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RTM工艺树脂流动过程数值模拟

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摘 要: RTM工艺过程数值模拟对模具设计、工艺过程控制及参数优化非常重要。本文作者介绍了 RTM工艺过程及特点,给出了树脂渗流控制方程,阐述了 RTM工艺过程数值模拟存在的主要问题,采用贴体坐标/有限差分法和网格分区划分法模拟了模具内有插入物情形下的 RTM工艺树脂渗流过程,给出了不同时刻树脂流动前沿曲线、计算网格及终止时刻压力场分布,确定了排气孔位置,计算结果与其它研究结果吻合良好。结果表明: 贴体坐标/有限差分法和网格分区划分法适合解决复杂边界及可移动边界问题。

关键词: RTM; 数值模拟; 贴体坐标; 复合材料
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NUMERICAL SIMULATION OF RESIN FLOW IN RTM

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Abstract Numerical simulation of resin transfer molding is important to mold design, process control and parameter optimization. This paper introduces the RTM process and its characterizations briefly. The governing equations of resin flow are presented. Based on the exposition of main problems of the commonly used methods in modeling the RTM process, the boundary-fitted coordinate system and the finite difference method as well as the resin flow domain decomposition process are employed to simulate the RTM resin flow process in the case of mold with interior insert. The successive resin flow front position, calculating mesh and the pressure distribution at the final stage are obtained, which is helpful for locating the air vent, and good agreement is found between the results and other investigations. The results indicate that the method provided by this paper is convenient and effective in solving the moving boundary problems with irregularly geometric boundaries.

Key words RTM; numerical simulation; boundary-fitted coordinate system; composite

RTM(Resin Transfer Molding)即树脂传递模塑工艺已有近五十年的发展历史[1]。七十年代, RTM工艺主要用于航空领域,如生产雷达罩,航空飞行器螺旋桨叶片等等[2]。八十年代中期以后,随着增强纤维、树脂基体、树脂注射技术等工艺的不断发展和完善, RTM技术开始大量应用于航空、汽车、电子、体育设备、船舶制造等领域[3]。由于 RTM工艺成本低,产品质量高,易于实现工艺自动化等优点而在复合材料成型领域获得了广泛应用。

RTM工艺是在一定的温度及压力下把低粘度的树脂注入置有增强材料坯的模具中,然后加热并固化成型的一种复合材料成型方法。其过程可分为以下几个阶段: (1)模具制备过程。(2)预成型增强纤维坯制备过程。(3)树脂注射过程。(4)产品固化过程。(5)产品脱模过程。如图 1所示。

RTM工艺的主要任务之一是确定树脂注射口及排气孔位置,以使增强纤维充分润湿,树脂注射压力合适。因此,预先了解 RTM工艺树脂流动过程,特别是树脂流动前沿曲线及压力场分布对模具设计非常重要。

RTM工艺数值模拟的难点是求解区域随着树脂的注入不断发生变化,压力场,温度场及固化度场互相耦合。模拟方法主要有有限元/控制体积法[4-6]和贴体坐标/有限差分法[7-9]。有限元法适合解决复杂模具边界情形,但程序不易编制,计算过程复杂,对树脂流动前沿跟踪不准确。贴体坐标/有限差分法

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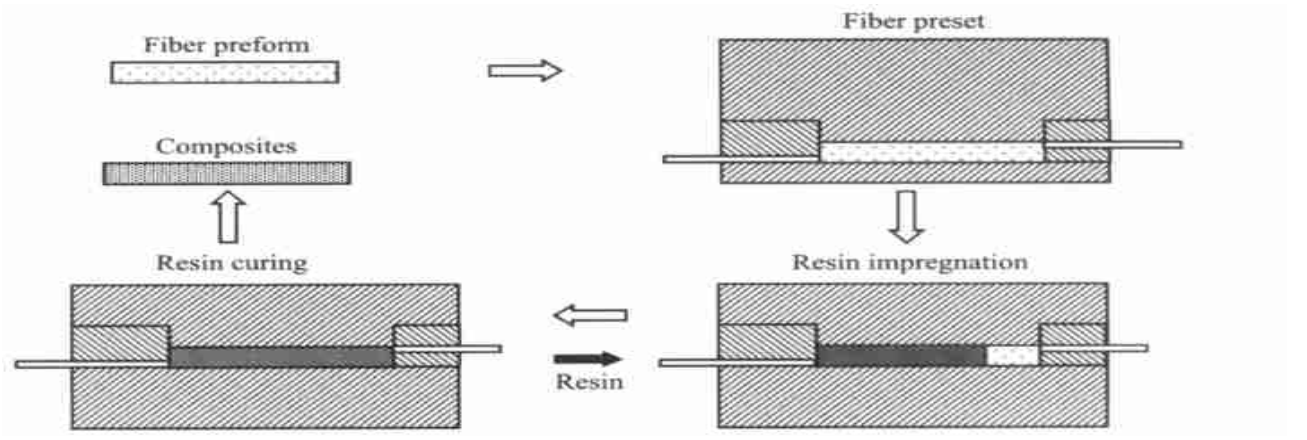

