論 文

Numerical Simulation of Mold Filling Processes of Castings by using of Predictor-two step Corrector-VOF

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Abstract

수정된 SIMPLE법과 VOF의 결합으로 predictor-two step corrector-VOF라고 불리는 새로운 알고리즘이 주조 시 용탕 충전과정을 해석하기 위해 개발되었다. 운동량보존으로부터 유도된 새 2단계 속도 경계조건 처리법은 용탕의 자유표면을 추적하는 데 사용되었다. 본 연구에서는 2개의 예제 계산을 통해 계산정확도와 속도에 대한 Courant 수의 영향을 살펴보았다. 그 결과 적당한 Courant 수의 증가는 계산 정확도의 감소 없이 용탕 계산 속도를 향상시킬 수 있는 것으로 나타났다. 또한 만족할 만한 계산 정확도와 효율이 이 알고리즘의 실제 제품 해석을 통해 얻어졌다.

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1. Introductions

The calculation accuracy and efficiency are very important when the simulation technology is put into practice. In the previous work of several researchers, the implicit algorithm and large time step were applied to simulate the mold filling processes in order to improve the calculation efficiency.

Jone R. Hartin developed an implicit method, and compared the calculating time with the explicit SOLA-VOF[1]. The results proved that the calculating time could be reduced 20%-50% when large and suitable time step size is used.

Woo-Seung Kim and Ik-Tae Im also gave us their modification methods for the SOLA-VOF[2]. An implicit algorithm was developed. The authors compared the difference between the explicit and implicit SOLA-VOF. According to their simulation results for several shape castings, there is no limit on the time step size even when the Courant number is larger than 10, but when large time step size is used, the solution accuracy will be reduced because of the false diffusion problem. 4.8 may be a good choice of Courant number according to their research.

Ma Xiangjun, Hou Jun and Zhao Lixin used SIMPLEST algorithm and implicit method to simulate the turbulent mold filling process, and Van Leer scheme and explicit method are applied to run after the 3 dimensional free surfaces[3]. A small Courant number is used to determine the free surface for several times in one time step of velocity and pressure calculation cycle, and large Courant number was used to calculate the velocity and pressure fields. The calculation results for the benchmark test proved that the calculation speed was increased 8 times with the Courant number increased from 1 to 10.

Based on the previous work, the purpose of this research is to combine an improved SIMPLE-like scheme with VOF to simulate the mold filling processes. The numerical simulation results proves that the application of large Courant number and implicit scheme will improve the calculation efficiency, but

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adoption of a too large Courant number will reduce the calculation accuracy. Moreover, the treatment method of free surface boundary of molten metal is also very important for the calculation efficiency and accuracy.

2. Model descriptions

Supposing the mold filling processes of castings are laminar fluid flow and heat transfer processes, the following conservation equations can be used to describe the mold filling processes of molten metal.

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial(\rho u_j\phi)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_\phi\frac{\partial\phi}{\partial x_j}\right)+S_\phi \qquad (1)$$

Where, Φ - generalized variables, which denotes mass, momentum, volume fraction of fluid and energy conservation equations respectively when it is set to 1, u_i, F and T; ρ - density of melt; Γ_Φ - generalized diffusion coefficient; t - time; u_j - velocity; x_j - coordinate; S_Φ - source term; F - volume fraction of fluid, 0< =F<= 1; T - temperature.

3. Algorithms

3.1 Derivations of discretization equations and relevant computation scheme

Central differential scheme is used to treat the mass conservation equation. The power-law scheme is used to treat the momentum conservation and the energy conservation equations. A control volume method developed by Date[6] is applied to solve the velocity and pressure fields. In Date's scheme, the velocity prediction and the first pressure correction procedures are same as SIMPLE, and a second pressure and velocity correction step, which considered the influences of convection-diffusion and source terms on the velocity and pressure fields, is added to the calculation procedure. Although the adding step increased the whole calculation amount, the simulation speed still can be improved greatly because the correction procedure can decrease the remaining iteration rapidly. Combining with VOF, the method described above is called predictor-two step corrector-VOF method. More details about Date's scheme can be found in relevant reference.

In original Date's scheme, under-relaxation factor is used for velocity calculation and no relaxation factor is set for pressure calculation. But in this research, the relaxation factors selected for velocity and pressure calculation are 0.6 and 1.6 respectively, and under-relaxation factor 0.7 is applied in temperature calculation. The following iteration formula is one of the examples used in velocity field calculation in x direction:

$$u_e^{\,n+1}=\alpha\left(\sum_{nb}a_{nb}u_{nb}^{n+1}+b\right)/a_e+(1-\alpha)u_e^{\,n} \qquad (2)$$

Where α - relaxation factor; u_e, u_{nb} - velocities of control volume and its neighbors; n+1, n - new and old time or iteration cycle; a_{nb} - discretization coefficients; b - source term;

The iteration formulae of velocities at other directions and energy conservation equation are similar to the above equation.

