Non-isothermal Mold Filling and Curing Simulation for Resin Transfer Molding

CHEN Ren-liang[1], GUI Bing[1,2], LI Ming-cheng[1], LIANG Zhi-yong[3]
(*1. College of Aeronautics & Astronautics, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, China*)
(*2. Department of Mathmatics, Nanjing Forest University, Nanjing 210018, China*)
(*3. College of Material & Engineering, Beijing University of Aeronautics & Astronautics, Beijing 100083, China*)

Abstract: A numerical model of 2.5D non-isothermal resin transfer molding simulation is developed for thin part based on the control volume/finite element method. The non-uniform temperature distribution and the heat generation during the filling stage are modeled with the lumped temperature system and the species balance. Numerical algorithm of the simulation are studied. The molding simulation for a part is performed to show the effectiveness of simulating filling time, temperature distribution and curing degree.

Key words: resin transfer molding; finite-element analysis; mathematical model; numerical simulation

树脂传递成型工艺中树脂流动和凝固过程的非等温仿真. 陈仁良, 桂冰, 李明成, 梁志勇. 中国航空学报(英文版), 2003, 16(4): 247-252.

摘 要: 采用控制体/有限元方法建立了模拟树脂传递成型工艺制造薄壁零件时树脂流动和凝固过程的2.5维非等温仿真数学模型, 该模型运用纤维、树脂的能量平衡和树脂凝固的质量平衡方程模拟树脂流动和凝固过程中的热量传递和温度变化过程,研究了树脂传递成型工艺过程中树脂流动、温度变化及树脂凝固的数值求解方法,算例结果表明所提出的仿真模型能有效地模拟树脂传递成型工艺过程中树脂流动、温度变化及树脂凝固程度。

关键词: 树脂传递成型; 有限元分析; 数学模型; 数值仿真
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Resin Transfer Molding (RTM) has become an attractive method in which liquid reactant cures in a mold with fabric reinforcement to produce a composite part. Interest in these technologies has grown dramatically, spurred by the military's need for affordability and high performance and the auto industry's emphasis on higher productivity and lower-volume market niches.

There are so many technical issues concerned with RTM processes[1-3]. Because of the anisotropic nature of the reinforcement fibers, the flow pattern in the mold can be very complicated. Cure of resins utilizes heat to cause a crosslinking reaction. The rate of the reaction is dependent on the temperature and extent of resin conversion. Heat generation and transfer can result in a non-uniform temperature distribution in the mold.

Owing to the interaction of different variables and the complexity of the process, mold and process design are currently conducted using trial and error. Experimental methods for optimization of mold and process design may be too time consuming and economically prohibitive. A compute numerical simulation model capable of predicting resin flow behavior, pressure gradient inside the mold, and curing process is needed to optimize injection

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port positions, injection pressure, filling time, temperature, and curing degree.

A number of studies have developed non-isothermal flow models with a heat transfer model[4-9]. These models are coupled by the fluid viscosity, which is the function of both temperature and cure conversion. However, most of them are concentrated on two-dimensional by simplifying the heat transfer form. In the actual case, the thermal effects are three-dimensional and require three-dimensional analysis. There are some studies on the non-isothermal RTM mold filling and curing processing with true three-dimensional analysis[10-13]. Unfortunately, the huge computation time limits its application. Moreover, three-dimensional model makes the numerical algorithm more complicated.

In order to improve the two-dimensional model and avoid the huge computation time and numerical algorithm difficulty in the three-dimensional model, a 2.5D simulation RTM non-isothermal model is proposed for thin part in this paper. The meaning of 2.5D is that the flow is 2D while the heat transfer is 3D. In this 2.5D model, the flow is determined by Darcy's law and the heat transfer and resin reaction are developed based on the lumped temperature system (*i.e.* local thermal equilibrium between resin and fiber). The control volume/finite element method (CV/FEM) is used to solve the distributions of pressure, temperature and curing degree during the RTM processing.

1 Simulation Scheme

1.1 Governing equations

In order to simulate the mold filling process of RTM, several assumptions must be made to simplify the problem. In general, the fiber reinforcement in the mold cavity is assumed to be rigid during the molding process. There is no exchange of mass between the solid and the fluid. The fluid is considered as incompressible and its viscosity is independent of shear rate (*i.e.*, the fluid is Newtonian). Inertia effect is neglected because of the low resin flow. Surface tension is negligible as compared with the dominant viscous force.

