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Simulation and prediction of flow patterns in mold filling①

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[Abstract] The potential of a 3D FDM (Finite Difference Method) computer code was presented, in prediction of flow patterns by modeling the mold filling phenomena through different gating systems. In this code, improvements and modifications were made on the original SOLA-VOF and Donor-Acceptor algorithms. A more accurate solution procedure for handling free surfaces is developed in order to describe the flows through complicated gating designs. A block casting of 200 mm × 200 mm × 50 mm with two different gating designs was chosen as the verifying problem. Water analog studies are carried out on these two gating designs. The comparison indicates that computer simulation could be a powerful tool in shaping gating systems.

[Key words] mold filling; free surface; gating design
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1 INTRODUCTION

Throughout the casting operation, mold filling plays a very important role in casting quality control. Many of the casting defects can be related to the fluid flow phenomena involved in this stage of the operation. It has been noted that the proper gating design is crucial to achieve the desired filling sequence and flow patterns for good quality castings. Therefore, gating systems have been in focus for casting production optimization.

Although the recent developments in modeling of mold filling have provided foundrymen a better insight and more information about the flow behavior during casting operations, most of the researches in literature merely demonstrate the flow patterns and velocity fields in casting cavities[1~6]. For most of the previous calculations, the mold filling process starts from ingates, where an inlet velocity is given. The effects of gating geometry on mold filling play no role in these calculations.

In this paper, an application of a FDM (Finite Difference Method) computer code developed by the author is presented. The mold filling processes of a block casting with two different gating designs are simulated. The flow patterns in gating systems, such as air entrapments and aspiration zones, are predicted. The influence of gating designs on flow patterns is simulated and predicted. Water analog studies are also carried out in order to verify the solution procedures. Direct comparison between the numerical predictions and the experimental observations is made. Good agreements are obtained.

2 MATHEMATICAL FORMULATION

In the simulation of mold filling, the fluid flow phenomena are governed by the momentum equations, the continuity equation stating a mass conservation law and some boundary conditions. If the fluid of interest is assumed to be incompressible, the following mathematical formulation can be written in a 3D Cartesian system.

The momentum equations with three velocity components and pressure as the primitive variables can be expressed as

$$\left.\begin{aligned}
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\\
&\qquad \nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{\partial p}{\rho\partial x}+g_x\\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\\
&\qquad \nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{\partial p}{\rho\partial y}+g_y\\
&\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\\
&\qquad \nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{\partial p}{\rho\partial z}+g_z
\end{aligned}\right\} \quad (1)$$

where u, v, w are the three velocity components in the three directions of coordinates x, y and z; p is pressure, t is time, g is gravity acceleration, ρ is fluid density and ν is kinematic viscosity.

The differential equations described above are the general mathematical formulation governing the conservation of momentum. They are absolutely applicable to anywhere within the fluid domain.

The equation stating the mass conservation is the

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continuity equation. There is no obvious equation available for determining the pressure field. This mass conservation law specifies the pressure field indirectly and implicitly. The continuity equation, under the same consideration as in the above section, can be written here as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (2)$$

The VOF technique is employed for the three-dimensional problems in the present work. Therefore, the F function for free-surface evolution can be written as

$$\frac{\partial F}{\partial t}+u\frac{\partial F}{\partial x}+v\frac{\partial F}{\partial y}+w\frac{\partial F}{\partial z}=0 \quad (3)$$

where F is a step function whose value is unity at any point occupied by fluid and zero otherwise. The average value of F in a given cell is the fractional volume of fluid filling the cell. All the other symbols are the same as defined above.

3 FREE SURFACE MODELING

Some shortcomings were found in the original Donor-Acceptor algorithm since it was established only basing on an one-dimensional analysis. Therefore, a better algorithm, named 3D Donor-Acceptor, is developed in this study. It is described as follows.

If the F in Eqn. (3) is integrated over a free surface cell, we can easily have a discrete equation for F as described below[7~10]:

$$\frac{F_p^*-F_p^n}{\Delta t}+\frac{F_e^*u_e-F_e^*u_w}{\Delta x}+\frac{F_n^*v_n-F_s^*v_s}{\Delta y}+\frac{F_t^*w_t-F_b^*w_b}{\Delta z}=0 \quad (4)$$

where the subscripts e, w, n, s, t and b denote the six surfaces of the free surface cell and p denotes the center of the cell. The super scripts indicate the time step levels. The reason that the F^* values are used in the equation is that the new F values at the time step level $n+1$ are not available at the moment, and a set of guessed F^* values for the six faces have to be given in order to get a guessed value F_p^* for the cell concerned at the new time level $n+1$. The question left is, however, how to guess the F values on the six surfaces because they are not constants during this time interval, but changing all the time in this small time duration. They are neither the upstream F values nor the downstream F values, but some values between 0 and 1. In this study, the original one-dimensional Donor-Acceptor method is adopted to make the guess.