图 1 RTM工艺过程示意图

Fig. 1 Schematic diagram for the process of RTM

由于适合解决复杂边界问题,程序相对易于编制而在计算流体力学领域有着广泛应用,缺点是对于动边界问题,计算过程需要重新生成网格,计算量大。目前采用的贴体坐标有限差分法都是单一网格划分方法,这种方法不适合模拟模具内有插入物或多孔注射情形下的树脂流动过程[10],本文作者将贴体坐标有限差分法和网格分区划分法相结合,模拟了模具内有插入物情形下的树脂流动过程,给出了不同时刻树脂流动前沿曲线、计算网格及终止时刻压力场分布。由于 RTM 工艺主要应用于薄板构件,本文作者只考虑二维情形,由于旨在模拟树脂流动过程,本文作者未考虑温度变化及树脂化学反应产生的影响。

1 树脂流动控制方程

树脂在纤维中的流动过程可认为是流体(树脂)在多孔介质(纤维)中的渗流过程,选择渗透率主轴方向为坐标系方向,Darcy定律可表示为

$$\begin{cases} k_x \dfrac{\partial p}{\partial x} + \mu u = 0 \\ k_y \dfrac{\partial p}{\partial y} + \mu v = 0 \end{cases} \tag{1}$$

式中: k_x, k_y 为纤维主轴方向渗透率, u, v 为树脂流动速度, p 为树脂压力, μ 为树脂粘度。本文作者假定树脂为不可压缩流体,根据不可压缩流体连续性方程得到

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

将(1)式代入(2)式,得到

$$k_x \frac{\partial^2 p}{\partial x^2} + k_y \frac{\partial^2 p}{\partial y^2} + \left(\frac{\partial k_x}{\partial x} - \frac{k_x}{\mu} \frac{\partial \mu}{\partial x} \right) \frac{\partial p}{\partial x} + \left(\frac{\partial k_y}{\partial y} - \frac{k_y}{\mu} \frac{\partial \mu}{\partial y} \right) \frac{\partial p}{\partial y} = 0 \tag{3}$$

(3)式即为树脂流动控制方程。不考虑树脂流动前沿表面张力,边界条件可写为

$$\begin{cases} p = p_0 & \text{(注射口)} \\ \dfrac{\partial p}{\partial n} = 0 & \text{(模具,障碍物边界)} \\ p = 0 & \text{(流动前沿)} \end{cases} \tag{4}$$

