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Numerical Simulation of Flow and Heat Transfer during Filling Process Based on SPH Method

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Abstract. Expected to the non-grid characteristics and pure Lagrangian properties of SPH, the simulation of casting's filling process would be simpler and precise. In this study, the implementations of SPH method are studied for liquid metal flow and heat transfer during the filling process. The temperature based thermophysical parameters are fitted and add into flow-heat coupling program. The temperature recovery method is included to consider the effect of latent heat. The validation of one-directional heat transfer problem shows that the SPH results have good agreement with the analytical results. The maximum relative error is less than 3%. Finally a circular part is calculated and proved that the SPH model used here works well and has enough precision to capture the behavior of the filling process.

Introduction

Casting's quality is dramatically influenced by filling process. Due to the filling process is invisible, using numerical simulation method to calculate and predict the filling process is very useful to not only ensure casting quality but also reduce the trial period and reduce production costs. At present, most simulation methods for the fluid filling process based on Eulerian grid, which are difficult to establish mesh for the casting. The methods also have many difficulties in free surface and interface capture because of artificial diffusion. Recently, a kind of Lagrangian method called Smooth particle hydrodynamics (SPH) has been widespread concerned[1-2]. Due to the non-grid characteristics and pure Lagrangian properties of SPH, the pretreatment of the geometry model could be simpler and the capture of free surface could be more precise, which will bring significant benefits for filling process simulation. Cleary et. al. used SPH to simulate metal forming and first introduced it into the casting process successfully [3]. V. Vishwakarma used the formula proposed by Cleary to investigate the steady state conduction through 2D irregular bodies [4]. However, there is little study on the interactions between liquid metal and mould during the filling process of SPH simulation. To obtain precisely results of filling process, many specific issues such as boundary conditions and latent heat treatments require in-depth study.

This work aims at the implementations of SPH method in liquid metal flow and heat transfer during the filling process. The conservation equations are derived in the SPH discrete scheme. As the variation of temperature would exert an influence on the physical property of liquid metal, a treatment of the temperature effect on physical property is introduced and a flow-heat coupling program is established. The model of contact thermal conductions has been proved by comparing the analytic solution with numerical solution in dealing with one-dimensional case. To investigate the effect of latent heat, a temperature recovery method is included into the simulation. Finally a circular part is calculated to validate the capability of filling process simulation with SPH method.

Numerical model in filling process

Conservation equations. The distributions such as fluid velocity and temperature can be gained from solving the conservation equations that include continuity equation, momentum equation and energy equation. From Monaghan[5], the continuity equation and momentum equation can be described as follows:

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t} = \sum_{j=1}^{N} m_j v_{ij}^{\beta} \frac{\partial W_{ij}}{\partial x_i^{\beta}} \tag{1}$$

$$\frac{\mathrm{d}v_i^{\alpha}}{\mathrm{d}t} = -\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \frac{\partial W_{ij}}{\partial x_i^{\alpha}} + \sum_{j=1}^{N} m_j \left(\frac{\mu_i \varepsilon_i^{\alpha\beta}}{\rho_i^2} + \frac{\mu_j \varepsilon_j^{\alpha\beta}}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial x_i^{\beta}} + F^{\alpha} \tag{2}$$

Where W_{ij} is so called kernel function, m_j and ρ_j denote particle j's mass and density, respectively. N is the sum of particles in i's compact domain. $v_{ij}^{\beta} = v_i^{\beta} - v_j^{\beta} = -v_{ji}^{\beta}$, v_i^{β} and v_j^{β} refers to speed, p denotes to particle pressure, μ is dynamic viscosity, $\varepsilon^{\alpha\beta}$ is shear stain rate, the subscript i and j denotes particle i's and j's variables, while α and β indicates the coordinate directions. The terms Π_{ij} is the artificial viscosity between particles i and j, which is introduced in Monaghan's work[1].

In the present work, weakly compressible model is considered to calculate the dynamic pressure p, in which an equation of state is used:

$$p = K\left(\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right) \tag{3}$$

Where ρ_0 is the reference density, γ is chosen to 7 to govern the weak-compressibility of the fluid. Parameter K is the magnitude of the pressure, which is chosen to ensure the maximum density oscillation is less than 1% around the reference density.

The positions of SPH particles can be determined directly from the velocity field as:

$$\frac{\mathrm{d}\mathbf{x}_i}{\mathrm{d}t} = \mathbf{v}_i \tag{4}$$

To obtain the temperature distribution, the heat conduction formula was used followed Cleary[6], that is:

$$\frac{\mathrm{d}T_i}{\mathrm{d}t} = \frac{1}{\rho_i c_{pi}} \sum_{j=1}^{n} \frac{m_j}{\rho_j} \frac{4\lambda_i \lambda_j}{\lambda_i + \lambda_j} (T_j - T_i) \frac{\left(x_j^{\beta} - x_i^{\beta}\right)}{r_{ij}^2} \cdot \frac{\partial W_{ij}}{\partial x_i^{\beta}} \tag{5}$$

Where T denotes temperature of the particle, c_p is specific heat coefficient, λ is thermal conduction parameter, r_{ij} is the distance between particle i and j. The advantage of this form is that only the first order of kernel function is used to approximate the Fourier equation, which would be more stable and precise.