Two methods are used in the treatment of latent heat if the temperature of fluid decreased below liquidus. When the difference between liquidus and solidus is less than 1K, the temperature recovery method is applied. Otherwise, the equivalent specific heat method is used to handle the latent heat. When the solid fraction of all free surface cells become less than a criterion, calculation stops, and a cold shut warning is given.

3.2 Boundary conditions

In fluid flow calculation, velocity boundary conditions include wall boundary condition and free surface boundary condition. The wall boundary condition is divided into slip condition and no slip condition which was handled in the program directly. For the free surface boundaries of melt, due to some problems such as wrong velocity and pressure prediction or iteration calculation failure have been found in the treatment of these conditions by using of mass conservation equation, especially when the melt meet wall or meet each other, a new method is developed in this research. This method is divided into two steps. Fig. 1 is one of examples. For the cell (i, j) near the free surface of fluid at new time step or new iteration cycle, the following equations are firstly used to get the unknown relevant velocities of void cells.

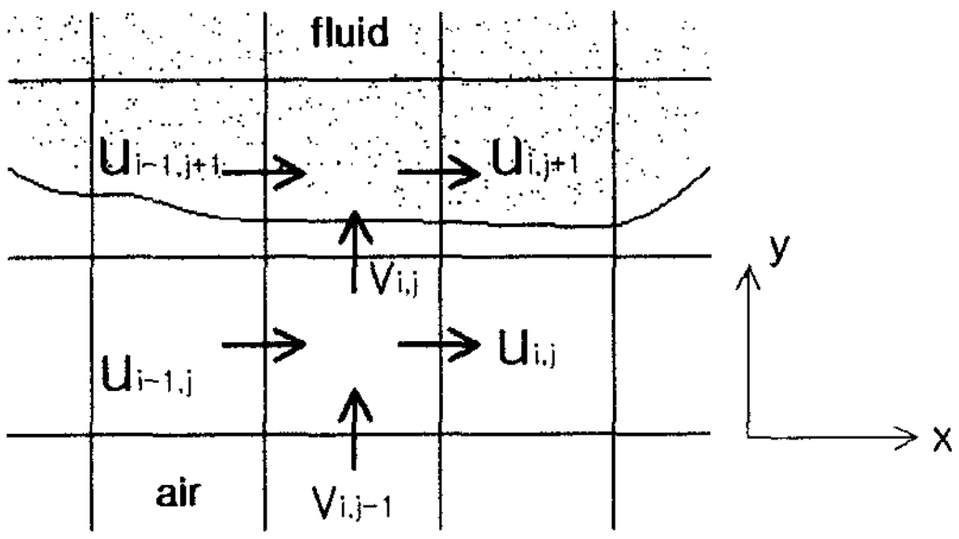


Fig. 1. Velocity handling at fluid-air boundary.

$$u_{i,j} = u_{i,j+1} \tag{3a}$$

$$u_{i-1,j} = u_{i-1,j+1} \tag{3b}$$

$$v_{i,j-1} = v_{i,j} \tag{3c}$$

If the relevant void cells have several fluid neighbors, the velocities of void cells are set to average value of velocities of neighboring fluid cells. Then, setting the velocities obtained through (3a)~(3c) as old time step velocities, modify the velocities through discrete equations similar with equation (2). The first step is a general interpolation method, and the second one is given according to the momentum conservation. The free surface cells of melt take part in the whole velocity and pressure iteration calculation, and their velocities will not be set in the velocity boundary condition. Numerical tests proved that reasonable simulation results and stable and faster calculations would be obtained through the above methods.

3.3 The treatment of melt transportation

Because the VOF method has a limitation for the calculation time step (1/3~1/4 Courant number is used) in order to avoid the smearing or false convection phenomenon, large Courant number can not be applied although an implicit scheme is used for the velocity, pressure and temperature calculation. To solve this conflict, two calculation procedures are adopted during numerical simulation. One is implicit calculation with a large Courant number or large time step δt for velocity, pressure and temperature fields, another one is explicit calculation with a small Courant number or small time step δt/n. δt/n is for the range limited by VOF method, and the second calculation procedure is implemented n times at the new time step to get a new evolution of fluid.

