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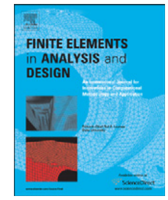

3D numerical simulation of filling and curing processes in non-isothermal RTM process cycle

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ABSTRACT

It is important to simulate non-isothermal RTM process cycle due to the high speed of filling mold during the filling stage and the long curing period during the curing stage. In this paper, we present numerical formulations for resin flow based on the concept of quasi-steady state situation at the filling stage and for resin cure at the curing stage. To make sure the applicability to complex product shapes, we use the four-node unstructured tetrahedron mesh, based on which the numerical formulation of temperature and cure convection is developed. The validity of our method is established in the case where flexible meshes are used. The results show that the numerical procedure, tested on known data, provides numerically valid and reasonably accurate predictions.

1. Introduction

The Resin Transfer Molding (RTM) process cycle consists of two sequential stages, i.e. the filling and cure stages. The simulation of non-isothermal RTM process is very difficult because the flow, heat transfer, and resin cure are highly interrelated at the filling and curing stages. The flow pattern and cure process are strongly affected by heat transfer and resin cure since the viscosity changes as a function of temperature and conversion [18,19], which in turn are determined by the flow and cure. In order to model the process accurately, the flow, heat transfer, and resin cure must be incorporated correctly.

In most of the previous researches [5,11,3,15,14,24], the simulations were simplified by calculating the flow under the two-dimensional (2D) setting and assuming the heat diffusion to be only in the plane. Because of the deeply decreased computation cost, this method was widely applied even though the generated results could be inapplicable for the actual process. Some previous researches [7,9,13] developed 2.5-dimentional (2.5D) non-isothermal models, which include the flow in plane and heat diffusion in the thickness for the thin parts based on the Control Volume/Finite Element Method (CV/FEM). In Ref. [1], the authors presented a numerical simulation to predict the flow pattern, extent of reaction, and temperature change during filling and curing in a thin rectangular mold. In practice, 2D or 2.5D model is in general not valid, especially for thicker parts. The flow in the thickness must be carefully taken into account and the heat transfer and resin cure must be computed in three-dimensional (3D) space. To address this issue, in Ref. [16], the authors considered flow within each nodal volume as a one-dimensional (1D) flow regardless of the number of upstream or downstream nodes based on the Lagrangian interpretation of the first order upwind scheme. In some other researches [22,23], the 3D simulation of filling was performed during the RTM using the CV/FEM based on regular structured mesh. There are also previous studies, say Refs. [4,10], focusing on applying the 3D Galerkin finite element methods to simulate the filling stage or the curing stage. In these researches, the structured hexahedral mesh was used and hence the flexibility of dealing with complicated shapes was not sufficient. Therefore, they were limited to regular parts and simple flow fields. When calculating complicated shape parts, the results are usually not satisfactory. In the presented paper, by using the four-node unstructured tetrahedron mesh that fits complicated shapes and flow fields, we derive the discretization schemes of the energy equation and the chemical equation based on upwind scheme in the three directions. Hence, our method can be widely applied to different kinds of parts and significantly improve the calculation precision.

The rest of the paper is organized as follows. In Section 2, we provide the basic formulation used in the paper. Following it, in Sections 3 and 4, we discuss the derivation of numerical formulations based on four-node unstructured tetrahedron mesh and calculation procedure, which is used during developing code. We then present a case study to verify our method on known dataset in Section 5.

2. Control equations

In this section, we present the basic control equations. For the non-isothermal RTM process under investigation, we make the

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following assumptions:

(1) The resin is an incompressed liquid and its viscosity is a function of the temperature and curing ratio.
(2) The temperature of the resin and fiber is identical at each position.
(3) There is no resin before the flow front and the control volume is fully saturated after the flow front.
(4) There is a quasi-steady time window, in which the viscosity dissipation energy can be neglected.
(5) Resin stops flow at the curing stage.

2.1. Flow control equation

At filling stage, Darcy's equation, which describes how the resin flows in the fiber, is still applicable. In the case, Darcy's law, which describes the flow within the mold, can be written as follows:

$$\mathbf{v} = -\frac{1}{\mu}\mathbf{K}\nabla p \tag{1}$$

where $\boldsymbol{v}$ is the Darcy velocity vector, $\boldsymbol{K}$ is the permeability tensor, ∇p is pressure gradient, and μ is the resin viscosity, which is a function of the resin temperature and degree of cure given below

$$\mu = \mu_0 e^{E_\mu/RT}\left[\frac{\alpha_g}{\alpha_g-\alpha}\right]^{d_1+d_2\alpha} \tag{2}$$

where μ_0 is the initial degree of viscosity, E_μ is the activation energy of resin, α_g is the degree of cure of the resin gel point, d_1 and d_2 are two constants, R is the gas constant, and T and α are the temperature and the degree of cure, respectively.