Under these assumptions, Darcy's law for flow through porous media can be used as the momentum equation.

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

where $\boldsymbol{v}$ is the velocity vector, ∇P is the pressure gradient, μ is the viscosity, and $\boldsymbol{K}$ is the permeability tensor. For the part with small thickness, the flow can be modeled as two-dimensional flow

$$\begin{Bmatrix} v_x \\ v_y \end{Bmatrix} = -\frac{1}{\mu}\begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}\begin{Bmatrix} \dfrac{\partial P}{\partial x} \\ \dfrac{\partial P}{\partial y} \end{Bmatrix} \tag{2}$$

where v_x, v_y are the flow velocity components and K_{ij} $(i, j = x, y)$ is the component of the permeability tensor defined in the two-dimensional Cartesian coordinate system.

For an incompressible fluid, the continuity equation is

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \tag{3}$$

Eq. (2) and (3) are combined and integrated over a control volume to have

$$\iint_S \frac{1}{\mu}[n_x \quad n_y]\begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}\begin{Bmatrix} \dfrac{\partial P}{\partial x} \\ \dfrac{\partial P}{\partial y} \end{Bmatrix} \mathrm{d}s = 0 \tag{4}$$

where n_x, n_y are the components of the vector normal to the surface of the integrated volume.

In RTM process, if the temperature is assumed to be in local equilibrium at any specific time due to its slow filling speed (*i.e.*, the temperature is the same for both resin fluid and fiber mat at each local position), the equations of energy and species balance can be expressed as

$$\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} \bar{v} \cdot \nabla T = k \nabla^2 T + \phi \Delta H \mathring{m} \tag{5}$$

$$\frac{\partial \alpha}{\partial t} + \frac{\bar{v}}{\phi} \nabla \alpha = \mathring{m} \tag{6}$$

where T is the temperature, α is the resin conversion, $\mathring{m}$ is the mass generation rate, ϕ is the fiber mat porosity and ΔH is the volumetric heat generation per unit volume. The lumped thermal parameters are defined as

$$\rho = (\rho_f \rho_r) / (\rho_f w_r + \rho_r w_f)$$

$$c_p = c_{pr} w_r + c_{pf} w_f$$

$$k = (k_r k_f) / (k_r w_f + k_f w_r)$$

$$w_r = \frac{\phi}{\rho_f} \Big/ \left(\frac{\phi}{\rho_f} + \frac{1-\phi}{\rho_r} \right)$$

$$w_f = 1 - w_r$$

where ρ is the density, c_p is the specific heat coefficient and k is the thermal conductivity. The subscripts r and f denote resin and fiber respectively.

1.2 Boundary conditions

The boundary conditions for equation 4 through 6 are as follows

At the flow front

$$P = 0$$

$$k \frac{\partial T}{\partial \boldsymbol{n}} \bigg|_{\text{front}} = (1 - \phi) \rho_f c_{pf} \boldsymbol{v}_n (T_{f0} - T)$$

$$\frac{D}{Dt}(F\alpha) = F\mathring{m}$$

where F is the resin volume fraction of a control volume.

At the inlet gate

(a) For the constant pressure mold filling

$P = P_0$, $T = T_{resin}$, and $\alpha = 0$

(b) For the constant flow rate mold filling

$$\iint_S \frac{1}{\mu} [n_x \quad n_y] \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \end{Bmatrix} ds = -Q$$

$$T = T_{resin}, \quad \alpha = 0$$

At mold boundaries

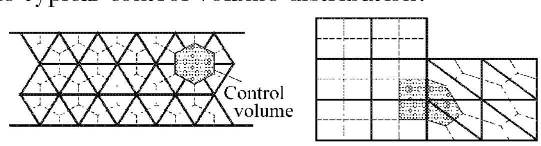
$$\frac{\partial P}{\partial \boldsymbol{n}} = 0, \quad T = T_{wall}$$

where Q is the volume injecting rate at the inlet gate, T_{f0} is the initial fiber temperature that is the same as the mold wall temperature T_{wall} and T_{resin} is the initial resin temperature. At the flow front, the parameter F represents the status of each control volume in the flow domain. F is zero for an empty control volume, while it is 1 for an entirely filled control volume. For a partially filled control volume, F is equal to the volume fraction occupied by the resin. Pressure is assumed vanished at the flow front where the temperature and conversion follow the energy and mass balance of a control mass. For the case of specified injecting flow rate, a specified flow rate is assigned to the control volumes enclosing the inlet nodes. For the case of the specified injecting pressure, a specified pressure is assigned to the inlet nodes. For the outlets, the pressure depends on the filling condition. If the vacuum is used during mold filling, the outlet pressure is equal to the vacuum pressure; otherwise, the outlet pressure is zero.