3.4 The solution steps

The implementation sequence of the predictor-two step corrector-VOF scheme is described as following.

(1) Calculating new evolution of melt through VOF.

(2) Calculating new velocity and pressure fields by using of Date's scheme.

(3) Calculating temperature field.

(4) Repeat from (1) to (4) till mold filling is finished.

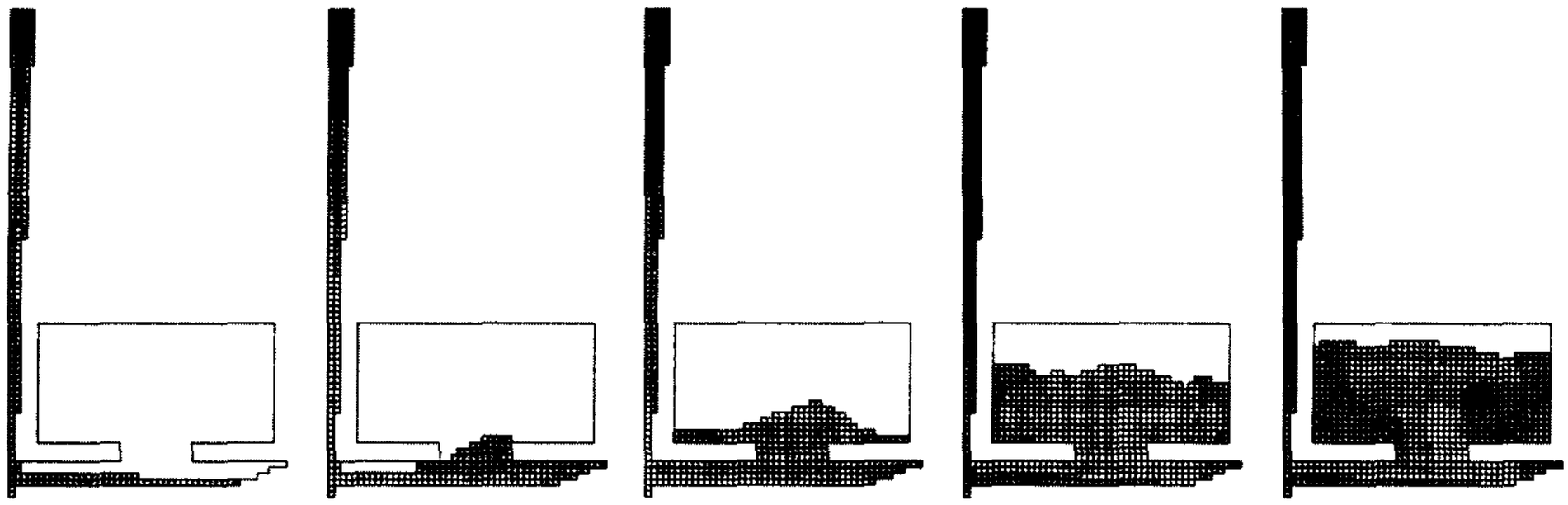
4. Simulation Results and Discussions

Fig. 2 showed the simulation results of benchmark test by using of the predictor-two step corrector-VOF algorithm. The simulation conditions are listed below. Computer: Pentium (r) II, 640MB RAM; Mesh: $60\times15\times87=78300$; Inflow velocity: 56.5 cm/s; Courant number: 4.0; Convergent criterion of velocity field iteration: 0.01; Casting: Aluminum; Mold: furan resin sand; Pouring temperature: 710°C; Environment temperature: 25°C.

Comparing with the experimental results[7], the simulation results of the initial evolution is little bit slow, and this may be due to a constant inflow velocity, coarse mesh size and no slip condition are applied during the calculation. The whole process is close to the real casting. Apart from some places the pressure abruptly changed, the average iteration number is over a range of 30~70 when the new algorithm is used, and the maximum iteration cycle of velocity and pressure calculation is less than 500 under the calculation conditions described above. 1h 15min is the time for this simulation.

