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Integrated Three-Dimensional Mold Filling Simulations in Resin Transfer Molding

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ABSTRACT

RTM (Resin Transfer Molding) is a versatile and attractive process for high volume, high performance, and low cost manufacturing of polymer composites. Numerical modeling of RTM has been conducted by many researchers. This paper aims to develop an integrated 3-D computer simulation model for the mold filling process of RTM under isothermal condition based on the control volume finite element method. Three types of element, i.e. tetrahedron, pentahedron, and hexahedron element, are combinatively used to deal with the complicated geometry. Results of some numerical studies in RTM show the advantages and disadvantages of various types of element, and the application of the proposal combinative model.

1. Introduction

RTM has become an attractive processing method to produce a composite part. Extensive efforts have been put into numerical simulation of RTM mold filling. The mold filling process can be regarded as a phenomenon of flow through porous media. On the basis of Darcy's law for flow through porous media, one can develop a numerical model for the mold filling and curing processes, which can predict the essential parameters during the molding process including flow front advancing and variations of the pressure, temperature and conversion [1-5]. Furthermore, The mold filling model has been applied to predict the dry spot formation and optimize the inlet gate and outlet gate [6,7,8].

The numerical simulation of a manufacturing process is an essential element in the integration of computer aided design and manufacturing (CAD/CAM). It provides preliminary information for the design of tooling and determination of processing conditions. Most studies about RTM mold filling and curing processing are concentrated on two-dimensional thin part analysis. In actual applications, some parts can be very complicated and require true three-dimensional analysis, especially, for those with substructure. 3-D models under isothermal and nonisothermal conditions have been presented. However, the applied element, i.e. pentahedron element, has five surfaces (two are triangular, and three quadrilateral). Since triangular and quadrilateral shapes are incompatible, some inconveniences arise, and some complex part cannot be dealt with the pentahedron element. In this study, the authors developed an integrated three-dimensional mold filling simulation for RTM. The tetrahedron, pentahedron, and hexahedron element were used in the simulation program. The geometry can be discretized easily by the combination of three types of element. The detail formulae were presented. The advantage and disadvantage of these elements were discussed. Finally, a visual case study was conducted to illustrate the proposal approach.

3. Control Volume Finite Element Formulae

It has been proven that the Darcy's law can describe resin flow in fiber mat with acceptable accuracy. The law can be written in the form:

$$\vec{v} = -\frac{\bar{\bar{k}}}{\mu} \cdot \nabla P \quad (1)$$

Where $\vec{v}$ is the velocity vector, ∇P is the pressure gradient, μ is the viscosity, and $\bar{\bar{k}}$ is the permeability tensor.

For an incompressible fluid, the continuity equation can be reduced to the form:

$$\nabla \cdot \vec{v} = 0 \quad (4)$$

By using the divergence theorem, Eq. 5 can be written as:

$$\iint_s \vec{v} \cdot \vec{n} ds = 0 \quad (6)$$

Eq. 8, which is based on the mass balance, is the control equation for solving the problems of flow. The Control Volume Finite Element Method was used to solve Eq. 8 numerically.

In the Control Volume Finite Element Method, the entire calculation domain is first divided into a number of elements. The control volume is composed of several subarea/volume, which have a common node at the center of the control volume. The pressure distribution in each element can be obtained by considering the pressure of the element-connected node, and by assuming the shape function of pressure. The distribution form is:

$$P = \sum N_i P_i \tag{9}$$

Where N_i is the shape function, and P_i is the pressure at the element node.

The velocity in the element can be thus computed by Darcy's law. To substitute Eq. 9 into Eq. 8, the integration of Eq. 8 will take the form:

$$\sum_i \sum_j A_{ij} P_{ij} = 0 \tag{10}$$

where P_{ij} is the pressure of j node in i element of the control volume, and A_{ij} is the coefficient that can be calculated before solving Eq. 10. The sum of Eq. 10 represents the total mass flux into the control volume. Therefore, this method is based on the physical interpretation of mass conservation within a control volume.

In many RTM applications, the mold geometry is often considered to be two-dimensional, which means that the dimension of the thickness is much smaller than the dimensions in the planar directions. Therefore, mold filling in a 3-dimensional thin cavity can be modeled as a two-dimensional flow. In the actual applications, some parts can be very complicated, especially for those with substructures. As a result, the parts are no longer "thin". In order to solve this type of geometry, a 3-dimensional model is needed. There are three types of simple element, i.e. tetrahedron, pentahedron, and hexahedron element.