1.3 Computation schemes

Eqs. (4)-(6) are the governing formulations of non-isothermal mold processes. The solution of them requires the use of a numerical method to find the distribution of pressure, temperature and resin conversion within the filled domain. CV/FEM has many advantages in solving the moving boundary problems[5, 8, 9].

In the CV/FEM, the entire calculation domain is first divided into a number of elements. The control volume is formed based on the nodes of the adjacent elements. Each element is divided into several sub-areas by the lines connecting the centroid of the element to the midpoint/center of each side/surface. A control volume is composed of several sub-area/volumes, which have a common node at the center of the control volume. Fig. 1 is the typical control volume distribution.



(a) Triangle (b) Triangle and quardrangle

Fig. 1 Typical control volume distribution

For 2.5 D non-isothermal case, the heat transfer must be solved in three dimensions. Thus the cavity should be discretised through the thickness, which involves sub-dividing each control volume defined for the flow analysis into a number of layers. The energy balance is then carried out within each of these sub-domains. The layers through the thickness can be divided with collocate method[14].

Fig. 2 shows the diagram of computation schemes for 2.5D non-isothermal RTM simulation based on CV/FEM. At the beginning of mold filling, the simulation program assumes that the con-

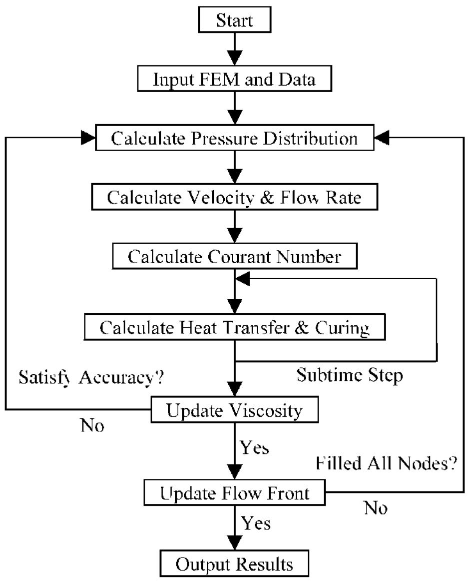


Fig. 2 The diagram of computation schemes

trol volumes enclosing the inlet nodes are filled with fluid. Then, with the boundary conditions mentioned earlier and the assumed viscosity, the pressure calculation is conducted to determine the pressures of nodes that are currently filled with fluid. After the pressure field is determined, the velocity field can be evaluated according to Darcy's law. Then, the temperature and conversion can be solved by the same way as the pressure based on the current velocity field. The resulting temperatures and conversions are used to compute the update viscosity. New values of viscosity are used to calculate the pressure field again, which leads to the same calculation procedure.

The Courant Number in the above numerical scheme is used in the improvement of convergence and accuracy of the solution. The convergence problem comes from the convection terms in equations (5) and (6). In order to reduce the divergence, the convection terms of the two equations are evaluated using the upwind scheme. The upwind scheme adds a numerical diffusion term to the system and reduces the instability. However, it increases the truncation errors. The truncation errors may result in a meaningless solution even though the scheme is stable. They are sensitive to the flow velocity, mesh size and time step if the flow is convection dominant. A sub-time step is used in the numerical model to improve the computational accuracy of temperature and conversion with reasonable Courant Number[2]. This sub-time technique can ensure the solutions to be as accurate as possible, although the truncation error is still very difficult to control because of the varying mesh sizes in the model.

2 Case Study and Discussion

A part in reference [9] is taken to demonstrate the use of the method described above. Figure 3 shows the finite elements generated by PATRAN software at the mid-plane of the part. The geometry of the part includes a circular cut-out with resin injected through a 20 mm diameter inlet port. Table 1 and 2 list the material data and molding parameters for simulation.