2 网格生成

贴体坐标法可把不规则的物理域问题变换到规则的计算域去求解,如图 2所示。

用贴体坐标生成网格主要有三种方法: 代数法、

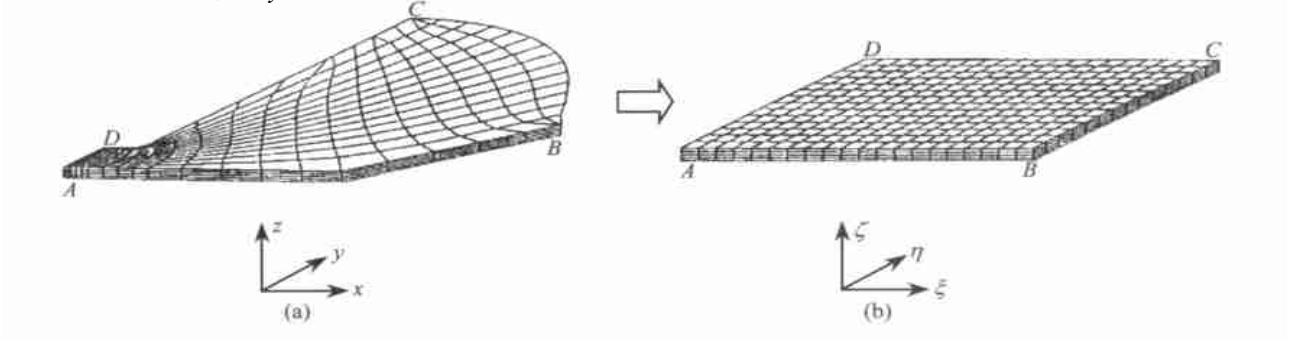

图 2 物理域和计算域的坐标系变换((a)物理域;(b)计算域)

Fig. 2 Coordinate transformation of physical plane and transformed plane (a) Physical domain (b) Calculation domain)

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微分方程法及保角变换法[11, 13]。本文作者采用微分方程法。设在物理域中形成的贴体坐标系为 α, Z,应用 Possion方程求解 α, Z的方程为

$$\begin{cases} \dfrac{\partial^2 \alpha}{\partial x^2} + \dfrac{\partial^2 \alpha}{\partial y^2} = P(x, y) \\ \dfrac{\partial^2 Z}{\partial x^2} + \dfrac{\partial^2 Z}{\partial y^2} = Q(x, y) \end{cases} \tag{5}$$

$$\begin{cases} \alpha = \alpha(x, y) \\ Z = Z(x, y) \end{cases} \tag{6}$$

由于在物理域中求解 α, Z很不方便,实际求解时用式(5)、式(6)的逆变换形式

$$\begin{cases} T\dfrac{\partial^2 x}{\partial \alpha^2} - 2U\dfrac{\partial^2 x}{\partial \alpha \partial Z} + V\dfrac{\partial^2 x}{\partial Z^2} + J^2\left(P\dfrac{\partial x}{\partial \alpha} + Q\dfrac{\partial x}{\partial Z}\right) = 0 \\ T\dfrac{\partial^2 y}{\partial \alpha^2} - 2U\dfrac{\partial^2 y}{\partial \alpha \partial Z} + V\dfrac{\partial^2 y}{\partial Z^2} + J^2\left(P\dfrac{\partial y}{\partial \alpha} + Q\dfrac{\partial y}{\partial Z}\right) = 0 \end{cases} \tag{7}$$

式中:

$$\begin{cases} T = \left(\dfrac{\partial x}{\partial Z}\right)^2 + \left(\dfrac{\partial y}{\partial Z}\right)^2, \quad U = \dfrac{\partial x}{\partial \alpha}\dfrac{\partial x}{\partial Z} + \dfrac{\partial y}{\partial \alpha}\dfrac{\partial y}{\partial Z} \\ V = \left(\dfrac{\partial x}{\partial \alpha}\right)^2 + \left(\dfrac{\partial y}{\partial \alpha}\right)^2, \quad J = \dfrac{\partial x}{\partial \alpha}\dfrac{\partial y}{\partial Z} - \dfrac{\partial x}{\partial Z}\dfrac{\partial y}{\partial \alpha} \end{cases} \tag{8}$$

源项 P, Q用于调节网格疏密程度,本文作者取为零。

本文作者模拟了模具内有插入物情形下的RTM工艺树脂流动过程,网格区域划分如图3所示。设模具边界为 $EFGH$,模具中间有一注射口,右上侧有一圆形插入物。沿虚线 FH剖分,将物理域 $EFGH$划分为 A, B两部分,分别生成计算网格并进行求解。

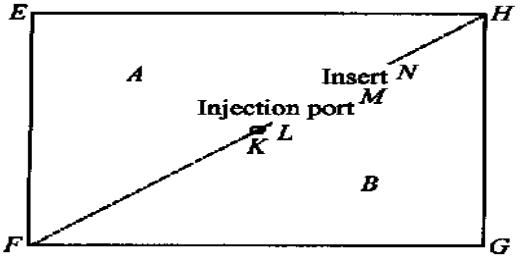

图 3　区域剖分示意图

Fig. 3　Schematic diagram of domain decomposition

3　方程变换及求解过程

网格生成后,控制方程及边界条件也应变换到计算域去求解。树脂渗流控制方程变换到计算域为

$$c_{11}\frac{\partial^2 p}{\partial \alpha^2} - 2c_{12}\frac{\partial^2 p}{\partial \alpha \partial Z} + c_{22}\frac{\partial^2 p}{\partial Z^2} + c_1\frac{\partial p}{\partial \alpha} - c_2\frac{\partial p}{\partial Z} = 0 \tag{9}$$

