Numerical simulation and process optimization for producing large-sized castings

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Abstract: 3-D velocity and temperature fields of mold filling and solidification processes of large-sized castings were calculated, and the efficiency and accuracy of numerical calculation were studied. The mold filling and solidification processes of large-sized stainless steel, iron and aluminum alloy castings were simulated by using of new scheme; their casting processes were optimized, and then applied to produce castings.

Key words: numerical simulation; mold filling; solidification process; process optimization; stainless steel; alloyed iron and aluminum castings

Since the 1960s there are 3 progressive periods for modeling and simulation of mold filling and solidification processes of castings. First, in 1988 3-D temperature fields were calculated successfully during solidification of steel casting [1-4]. Second, in 1995 3-D velocity fields of metal flow in mold filling were calculated successfully by B. Sirrell of Birmingham University [5-9]. Third, since 1990 a new task to model and simulate the microstructure and morphology of crystal grains is underway. In order to calculate nucleation in a macroscopic mesh, undercooling at each microscopic cell and the random number of nuclei by Monte-Carlo method, the 3-D velocity, temperature and concentration fields in the meshes of casting should be computed. Some researchers tried to simulate 3-D microstructure of superalloy and ductile iron castings [10-14]. Meanwhile, foundry technicians are more interested in simulating mould filling, solidification process of castings and optimizing the processing parameters to produce sound castings.

Since Re Number $\geq 2300$ is the practical value in the most of the mould filling processes, Lipinski, Yang and Sun considered the effects of turbulent flow on velocity and temperature fields, and solved more equations than those considered laminar flow only [15-17], but it needed quick and accurate calculating schemes of 3-D velocity and temperature fields. Powerful software was developed to increase efficiency and assure accuracy of numerical calculation. 24 million tons of castings were manufactured annually in China, therefore, proper numerical simulations by using of appropriate software are needed eagerly in order to produce sound and large-sized castings efficiently.

1 Modeling equations

When turbulent flow effects on processing parameters are taken into account and time averaged method is being used, the governing equations, including continuity, momentum, volume fraction, energy, turbulent kinetic energy, dissipate rate of turbulent kinetic energy equations, are as following:

\[
\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_j)}{\partial x_j} = \frac{\partial (\mu \frac{\partial u_j}{\partial x_j})}{\partial x_j} - \frac{\partial p}{\partial x_j} + \frac{\partial (\mu \frac{\partial u_j}{\partial x_j})}{\partial x_j} + \rho g_j
\]  

(1)

\[
\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_j)}{\partial x_j} = \frac{\partial (\mu \frac{\partial u_j}{\partial x_j})}{\partial x_j} - \frac{\partial p}{\partial x_j} + \frac{\partial (\mu \frac{\partial u_j}{\partial x_j})}{\partial x_j} + \rho g_j
\]  

(2)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = \frac{\partial (\mu \frac{\partial T}{\partial x_j})}{\partial x_j} + q_v
\]  

(3)

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial (\mu \frac{\partial k}{\partial x_j})}{\partial x_j} \frac{\partial (\mu \frac{\partial k}{\partial x_j})}{\partial x_j} + G - \rho c
\]  

(4)

\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho u_j e)}{\partial x_j} = \frac{\partial (\mu \frac{\partial e}{\partial x_j})}{\partial x_j} + c(f_1 C_1 G - f_2 C_2 \rho e)/K
\]  

(5)

Some variables of the equations are calculated as following:

\[
\mu_s = \mu + \mu_t
\]  

(7)

\[
\mu_t = \mu_P + \mu_t / \sigma_t
\]  

(8)
Where:
\[ R_e = \text{turbulence pulse Reynolds number}; \]
\[ \rho = \text{liquid density, kg/m}^3; \]
\[ x_i, x_j = \text{coordinate, m}; \]
\[ u_i, u_j = \text{velocity, m/s}; \]
\[ \mu = \text{molecular dynamic viscosity, Pa} \cdot \text{s}; \]
\[ \nu = \text{molecular kinematic viscosity, m}^2/\text{s}; \]
\[ \mu_t = \text{turbulent viscosity, Pa} \cdot \text{s}; \]
\[ \mu_n, \mu_K, \mu_f = \text{generalized diffusion coefficient, Pa} \cdot \text{s}; \]
\[ t = \text{time, s}; \]
\[ g_i = \text{gravity acceleration, m/s}^2; \]
\[ T = \text{temperature, K}; \]
\[ p = \text{pressure, N/m}^2; \]
\[ F = \text{volume fraction, } 0 \leq F \leq 1; \]
\[ q_v = \text{heat source term, kg} \cdot \text{K/s} \cdot \text{m}^3; \]
\[ K = \text{turbulent kinetic energy, m}^2/\text{s}^2; \]
\[ P_r = \text{molecular Prandl number}; \]
\[ \epsilon = \text{dissipate rate of turbulent kinetic energy, m}^2/\text{s}; \]
\[ G = \text{the producing term of turbulent kinetic energy, Pa/s}; \]
\[ \text{coefficients: } \sigma_f = 0.9-1.0, \sigma_K = 1.0, \sigma_v = 1.3, \text{C}_1 = 1.44, \text{C}_2 = 1.92, C_n = 0.09, f_i = 1.0 \]