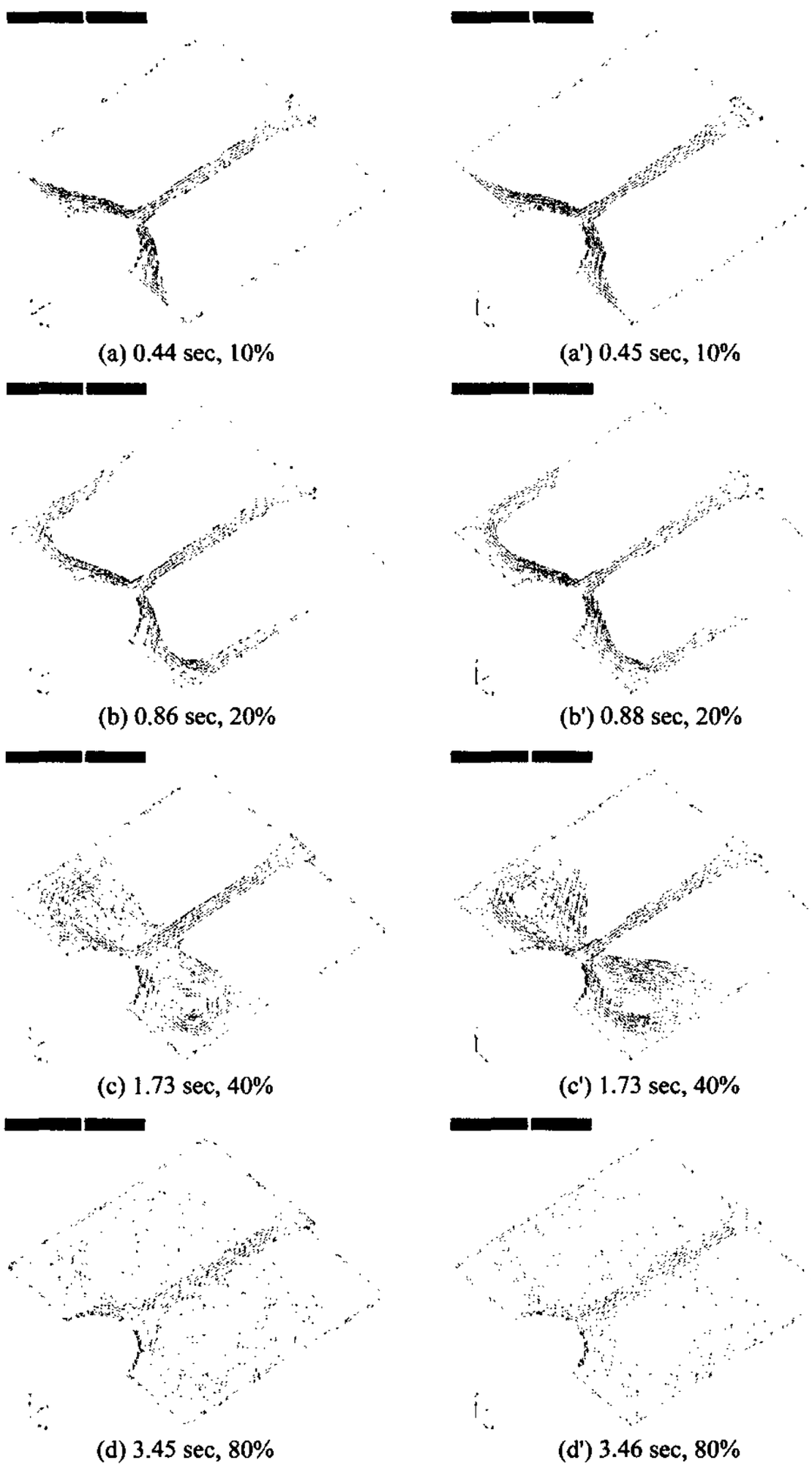
Fig. 3 showed velocity field simulation results of a plate. The purpose of this calculation is to find the effect of Courant number on the calculation speed and accuracy. The calculation conditions are listed below. Mesh: $110\times110\times5=60500$; Inflow velocity: $V_{in}=50$ cm/s; Gravity: $g_y=-981$ cm/s^2; Kinetic viscosity: $\mu=0.108$ g/cm·s; Fluid density: $\rho=2.4$ g/cm^3; Convergence criterion: $\omega=2.5\times10^{-4}$; Computer: Pentium II.

6h 32min is the time for whole simulation process when Courant number 4.0 is applied, and 5h 17min is the time for the same simulation when Courant number



(a) 0.52 sec. (b) 0.77 sec. (c) 1.01 sec. (d) 1.49 sec. (e) 1.74 sec.

Fig. 2. Simulation result for benchmark test.