式中:

$$\begin{cases} c_{11} = k_x\left(\dfrac{\partial y}{\partial Z}\right)^2 + k_y\left(\dfrac{\partial x}{\partial Z}\right)^2 \\ c_{12} = k_x\dfrac{\partial y}{\partial \alpha}\dfrac{\partial y}{\partial Z} + k_y\dfrac{\partial x}{\partial \alpha}\dfrac{\partial x}{\partial Z} \\ c_{22} = k_x\left(\dfrac{\partial y}{\partial \alpha}\right)^2 + k_y\left(\dfrac{\partial x}{\partial \alpha}\right)^2 \end{cases} \tag{10-1}$$

$$\begin{cases} c_1 = \dfrac{1}{J}\left(d_1\dfrac{\partial x}{\partial Z} - d_2\dfrac{\partial y}{\partial Z}\right) + d_3\left(\dfrac{\partial y}{\partial Z}\right)^2 - d_4\dfrac{\partial y}{\partial \alpha}\dfrac{\partial y}{\partial Z} + d_5\left(\dfrac{\partial x}{\partial Z}\right)^2 - d_6\dfrac{\partial x}{\partial \alpha}\dfrac{\partial x}{\partial Z} \\ c_2 = \dfrac{1}{J}\left(d_1\dfrac{\partial x}{\partial \alpha} - d_2\dfrac{\partial y}{\partial \alpha}\right) + d_3\dfrac{\partial y}{\partial \alpha}\dfrac{\partial y}{\partial Z} - d_4\left(\dfrac{\partial y}{\partial \alpha}\right)^2 + d_5\dfrac{\partial x}{\partial \alpha}\dfrac{\partial x}{\partial Z} - d_6\left(\dfrac{\partial x}{\partial \alpha}\right)^2 \end{cases} \tag{10-2}$$

系数 $d_1, d_2, \cdots d_6$为

$$\begin{cases} d_1 = a_{11}\dfrac{\partial^2 y}{\partial \alpha^2} - 2c_{12}\dfrac{\partial^2 y}{\partial \alpha \partial Z} + c_{22}\dfrac{\partial^2 y}{\partial Z^2} \\ d_2 = a_{11}\dfrac{\partial^2 x}{\partial \alpha^2} - 2c_{12}\dfrac{\partial^2 x}{\partial \alpha \partial Z} + c_{22}\dfrac{\partial^2 x}{\partial Z^2} \\ d_3 = \dfrac{\partial k_x}{\partial \alpha} - \bar{k}_x\dfrac{\partial}{\partial \alpha} \\ d_4 = \dfrac{\partial k_x}{\partial Z} - \bar{k}_x\dfrac{\partial}{\partial Z} \\ d_5 = \dfrac{\partial k_y}{\partial \alpha} - \bar{k}_y\dfrac{\partial}{\partial \alpha} \\ d_6 = \dfrac{\partial k_y}{\partial Z} - \bar{k}_y\dfrac{\partial}{\partial Z} \end{cases} \tag{11-1, 11-2}$$

边界条件变换到计算域为(见图3)

$$\begin{cases} p = p_0 \quad (\text{注射口}) \\ \left[k_x\left(\dfrac{\partial y}{\partial \alpha}\right)^2 + k_y\left(\dfrac{\partial x}{\partial \alpha}\right)^2\right]\dfrac{\partial p}{\partial Z} - \left[k_x\dfrac{\partial y}{\partial \alpha}\dfrac{\partial y}{\partial Z} + k_y\dfrac{\partial x}{\partial \alpha}\dfrac{\partial x}{\partial Z}\right]\dfrac{\partial p}{\partial \alpha} = 0 \\ \quad (\text{模具, 障碍物边界}) \\ p = 0 \quad (\text{流动前沿}) \\ p^A = p^B, v^A = v^B \quad (\text{剖分线 } FK, LM, NH) \end{cases} \tag{12}$$