However, as mentioned above, because there are some shortcomings in this one-dimensional method, there are still risks to get a negative F_p^* value or an F_p^* value greater than 1 if Eqn. (4) is directly calculated. Some adjustments to the guessed values are needed. If all the guessed F^* values on the six faces of the free surface cell are adjusted with a small correction F', the fluxes crossing the six faces may be corrected by the following flux correction formulas:

$$\left.\begin{aligned}F_e^{n+1}u_e&=F_e^*u_e+F'R_e\\F_w^{n+1}u_w&=F_w^*u_w-F'R_w\\F_n^{n+1}v_n&=F_n^*v_n+F'R_n\\F_s^{n+1}v_s&=F_s^*v_s-F'R_s\\F_t^{n+1}w_t&=F_t^*w_t+F'R_t\\F_b^{n+1}w_b&=F_b^*w_b-F'R_b\end{aligned}\right\} \quad (5)$$

where

$R_e=\max(u_e, 0)$, $R_w=\max(-u_w, 0)$,

$R_n=\max(v_n, 0)$, $R_s=\max(-v_s, 0)$,

$R_t=\max(w_t, 0)$, $R_b=\max(-w_b, 0)$.

By substituting the starred F values in Eqn. (4) with the corrected values, we can get an equation similar to Eqn. (4) for the new fluid fraction F_p^{n+1} in Cell P at the new time level $n+1$. The subtract Eqn. (4) from the new equation and solve it for F'. Finally, the correction term can be expressed as:

$$F'=\frac{-\dfrac{D}{\Delta t}}{\left[\dfrac{R_e+R_w}{\Delta x}+\dfrac{R_n+R_s}{\Delta y}+\dfrac{R_t+R_b}{\Delta z}\right]} \quad (6)$$

where

$$D=F_p^{n+1}-F_p^*,$$

$$F_p^{n+1}=\begin{cases}0, & \text{if } F_p^*\leqslant 0\\F_p^*, & \text{if } 0<F_p^*<1\\1, & \text{if } F_p^*\geqslant 1\end{cases}$$

Now, if we go cell by cell through the whole calculation domain with the procedure from Eqn. (4) through Eqn. (6), all the volume errors miscalculated with the guessed flux values will be corrected. But this should be an iteration procedure because the corrections made in one cell may influence the balance in its neighbors. In order to ensure the algorithm stable, an under-relaxation method is suggested in this iteration operation.

4 EXPERIMENTAL METHOD

A block casting cavity of dimension 200 mm × 200 mm × 50 mm was chosen as the verifying problem. Two different gating designs were selected. One had a straight down-sprue and the other had a horizontal runner bar between the pouring basin and the down-sprue as shown in Figs. 1 and 2. Water analog studies were carried out on both gating designs in order to observe the flow patterns through different gating systems. Vertical parting was selected to make the observation easier. The mold was made of quartz sand and impregnated with liquid silicone coating materials to make it water tight. A plastic plate was fixed against the mold face and sealed with silicone