Based on these equations, with appropriate initial and boundary conditions, 3-D velocity and temperature fields can be calculated.

### 2 Program for the calculation and display of 3-D velocity and temperature fields

#### 2.1 Pre-processing and post-processing

Pre-processing and post-processing programs were developed. It increases the enmeshment speed by 13 times by using new algorithm; for example, 1.93 million meshes can be generated in 5 seconds. The new program can read STL format file of casting solid geometry and is able to repair defects in STL file automatically; the inflow boundary condition can be set up and changed by mouse indicator; post-processing may show filling pattern, 3-D velocity vector variation, 3-D temperature distribution and result of \( u, p \) and \( T \) on any section of the casting, and operation is quick and convenience. It is able to choose 19 different kinds of materials to represent different attribution of meshes during numerical calculation of mold filling and solidification process of casting, which brings more practicality for engineering analysis [18].

#### 2.2 Fluid flow and heat transfer calculation by high resolution MINMOD scheme

In this study, high resolution MINMOD mesh with 5 points was adopted to make the discretization of momentum and energy conservation equations on unequal size of meshes [19]; improved VOF method was used to deal with the evolution of free surface and SOLA technique was used to calculate the velocity of fluid flow. Results showed that numerical accuracy was increased, as shown in Fig. 1, false diffusion and virtual physical phenomenon that generated from the numerical calculation were eliminated. The symmetrical distribution of temperature was reasonable during mold filling process of aluminum alloy plate casting.

**Fig. 1 Mould filling simulation of plate casting by high resolution MINMOD scheme**

### 3 Exploration for increasing efficiency of numerical simulation

Since large portion of computing time was consumed in the simulation of velocity field during mold filling, so many efforts were devoted to increase the calculation efficiency. Velocity field during mold filling was calculated by using of a new algorithm named predictor-two step corrector-VOF, which applied the implicit algorithm and large time step \( \delta_t \) on calculation of velocity, pressure and temperature; and explicit algorithm with a small time step \( \delta_t/n \) over the free surface range \( n \) is times cycles to get a new evolution of fluid. Figure 2 showed the simulation results of Benchmark test by using of the new algorithm with Courant Number equal to 4, where \( C=u \Delta t/\Delta x \). The simulated results were in agreement with the Benchmark test.

Figure 3 showed the velocity field simulation results of a plate casting with inflow velocity of 50 cm·s\(^{-1}\). Time cost for the whole simulation process was 392 min and 317 min, when Courant Number, C, equal to 4.0 and 8.0, respectively. Computing time can be shortened by 19% if Courant Number of 8.0 was used instead of 4.0. Although the adoption of a
large Courant Number can lead to good simulation efficiency and the general tendency of fluid flow is similar, some obvious differences exist. The details can be found in Figs. 3 (b), (b’) and (c), (c’).

Therefore, a suitable Courant Number should be selected carefully in order to speed up the simulation without much loss of engineering accuracy.

Fig. 2 Mould filling simulation of the Benchmark test by predictor-two step corrector-VOF scheme with C=4

Fig. 3 Velocity fields of mould filling by predictor-two step corrector-VOF scheme for plate casting (a)–(c): C=4.0, (a’)–(c’): C=8.0

Fig. 4 Temperature fields of mould filling for plate casting

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4 Numerical simulation and process optimization of large-sized castings

4.1 Dual-phases stainless steel casting

Aim at producing dual-phases stainless steel impeller casting of 2,667 kg, numerical simulations for 3 different casting process techniques were carried out. Figure 5 showed the solid geometry of the impeller casting. Figure 6 showed the chill design and the solidified time field of casting process 1. Figure 7 showed the increased chill size to enlarge the cooling ability and the simulated result using casting process 2. In both technique 1 and technique 2, there are some isolated regions near blade bottoms or middle parts of the impeller casting, therefore shrinkage or porosity may be formed in the corresponded regions. This cannot meet the requirements of high strength and no defects in the connecting part of the blade root and the main body of the impeller, so techniques 1 and 2 were denied. Figure 8 showed the solid geometry and enmeshment of impeller casting with in-gate and risers, using casting technique 3, no any of chills, and enhancing feeding ability from inside of main body. Figure 9 showed the flow pattern, free surface evolution and temperature distribution during mold filling.