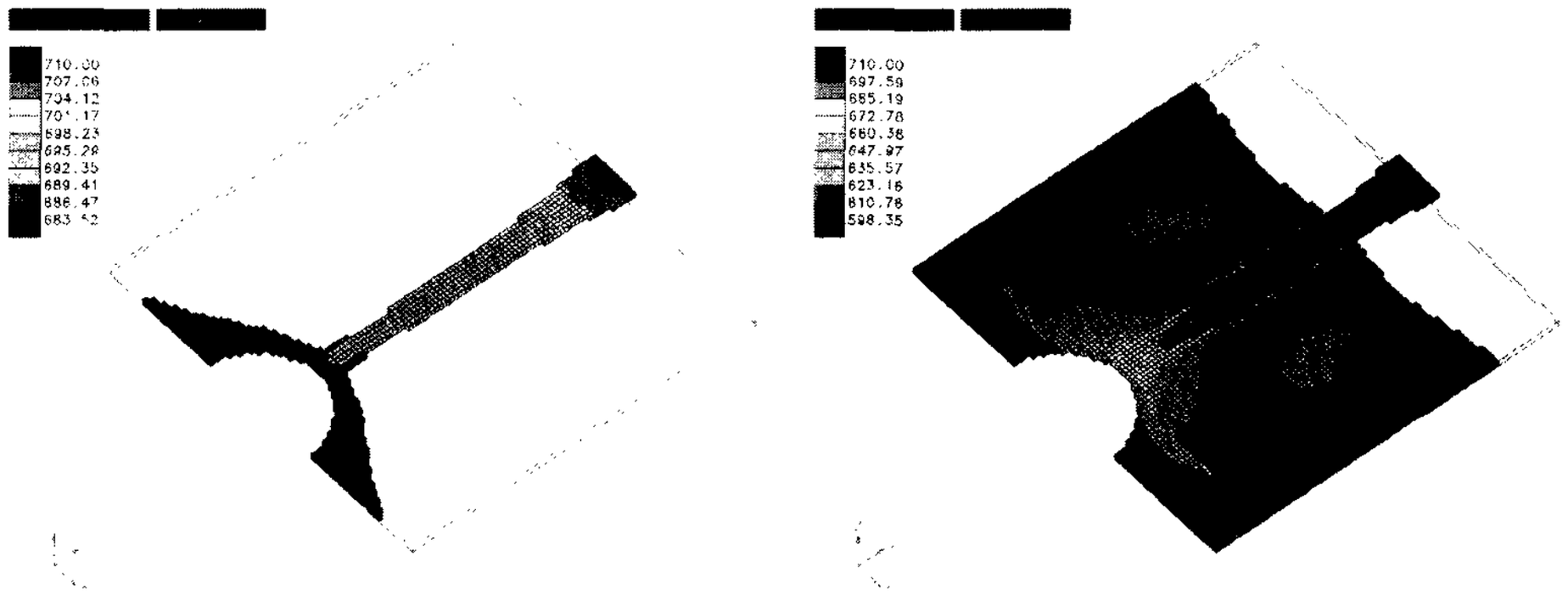
(a) 0.44 sec, 10% (a') 0.45 sec, 10%

(b) 0.86 sec, 20% (b') 0.88 sec, 20%

(c) 1.73 sec, 40% (c') 1.73 sec, 40%

(d) 3.45 sec, 80% (d') 3.46 sec, 80%

Fig. 3. Velocity simulation results of a plate. (a)~(d): Courant number is 4.0 (a')~(d'): Courant number is 8.0



(a) 0.44 sec., 10% (b) 3.45 sec., 80%

Fig. 4. Temperature simulation results of a plate, Courant number is 4.0.

8.0 is applied. The simulation results proved that, although the adoption of a large Courant number can lead to a good efficiency of the simulation process, and the whole tendency of fluid flow is similar, too, but some obvious differences still exist when different Courant number are applied. The details can be found in Fig. 3(b), (b') and (c), (c'). So, a suitable Courant number should be selected carefully in order to speed up the simulation without much lost of engineering accuracy.

Fig. 4 showed the temperature calculation result by using of predictor-two step corrector-VOF method, and the Courant number is 4.0. Jacobi iteration method is used, so the temperature distribution is symmetrical, and also reasonable.

5. Conclusions

(1) A control volume method named predictor-two step corrector-VOF has been developed and successfully simulated the mold filling processes.

(2) The implicit method is used to calculate the velocity, pressure and temperature fields during mold filling processes of castings, and a large and suitable Courant number is applied in this calculation. At the same time, small Courant number is used to calculate the volume transportation of fluid for n times in one calculation time step in order to ensure the accuracy of the evolution of free surface. The above method speeded up the calculation of mold filling process without much loss of simulation accuracy.

(3) A new two step velocity boundary condition based on the interpolation and momentum conservation equation is applied in the void cells, which are neighbors of free surface fluid cells, and the velocity and pressure iteration calculation are implemented on whole fluid cells. Numerical tests proved that the new boundary treatment method would lead to an accurate and efficient calculation.

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