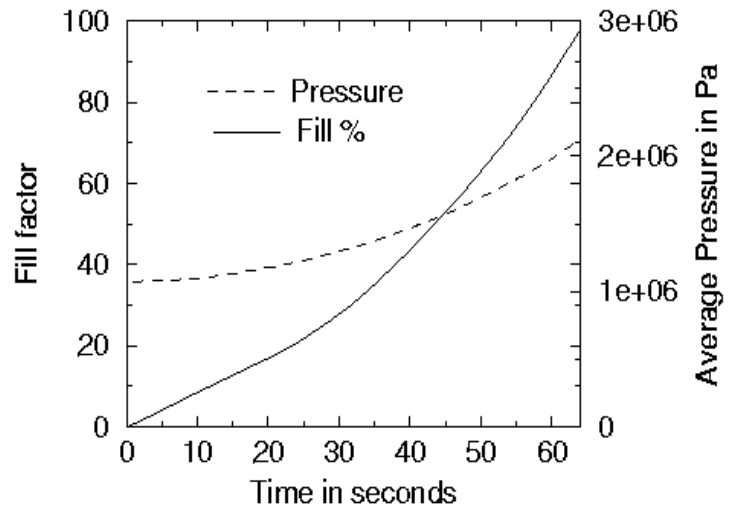


Figure 6. The fill factor and the average pressure plot for the boat hull.

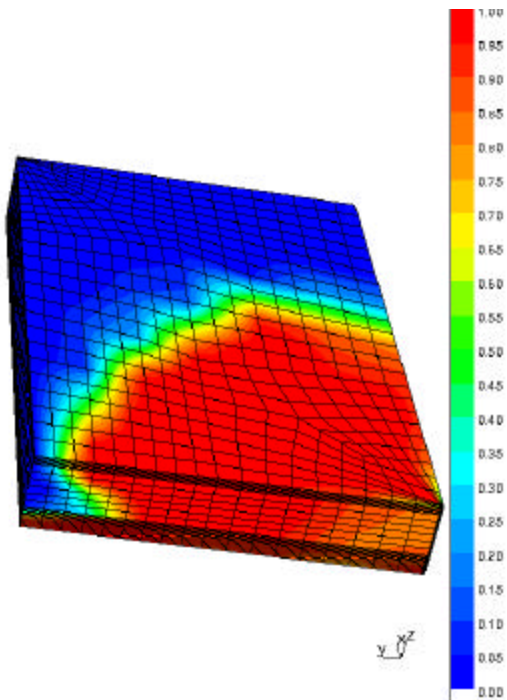


Figure 7. The saturation distribution in the panel preform during VARTM infusion.

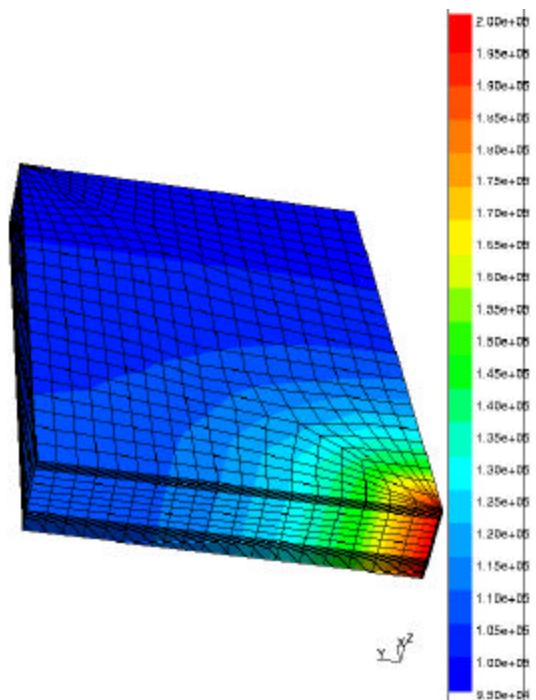


Figure 8. The pressure distribution in the panel preform during VARTM infusion.