Fig. 5 Solid geometry of impeller casting

Fig. 6 Casting technique 1

(a) Chill design
(b) Solidified time field

Fig. 7 Casting technique 2

(a) Chill design
(b) Solidified time field

Fig. 8 Casting technique 3

(a) Solid geometry of casting with feeders
(b) Enmeshment

Fig. 9 Flow patterns and temperature fields during mould filling of impeller casting for casting technique 3

(a) 5.52 s, 25%
(b) 16.55 s, 75%
(c) 22.07 s, 100%
Figure 10 showed the solidified time fields during solidification process. From these results it can be sure that liquid metal fills the mold cavity steadily. This solidification process can meet the requirement of sequential solidification, and thus no shrinkage and porosity appear. Mold filling time was 22 s and solidifying time was 3.26 h, both of these times were suitable for foundry operation. Figure 11 showed the side and top views of the produced sound casting.

4.2 Alloyed iron casting

Numerical simulation of JT30-54 alloyed iron air compressor block casting with a weight of 7,665 kg was carried out to calculate temperature fields under 3 different casting processes. Two typical results for the casting technique 1 and 3 are shown in Figs. 12 and 13. For the casting technique 2, the simulated result was between the casting technique 1 and 3.

Figure 12 shows the solid geometry, riser and chill positions in the mold, and also defect prediction of the casting under casting technique 1. As shown in Fig 12 (c), there exists a large range of isolated solidified region in the middle part of casting. Large area of shrinkage and porosity defects may be formed in this region. Leakage defect was detected when the produced casting was under pressurized testing. It demonstrated that the simulated results were reliable. Figure 13 shows the solid...
geometry, riser position, chill distributions in the mold and also defect prediction of the casting under casting technique 3. Compared with those of casting technique 1, casting technique 3 enhanced the cooling ability by increasing both the quantity and size of the chills, and thus reduced the isolated volume significantly. The isolated volume distributed separately and no linked porosity defects can be formed. The produced block casting, as shown in Fig. 14, was machined and pressurized at 0.6 MPa, no leakage was detected. The casting satisfied the requirements in specification.

4.3 Aluminum casting

Numerical simulation of large thin walled ZL114A aluminum casting with a weight of 586 kg, pouring temperature of 710°C, mould temperature of 25°C (no-bake furan resin bonded sand) and inflow velocity 20–50 cm·s⁻¹ was carried out to calculate velocity and temperature fields under 2 different casting processes by using of low pressure casting method. The solid geometry and enmeshment of aluminum casting with 15.03 million meshes are shown in Fig. 15 (a). There was a misrun defect if low inflow velocity of 20 cm·s⁻¹ was used, as shown in Fig. 15 (b). No misrun was appeared if inflow velocity of 50 cm·s⁻¹ was used, as shown in Fig. 15 (c), in this case the filling time was 44 s. Figures. 15 (d) and 15 (e) showed the temperature fields during solidification process in which the whole casting solidified in about 24 min. So final casting process parameters adopted were that the time of increasing pressure was 44 s, inflow velocity at elevated liquid metal tube was 50 cm·s⁻¹, holding pressure time was 24 min. By using these parameters, sound casting was produced, as shown in Fig. 15(f).
5 Conclusions

(1) Time averaged governing equations, include continuity, momentum, volume fraction, energy, turbulent kinetic energy, dissipate rate of turbulent kinetic energy equations were established. It is able to calculate the velocity and temperature fields for laminar and turbulent flow during mold filling and solidification process.

(2) The developed computer program can read STL file, enmeshing solid geometry, displaying velocity vector, 3-D velocity and temperature fields, filling pattern, temperature distribution of mold filling and solidification process.

(3) The numerical simulation can be used to predict the casting defects and to optimize the casting process parameters to produce large-sized sound stainless steel, alloyed iron and aluminum castings.

References