式中:下标 A和 B表示计算域 A和 B。

采用有限差分法求解坐标变换方程,控制方程,速度方程过程为(以计算域 A为例)

(1) 在每一个时间步内求解坐标变换方程,得到计算域内各点对应的 x, y坐标。

(2) 求解控制方程,得出流场内各点压力值。

(3) 求解速度方程,确定边界各点速度。

(4) 选择合适的时间步长,得到新的计算域及物理域并重新生成计算网格。

(5) 重复第一步,直到流体充满整个物理域为止。

4　算　例

4.1　Martin等人[14]采用有限元法对二维问题进行了数值模拟,树脂注射口在模具左侧,物性参数为:纤维渗透率 $k_x = k_y = 1.0 \times 10^{-9}\ m^2$,树脂粘度 $\eta = 1.44\ Pa \cdot s$,注射压力 $p = 152\ kPa$。本文作者,先用单一网格划分方法对上述过程进行了数值模拟,计

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算结果如图 4所示. 可以看出,树脂开始时刻流动前沿曲线为半圆形,然后逐渐过渡成直线,与 Martin 等人研究结果 (图 5)相吻合.

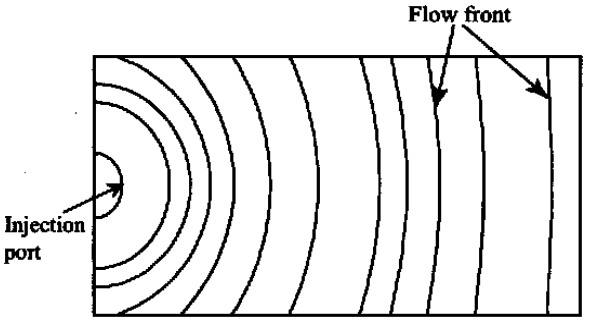

图 4 不同时刻树脂流动前沿曲线

Fig. 4 Computed successive resin flow front position

4.2 Bruschke等人对图 3所示情形下树脂流动过程做了数值模拟及实验研究. 物性参数为: 模具长 0.7 m,宽 0.7 m, 纤维渗透率 $k_x = k_y = 2.8 \times 10^{-9}$ m^2,纤维空隙率为 0.7, 树脂粘度 $\mu = 0.082$ Pa·s, 注射压力 $p = 400$ kPa. 本文作者采用分区网格划分方法,得到不同时刻树脂流动前沿曲线及计算网格如图 6所示.