3.1 Pentahedron Element

The pentahedron element has been selected in many studies. The constitution of control volume and local coordinate system are shown in Fig. 2. The integral surface of each element in the control volume includes three sub-surface (A, B, and C). The control volume of one node is enclosed by A, B, and C surfaces of all elements that are connected with the node. The pressure in pentahedron element is given by:

$$P = \sum_{i=1}^{6} N_i P_i \tag{11}$$

Where

$$
\begin{aligned}
N_1 &= (1-\xi-\eta)(1-\zeta) \\
N_2 &= \xi(1-\zeta) \\
N_3 &= \eta(1-\zeta) \\
N_4 &= (1-\xi-\eta)\zeta \\
N_5 &= \xi\zeta \\
N_6 &= \eta\zeta
\end{aligned}
\tag{12}
$$

Where ξ, η, and ζ are the axes of the transformed normal coordinates.

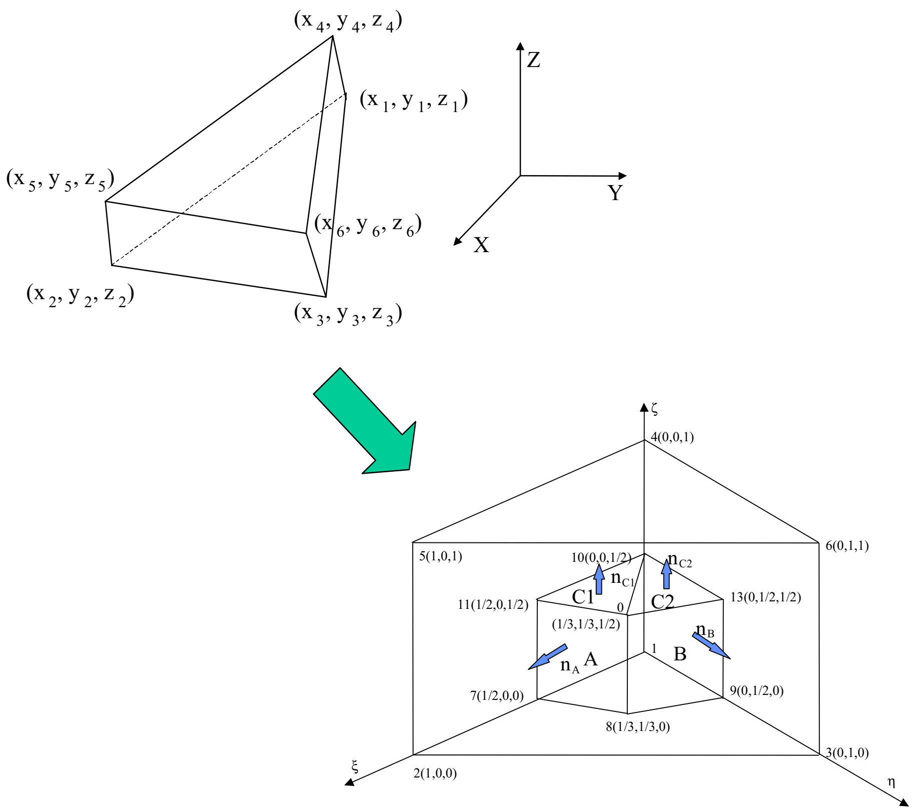

Fig. 2 Typical pentahedron element and corresponding normalized element.

$$
\iint_S \frac{1}{\mu}\left[n_x \;\; n_y \;\; n_z\right][K]\left[J^{-1}\right][N][P]ds = 0 \tag{16}
$$

The pentahedron element has two types of surfaces, i.e. triangular surface and quadrilateral surface. If the triangular surface of one element and the quadrilateral surface of other element become partially co-surface, one sub-surface of control volume cannot be covered by respective another sub-surface. The uncovered surface becomes a partial surface of control volume. Since that the uncovered surface doesn't belong to any part of integral surface A, B, or C. Consequently, Eq. 5 cannot be rewritten as Eq. 7 by the divergence theorem. The local coordinate system of pentahedron elements are generally various from element to element. If the permeability is nonisotropic, the variation of local coordinate system makes the assignment of permeability inconvenient.

3.2 Tetrahedron Element

The tetrahedron element is shown in Fig. 8. The integrating surface of control volume in one element includes A, B, and C.