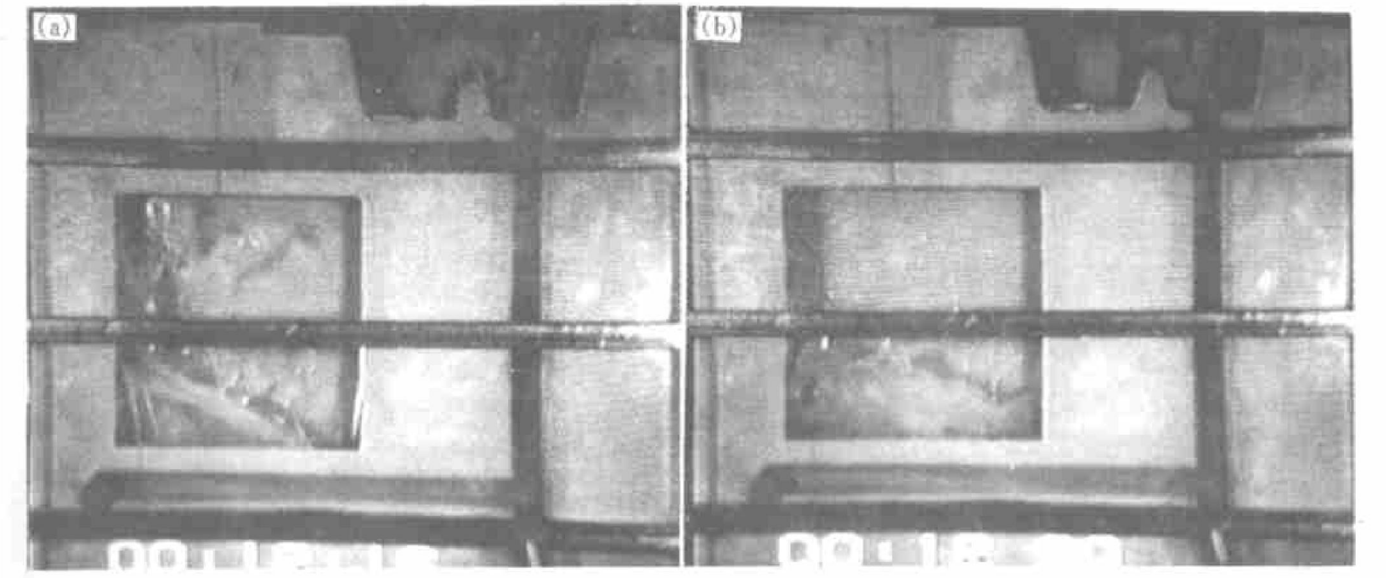

Fig. 1 Observed flow patterns through first gating design
(a) —t = 0.50 s; (b) —t = 0.94 s

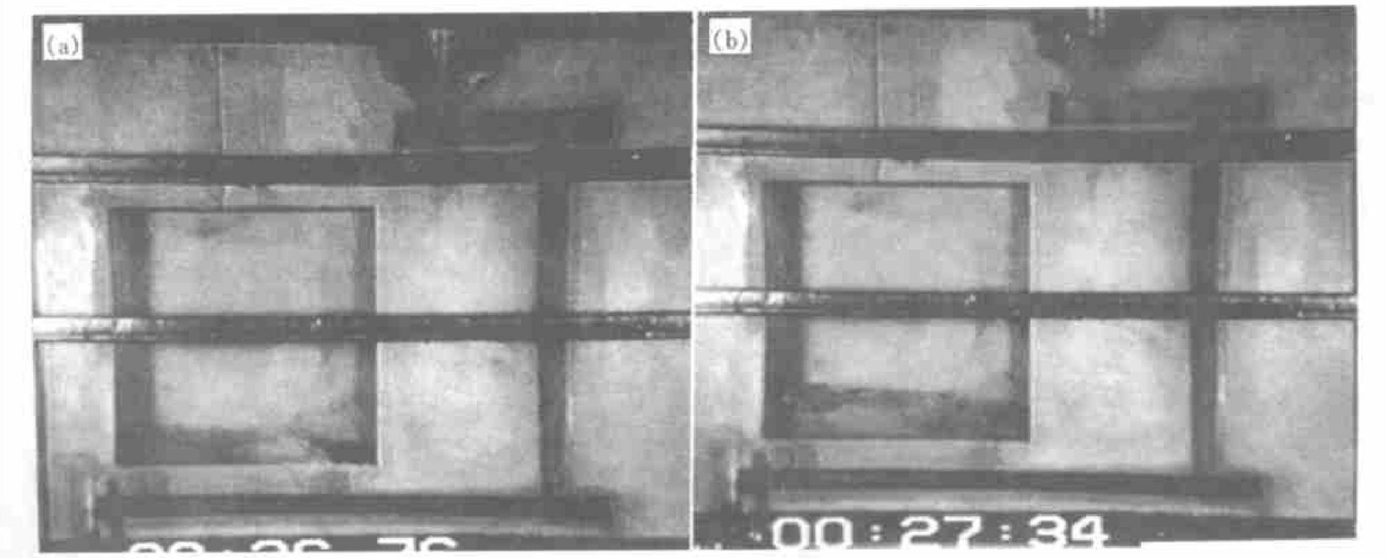

Fig. 2 Observed flow patterns through second gating design
(a) —t = 1.28 s; (b) —t = 1.86 s

rubber. The mold filling processes were recorded by a video camera.