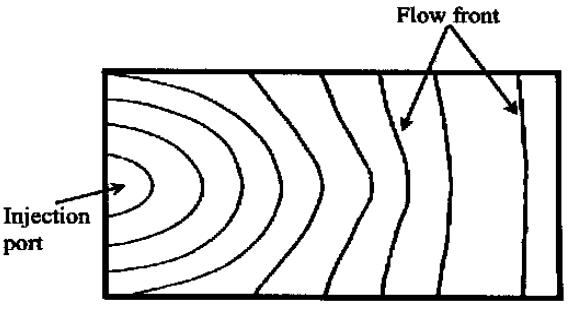

图 5 Martin等人得到的树脂流动前沿曲线

Fig. 5 Successive resin flow front position by Martin, *et al*

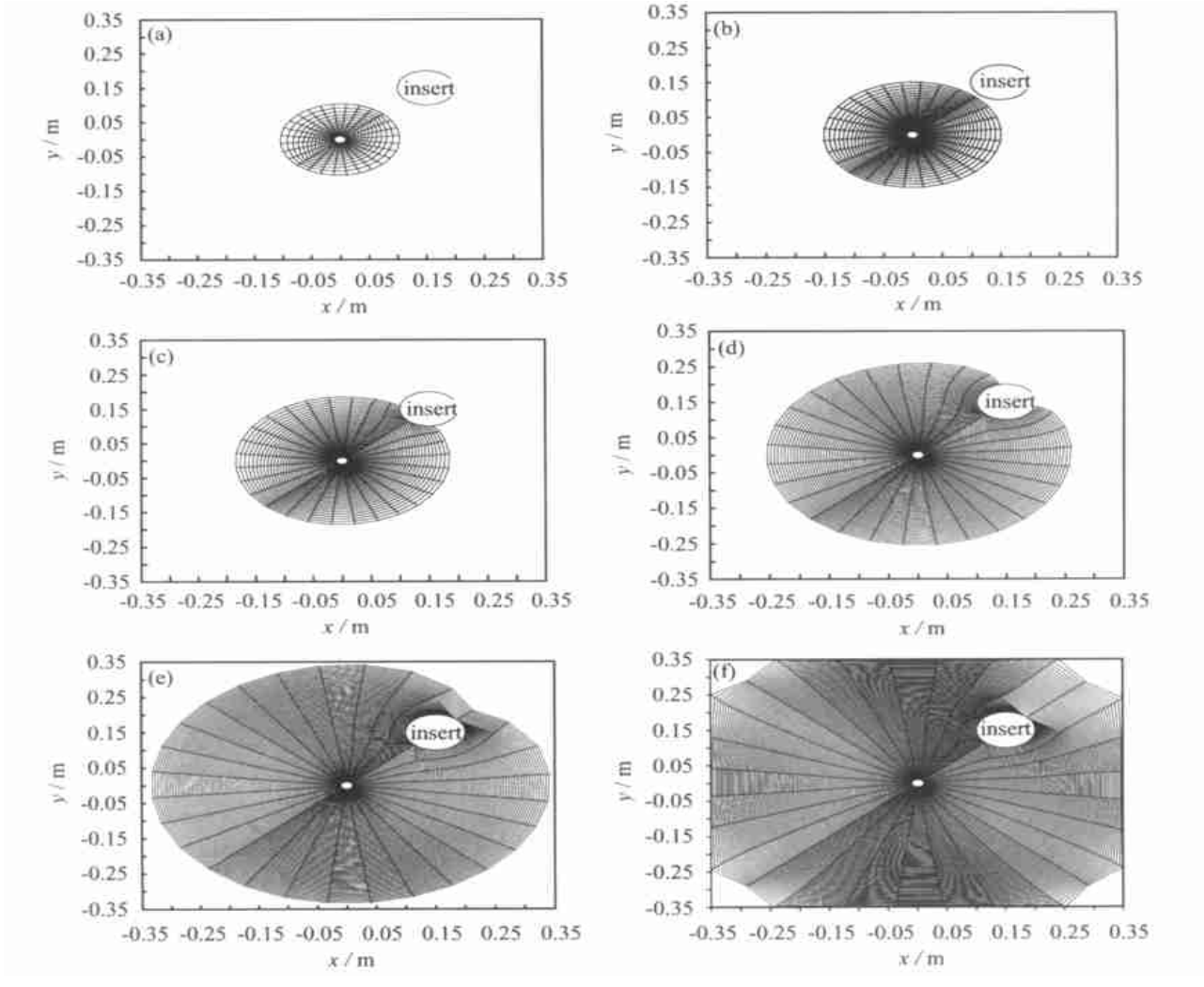

图 6 不同时刻流动前沿及计算网络

Fig. 6 Resin front position and the mesh at different time

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终止时刻等压线如图 7所示,各等压线间压力差为 25 kPa 压力场分布如图 8所示。各时刻树脂流动前沿曲线如图 9所示。从图 9可见,树脂最后充满的区域,即模具四角位置应留有气孔。 Bruschke等人[15]采用有限元法对上述工艺过程进行了数值模拟及实验研究,得到不同时刻树脂流动前沿曲线如图 10所示。 Trochu等人[16]采用有限元法也得到相似的模拟结果,如图 11所示。 从图 10 图 11可见,本文作者得到的模拟结果与 Bruschke等人和 Trochu等人的研究结果吻合良好。