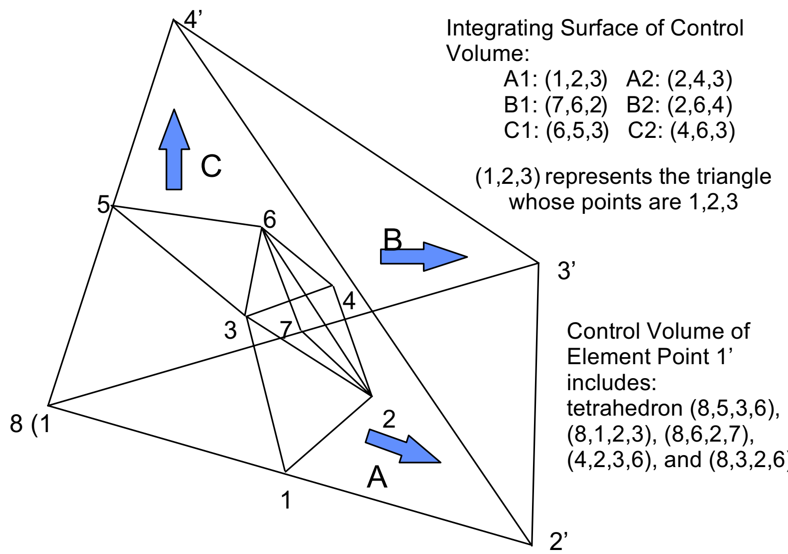

Figure 8. Control volume of tetrahedron element

By using the linear function, an approximate solution of Eq. 8 can be given by:

$$p = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 z = \sum N_i P_i \qquad (25)$$

Therefore, based on Eq. 29 and 30, The sum of Eq. 29 gives the final control equation for pressure solution:

$$\sum_{i=0}^{m} \left(\sum_{X=A,B,C} \begin{bmatrix} w_{X1} & w_{X2} & w_{X3} & w_{X4} \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{Bmatrix} \right)_i = 0 \qquad (31)$$

3.3 Hexahedron Element

The hexahedron element is shown in Fig. 10. The integrating surface of control volume in one element includes A, B, and C.

The approximate solution of Eq. 8 can be given by

$$P = \sum_{i=1}^{8} N_i P_i \tag{32}$$

Where shape function: $N_i = \frac{1}{8}(1+\xi_i\xi)(1+\eta_i\eta)(1+\zeta_i\zeta)$, ξ_i, η_i, ζ_i are listed in Table 1.

Table 1. Three parameters in shape function

i	ξ_i	η_i	ζ_i
1	-1	-1	-1
2	1	-1	-1
3	1	1	-1
4	-1	1	-1
5	-1	-1	1
6	1	-1	1
7	1	1	1
8	-1	1	1

The coordinate transformation from X, Y, and Z to ξ, η, and ζ can be written as

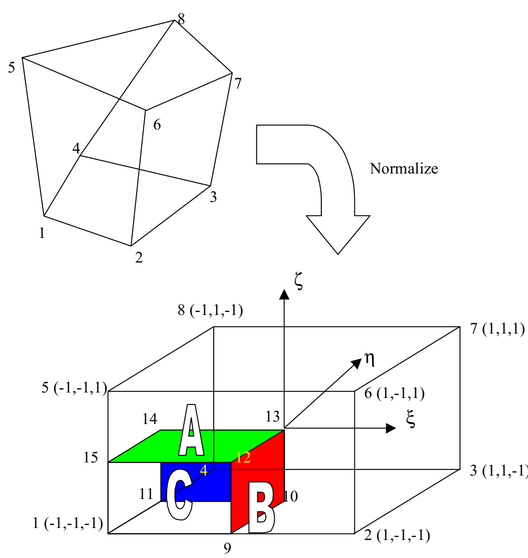

Figure 10. Typical hexahedron element and corresponding normalized element

To integrate Eq.24, 31, and 40, one can get the control equation for the integrated three-dimensional mold filling simulation:

$$\sum_{i=0}^{m} \sum_{X=A,B,C} \sum_{i=1}^{n_i} W_{Xi} \cdot P_i = 0 \tag{41}$$

where n_i is the number of nodes of one element, m is the number of elements in one control volume.

4. Discussions

In order to compare the various elements, a cube was selected to conduct mold filling simulation. The model has 216 nodes (6*6*6 nodes). The number of elements was depended on the type of elements that were selected to generate the mesh. The number of hexahedron element is 125, the number of pentahedron one is 250, and the number of tetrahedron one is 625. The inlet node was set to be the vertex node. The permeability was assumed to be isotropic.

The results of three models were shown in Fig. 12. The computational times of simulation are 47, 102 and 190 seconds (hexahedron, pentahedron and tetrahedron) by Pentium II 450 PC.