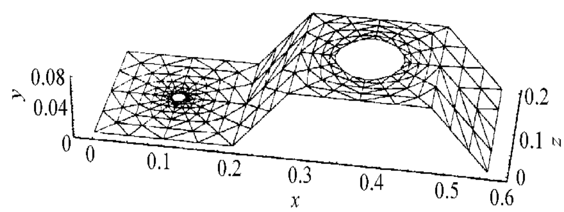


Fig. 3 Finite element mesh at the mid-plane of the part

Table 1 Material data

	Resin	Fiber
$\rho/(\mathrm{kg\cdot m^{-3}})$	1120	2540
$c_p/(\mathrm{J\cdot(kg\cdot K)^{-1}})$	1400	840
$k/(\mathrm{W\cdot(m\cdot K)^{-1}})$	0.13	0.1/0.01
$\Delta H/(\mathrm{J\cdot m^{-3}})$	2.5768×10^{8}	
ϕ		0.7
K/m^2		1.0×10^{-8}

Table 2 Molding parameters

Injection rate (constant)/$(\mathrm{m^3\cdot s^{-1}})$	6.5×10^{-5}
Cavity thickness/mm	3
Resin inlet temperature/K	310
Initial perform temperature/K	350
Mold surface temperature/K	370

The reaction rate is

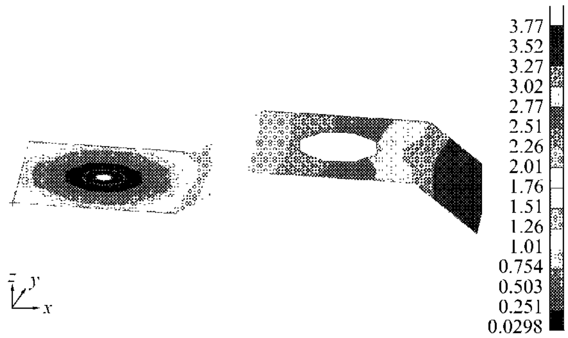
$$f(\alpha, T) = 300\exp\left(-\frac{3277}{T}\right)(1-\alpha)^2$$

The relationship among resin viscosity, temperature and degree of conversion used is

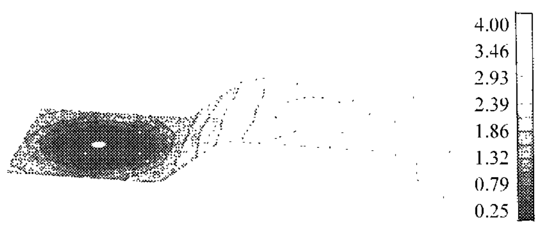
$$\mu = 2.56\times10^{-21}\exp\left(\frac{1.45\times10^{4}}{T}\right)\cdot$$

$$\exp\left(\frac{0.695}{0.487-\alpha}-1.502\right)$$

Fig. 4(a) shows the predicted flow pattern. In this figure, the initial radial flow quickly becomes rectilinear until the cut-out is reached. Once the flow passes the cut-out the two flow fronts merge, after which the flow becomes rectilinear again. The total fill time for this case is approximately 3.8 seconds. Fig. 5(b) is the flow patter in reference [9]. It can be found that the predicted flow pattern is in a good agreement with those in reference [9]. The difference in filling time comes from the fact that the model in reference [9] does not consider the in-plane heat conduction which affects the resin viscosity.



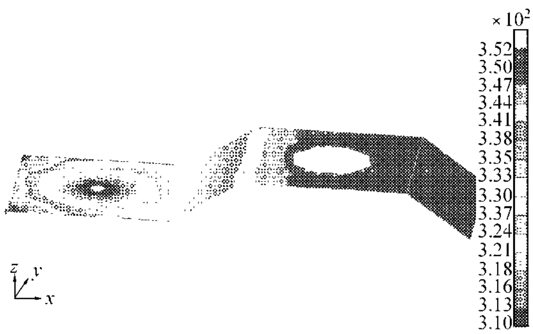
(a) Predicted flow pattern and filling time