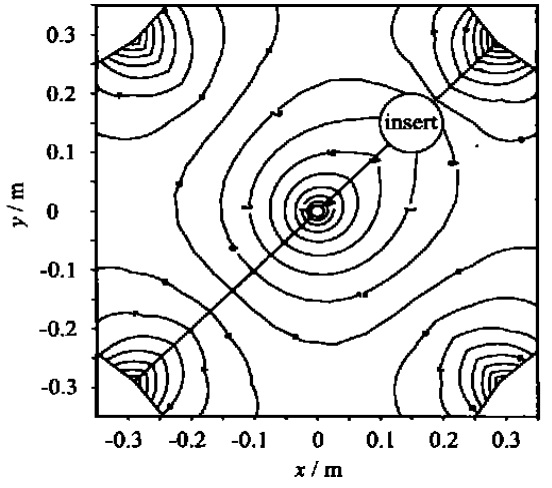

图 7 终止时刻等压线分布

Fig. 7 Isopressure lines at the final stage

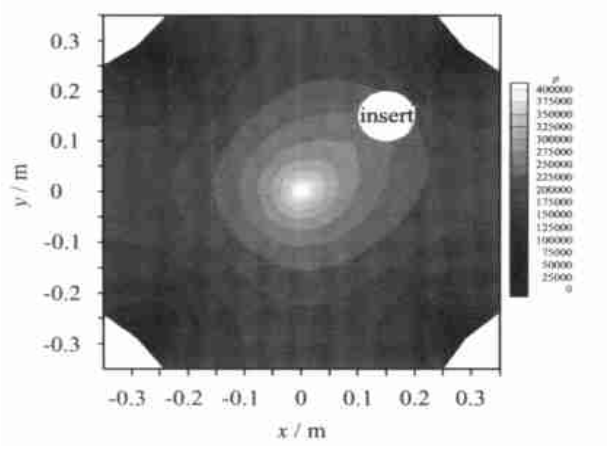

图 8 终止时刻压力场分布

Fig. 8 Pressure distribution at the final stage

5 结　论

(1) 采用贴体坐标 有限差分法和分区网格划分法可以模拟模具内有插入物情形下的 RTM 工艺树脂渗流过程。

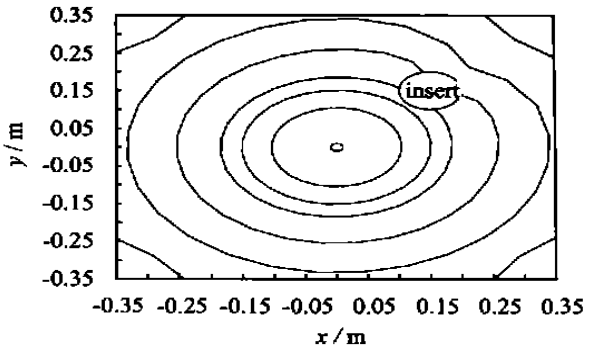

图 9 不同时刻树脂流动前沿曲线

Fig. 9 Successive resin flow front position

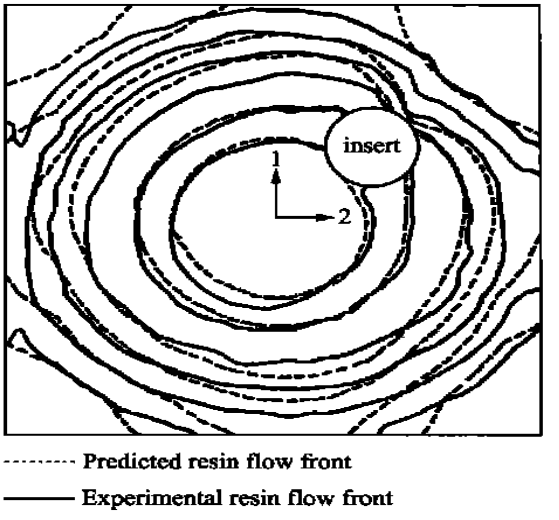

图 10 Bruschke等人得到的树脂流动前沿曲线

Fig. 10 Successive resin flow front position by Bruschke, *et al*

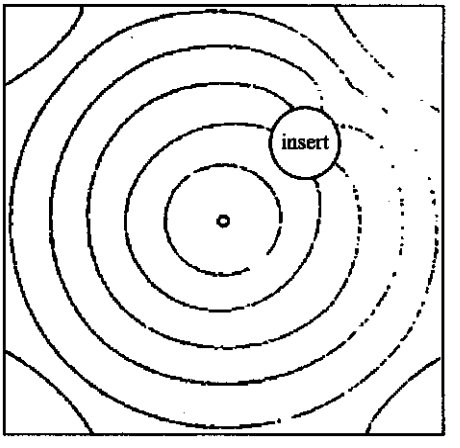

图 11 Trochu等人得到的树脂流动前沿曲线

Fig. 11 Successive resin flow front position by Trochu, *et al*

(2) 给出了不同时刻树脂流动前沿曲线及终止时刻压力场分布,确定了排气孔位置。

(3) 本文作者提供的方法可对 RTM 多孔注射

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