Based on the quasi-steady state assumption, the mass balance equation at each node is given by

$$-\nabla\cdot\mathbf{v} = 0. \tag{3}$$

Substituting Eq. (1) into Eq. (3), the flow control equation can be expressed as

$$\iint_S \frac{1}{\mu}[n_x,n_y,n_z]\mathbf{K}\begin{bmatrix}\frac{\partial p}{\partial x}\\ \frac{\partial p}{\partial y}\\ \frac{\partial p}{\partial z}\end{bmatrix} dS = 0 \tag{4}$$

where n_x, n_y, n_z is the normal tensor $\boldsymbol{n}$ in x, y, z directions of the surface of the integrated volume, and S is the surface in which the control volume is enclosed.

The possible boundary conditions are:

(1) $p=p_0$ for constant pressure injection or $u=u_0$ for constant velocity injection at the inlet;
(2) $p=0$ at the flow front;
(3) $\partial p/\partial \boldsymbol{n}=0$ at the mold wall.

2.2. Energy equation

For the 3D simultaneous equations, it is supposed that the heat convection of the resin and fiber occurs at the same time, that is to say, $T_f=T_r=T$. In the filling stage, the energy equation of the balance mode is written as

$$\left[\phi\rho_r c_{pr}+(1-\phi)\rho_f c_{pf}\right]\frac{\partial T}{\partial t}+\rho_r c_{pr}\left(v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}+v_z\frac{\partial T}{\partial z}\right) = k_L\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\phi\dot{s} \tag{5}$$

where ϕ is the porosity, ρ_r and ρ_f are the resin density and the fiber density, respectively, c_{pr} and c_{pf} are the resin specific heat and the fiber specific heat, respectively, v_x, v_y, v_z is the velocity in x, y, z directions, k_L is the whole heat conductivity of fiber and resin, which can be expressed as

$$k_L = \frac{k_r k_f}{k_r W_f + k_f W_r},$$

where

$$W_r = \frac{\phi}{\rho_f}\Big/\left(\frac{\phi}{\rho_f}+\frac{1-\phi}{\rho_r}\right), \quad W_f = 1-W_r$$

$\dot{s}$ denotes the quantity of the heat during the resin curing process, which can be expressed as $\dot{s}=\Delta H G(\alpha,T_r)$, where ΔH is the heat of reaction and the curing kinetics equation $G(\alpha,T_r)$ (based on Kamal's model [20,8,12] is expressed as follows:

$$G(\alpha,T_r) = (A_1 e^{-E_1/RT_r}+A_2 e^{-E_2/RT_r}\alpha^{m_1})(1-\alpha)^{m_2}$$

where A_1, A_2, E_1, E_2, m_1, m_2 are all constants, and t is the time variable. In Section 5, we will glimpse at curves of G vs. t and α vs. t at variable temperatures in Fig. 4.

In the above equation, the first part of the left hand side describes energy change of the resin and fiber, and the second part corresponds to the heat convection of resin. The first part of right hand describes the heat conduction of resin and fiber, and the second corresponds to heat release due to curing of resin.

The boundary conditions are given as

(1) $T=T_0$ at the inlet gate;
(2) $T=T_f$ or $k_L\partial T/\partial\mathbf{n}|_{ff}=(1-\phi)\rho_f C_{pf}\mathbf{v_n}(T_{f_0}-T)$ at the flow front [2];
(3) $T=T_m$ at the mold wall.

Clearly, the boundary condition imposed at flow front may be expressed either by a constant temperature equal to the temperature of the fiber mat or a heat balance equation. Comparison of different boundary conditions provided by Antonucci et al. [2] shows that both the constant temperature and the heat balance equation lead to similar temperature results at the flow front especially at the end of mold filling. We use both the constant temperature and the heat balance equation given earlier as thermal boundary conditions in our numerical simulation.

When filling is over, the process is changed into curing and the resin stops flow in the fiber. So, in Eq. (5), $v_x=v_y=v_z=0$.

2.3. Chemical equation

In the resin curing process, it is assumed that molecular diffusion of macromolecules is negligible. At the filling stage, the resin chemical reaction follows the chemical equation that is

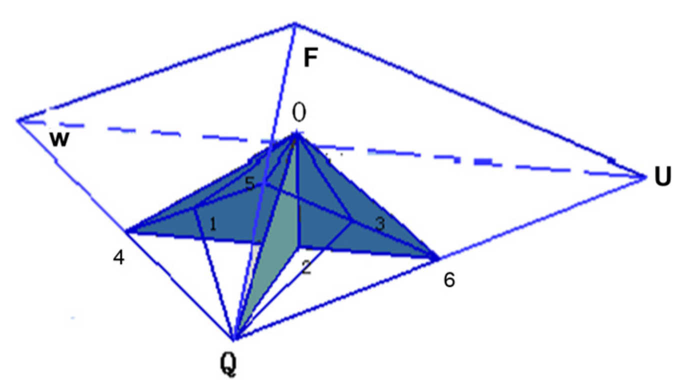

Fig. 1. Control volume composed of the tetrahedron element.