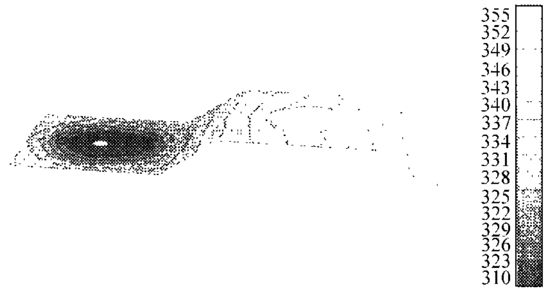
(b) Flow pattern and filling time from reference [9]

Fig. 4 Flow pattern and filling time

Fig. 5(a) and 6(a) are the distributions of predicted temperature and cure convection for the

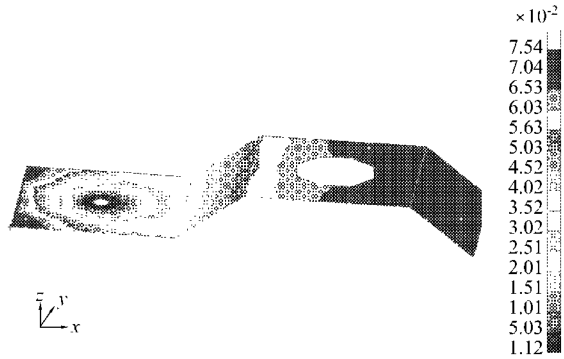


(a) Predicted temperature field

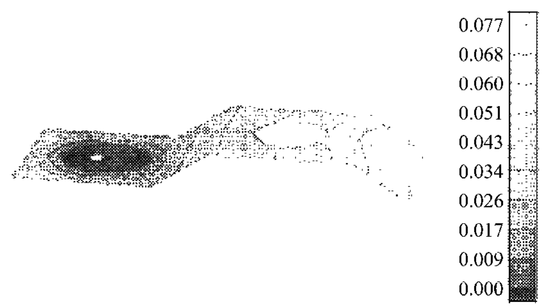


(b) Temperature field in reference [9]

Fig. 5 Temperature field



(a) Predicted conversion field



(b) Conversion field in reference [9]

Fig. 6 Flow pattern and filling time

layer located between the mold surface and the mid-plane, For this particular case, the maximum degree of conversion is 0.0752, occurring at the location furthest from the injection gate (where the resin has the greatest residence time). mid-plane. For this particular case, the maximum This value is significantly lower than the resin gel point of 0.487, which indicates that the heat transfer during the filling stage is caused mainly by the convection. The temperature at each location decreases after the cold resin touches the hot fiber. After the resin moves forward, colder resin arrives which resultes in lower temperature, but still higher than that at the injection port, at this location. As a result, the temperature shows a gradual increase as the filling time increases in the whole filling domain.

Fig. 5(b) and 6(b) are the temperature and conversion field at the same layer made by reference [9]. There is a good agreement between them. The difference between them also comes from the effect of in-plane heat conduction.

3 Conclusion

A 2.5 D non-isothermal RTM simulation model is developed for the thin part based on the CV/FEM. The lumped temperature system and the species balance are used in modeling the non-uniform temperature distribution and the heat generation during filling stage. The convergence and accuracy of numerical schemes are studied and simulation for a part is performed. Compared with 2D model, 2.5D model do affect the flow pattern, filling time, distributions of temperature and cure conversion in RTM process.

To verify the process model, experimental work is needed. Results from the experimental study and the comparison with the numerical simulation are the future study in this area.

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Biographies:

CHEN Ren-liang Born in 1963, he received B.S., M.S. and Ph.D. in aircraft design from Nanjing Aeronautical Institute in 1985, 1988 and 1998. From 2000 to 2002, he worked as post-doctoral in the field of RTM simulation at Florida Composite Center for Advanced Technologies (FC^2AT) of USA. Several scientific papers have been published in various periodicals. Tel: (025) 4892141, 4892152, E-mail: crlae@nuaa.edu.cn

GUI Bin Born in 1958, she received M.S. in computation mathematics from Nanjing Aeronautical Institute in 1988. She is the associate professor in Nanjing Forest University and the candidate Ph.D. student in computation mathematics at Nanjing University of Aeronautics & Astronautics. Tel: (025) 3735120

LI Ming-cheng Born in 1957, he received M.S. in mechanics from Nanjing Aeronautical Institute in 1988. He is the associate processor of mechanics in Nanjing University of Aeronautics & Astronautics Tel: (025) 4892231, 4892152.