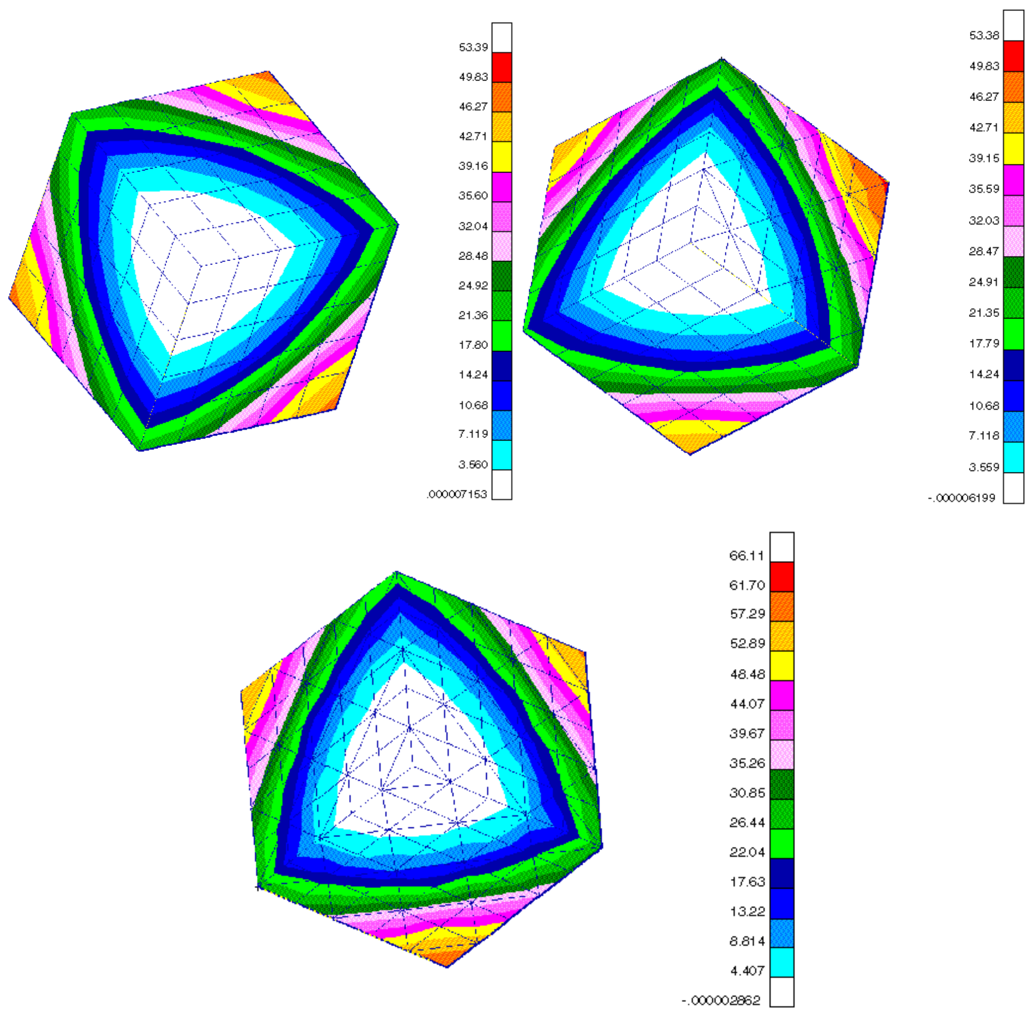

Figure 12. Simulated results of hexahedron, pentahedron, tetrahedron element model

Six nodes were selected to compare the computational accuracy. The compared results were shown in Fig. 14. Since the pentahedron element has two triangular surfaces and three quadrilateral surfaces, the formulas are asymmetrical in element local direction. Therefore, the error of pentahedron element was biggest. With considering that the compared nodes are located on different surface, the errors of pentatrahedron element are variable from node to node. The results of tetrahedron element are less variable from node to node than one of pentahedron element. On the other hand, the flow front of hexahedron and pentahedron element is smoother than one of tetrahedron element.