5 RESULTS AND DISCUSSION

Figs. 3 and 4 are pictures of the computational results. The grey scales shown on the pictures present the volume fraction occupied by fluid (water) in FDM cell. The pure white shows that the cells are fully filled with water and the light grey means that the cells are empty. The others show where the free surfaces are. In Fig. 3, it can be seen that the flow coming from the tap first runs down to the bottom of the sprue where it runs to the horizontalrunner, and then it goes along the runner until it reaches the left end. Further, this stream head meets the stream continuously coming from the sprue in the horizontal runner. Thus, a pressure is built up in the runner, which forces the flow to go through the thin slot ingate and shoot up to the top of the mold. Before it reaches the top wall, the water column collapses and falls to the bottom again.

In Fig. 4, the flow pattern is quite different from that in Fig. 3 because of the different gating design. The filling starts from the first runner bar and then goes down to the down-sprue. An interesting phenomenon appearing here is that, although the runner bar is completely filled, there are still some empty cells in the down-sprue. This means that, even though the sprue is felt to be completely filled by the pourer, it sometimes is not. Air entrapment often happens in a down-sprue. When the stream first reaches the left end of the second runner, it also turns over and runs back and then is squeezed into the cast-

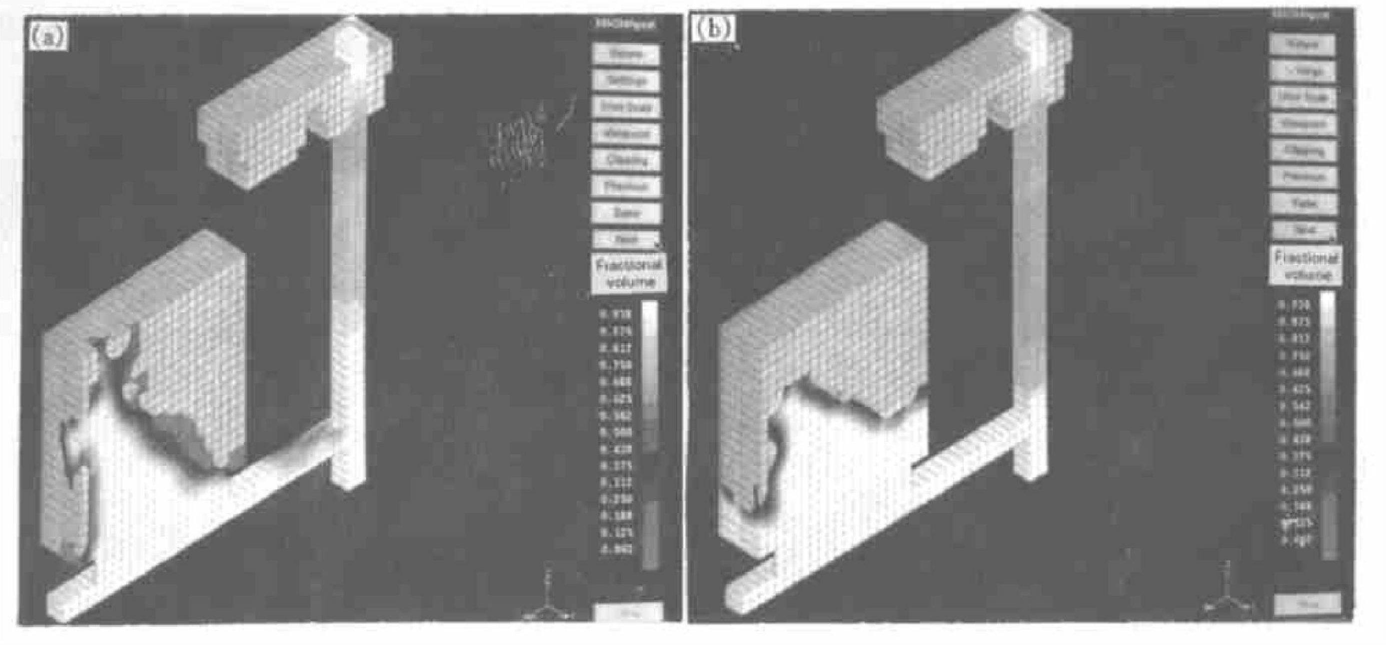

Fig. 3 Simulated flow patterns through first gating design
(a) t = 0.53 s; (b) t = 0.94 s

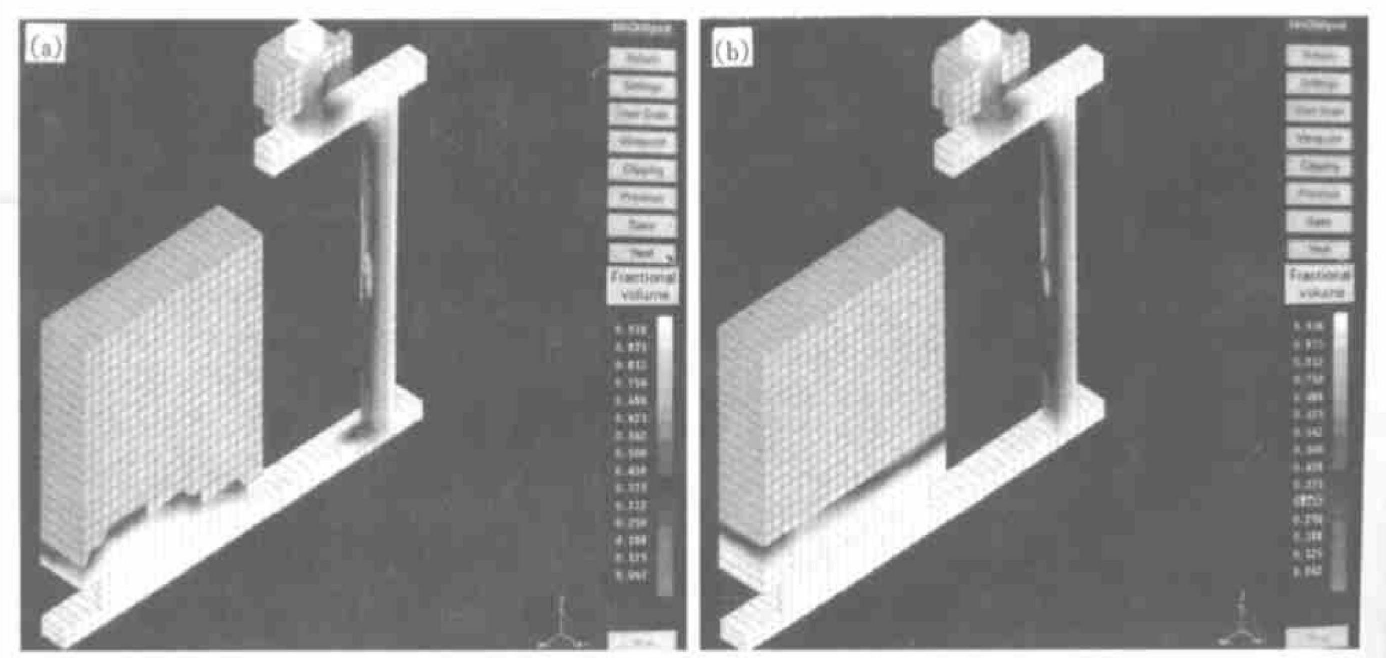

Fig. 4 Simulated flow patterns through second gating design
(a) t = 1.27 s; (b) t = 1.86 s

ing cavity through the slot ingate. But, because of the gating design, the flow speed or the velocity at the ingate, is much smaller than that of the first gating design shown in Fig. 3. The flow is very calm when it enters the cavity. The free surface of water is very flat and smooth, and there is nearly no wave on the surface until the whole cavity is filled. This is expected to give fewer casting defects.

Figs. 1 and 2 show the water analog results of the two different gating systems. These pictures have all the flow features discussed above and the free surface contour is nearly the same as computed. Directly comparing the computational results with the experimental observations, it can be seen that a very good agreement has been obtained. Using the present code, the prediction result is very similar to the experimental investigation and the details of the flow in gating systems can also be easily predicted.

6 CONCLUSIONS

In this paper, the mold filling of a block casting was studied by both water analog and numerical simulation. Two different gating designs were investigated. The flow patterns through these two gating systems were observed from the water analog studies and simulated by a FDM computer code. Direct comparison between the observed and the simulated results was made. According to this study, the following points can be summarized.

1) Gating systems have a great influence on flow patterns in mold filling. Even a small geometry difference in gating shapes can result in rather different flow patterns. Fortunately, computer simulation has a great potential in predicting the flow patterns of different gating designs and further in shaping gating systems.

2) The comparison between the experimental observations and computational results shows that the numerical techniques developed in this work are highly accurate and reliable. The computer code can be used to simulate the mold filling processes of really complex castings and to evaluate gating designs.

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