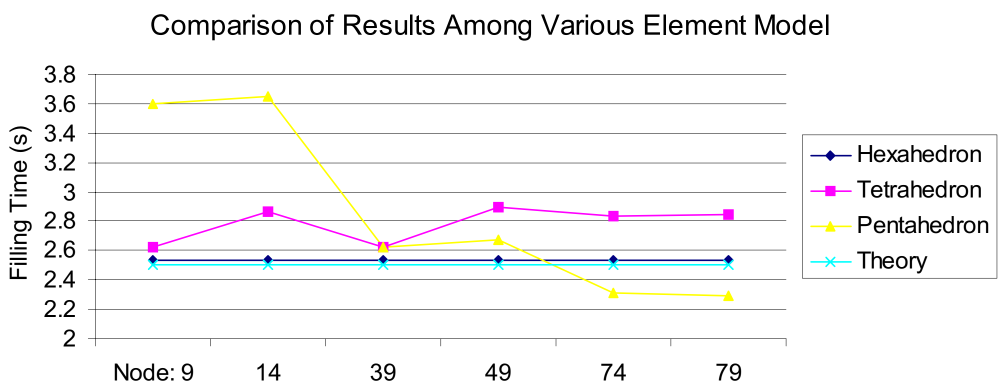

Figure 14. Comparison of results among various element model

To compare the computational efficiency, the denser mesh of the cube is regenerated. The model has 1331 nodes. The number of hexahedron element is 1000, the number of pentahedron one is 2000, and the number of tetrahedron one is 5000. The inlet node is set to be the vertex node. The computational times of simulation are 117, 140 and 423 minutes (hexahedron, pentahedron and tetrahedron) by Pentium II 450. Therefore, it can be concluded that the hexahedron element is the most efficient among these three elements.

Generally speak, the fiber mat is placed along the stream-line of geometry, thus the orient of principal permeability can be assigned to the hexahedron element easily. The local coordinate system of tetrahedron element varies more irregularly than the pentahedron's one. It is more complicated to assign the nonisotropic permeability locally to the tetrahedron element than to the pentahedron element.

Based on the above discussion, the hexahedron element is the best element. However, the hexahedron element cannot hold for any geometry by software. Some geometry cannot be meshed automatically just with the hexahedron element by some computer software, such as PATRAN. For example, solid cylindrical geometry cannot be meshed by the hexahedron element without the pentahedron element. The tetrahedron element can mesh any three-dimensional geometry. If the geometry is pentahedron, one can use only pentahedron element to generate automatically the finite element model. Some geometry can be modeled by tetrahedron, pentahedron, or hexahedron element. In the case, the number of model nodes is the same, but the number of model elements is different. The ratio of the number of elements is 6:2:1 (tetrahedron to pentahedron to hexahedron). The control equations are based on the control volume of nodes. The computation is conducted one element by one element in one control volume. Therefore, the simulation of tetrahedron model will take more time.

After all, the hexahedron element should be applied to model the objects as completely as possible, and the tetrahedron and pentahedron elements play the assistant roles in the model.

To verify the proposal simulation method, a visual example was simulated. Three types of element were utilized to generate mesh. The result was shown in Fig.16.

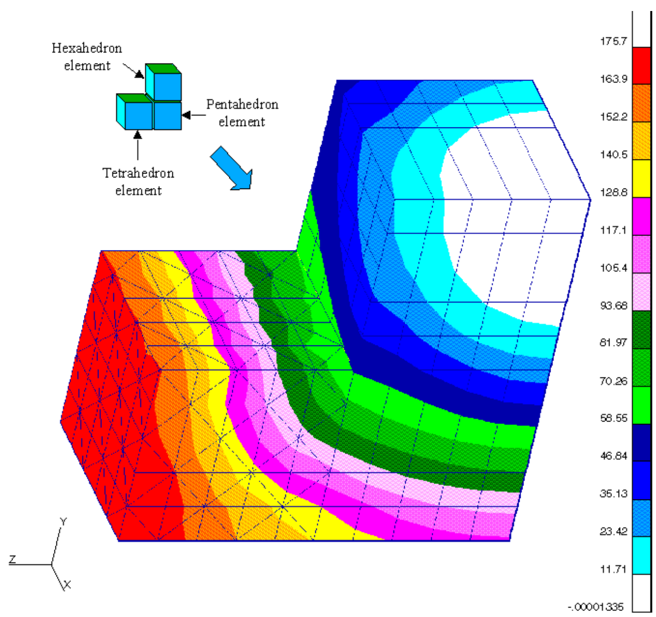

Figure 16. Simulation result of integral 3D model for RTM mold filling

5. Conclusion

This paper presented an integrated 3-D computer simulation model for the mold filling process of RTM under isothermal condition based on the control volume finite element method. Three types of element, i.e. tetrahedron, pentahedron, and hexahedron element, were used to deal with RTM simulation. According to computational accuracy and efficiency, the hexahedron element is the best element. However, the hexahedron element cannot hold for any geometry without the pentahedron and tetrahedron element assistance. The tetrahedron element can mesh any three-dimensional geometry but its accuracy is low. Thus, the hexahedron element should be applied to model the parts as completely as possible and the tetrahedron and pentahedron element play the assistant roles in the model. Finally, a visual example illustrates the proposal approach. The proposal approach can be applied to complex parts.

6. References

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