Thermophysical parameters treatment. During the filling process, the thermophysical parameters could be changed due to the temperature variation, which would influence the flow of liquid metal. To consider the temperature based thermophysical parameters, some fitting formulas obtained from experimental data are added into SPH calculation. For example, the dynamic viscosity of AlSi8Cu3 can be expressed as the followed quadratic expression:

$$\mu = 1.1017 \times 10^7 - 25039.9449T + 15.6628T^2 \tag{6}$$

Where the temperature is between 500℃ to 810℃. It should be declare that the Eq.6 is only for the facility of coding and doesn't have physical meaning. To maintain the efficiency of the SPH program, these parameters are updated every thirty time step.

Latent heat treatment. In order to consider the influence of latent heat during filling process, the temperature recovery method is investigated and implied into the current SPH model. At each time step, the temperature rate is obtained by Eq.5 firstly. Using time integration, the temperature at next time step marked as T^{n+1} can be calculated. In other words, the temperature of the particle has

changed from T^n to T^{n+1} in Δt. If $T^n>T_S$ and $T^{n+1}<T_L$, the T^{n+1} shall be fixed with latent heat based on the followed equations. The T_S and T_L denotes the solidus temperature and liquidus temperature respectively.

If $T^n>T_L$, the modified temperature T^{n+1*} can be expressed as:

$$T^{n+1*}=\begin{cases} T^{n+1}+\dfrac{L}{c_p}, & T^{n+1}<T_S-\dfrac{L}{c_p} \\ T_L-\dfrac{c_p}{c_p+\dfrac{L}{T_L-T_S}}\left(T_L-T^{n+1}\right), & \text{others} \end{cases} \tag{7}$$

If $T^n<T_L$, the modified temperature T^{n+1*} can be expressed as:

$$T^{n+1*}=\begin{cases} T^{n+1}+\dfrac{L}{c_p}\left(\dfrac{T^n-T_S}{T_L-T_S}\right), & T^{n+1}<T_S-\dfrac{L}{c_p}\left(\dfrac{T^n-T_S}{T_L-T_S}\right) \\ T^n-\dfrac{c_p}{c_p+\dfrac{L}{T_L-T_S}}\left(T^n-T^{n+1}\right), & \text{others} \end{cases} \tag{8}$$

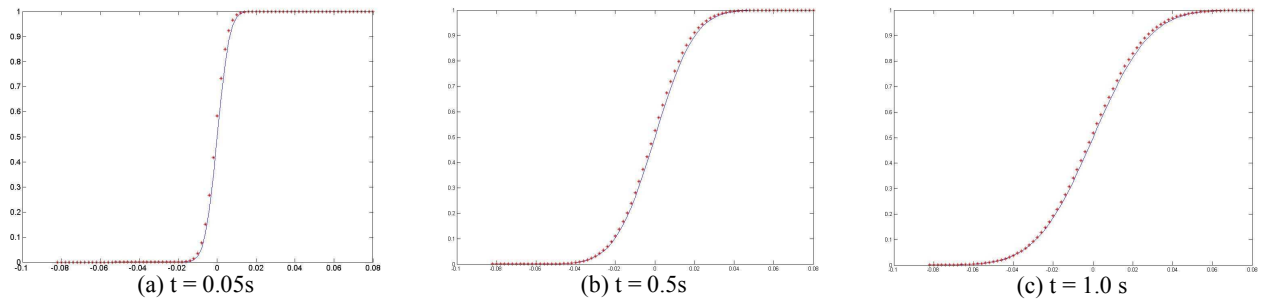
The parameter L denotes the latent heat of the molten metal. Then the modified temperature T^{n+1*} can be used as initial one for the next time step.

Simulation and discussion

One dimensional validation. In order to validate the precision of SPH thermal conduction, a one-dimensional problem was calculated by SPH algorithm and compared with analytical one. The problem denotes a homogeneous plate with different temperature in its two sides, where the hot side is 1℃ and the cold side is 0℃. The density, thermal conductivity, specific heat of the material is 1000.0kg/m^3, 1.0W/(m·K), 1.0kJ/(kg·K), respectively. The control function can be described as Eq.9. The analytical resolution is shown as Eq.10.

$$1000\frac{dT}{dt}=-\frac{\partial^2 T}{\partial x^2} \tag{9}$$

$$T=\begin{cases} \dfrac{1}{2}erfc\left(\dfrac{|x|}{\sqrt{0.001t}}\right) & x\le 0 \\ \dfrac{1}{2}\left(1+erf\left(\dfrac{x}{\sqrt{0.001t}}\right)\right) & x>0 \end{cases} \tag{10}$$



(a) t = 0.05s (b) t = 0.5s (c) t = 1.0 s

Fig.1 Comparison of temperature distribution between SPH and analytical solution

Fig.1 shows the temperature distribution comparison between SPH results and analytical solution. It can be seen that the SPH results described with points show good agreement with the analytical results described with solid line. The maximum relative error occurred at x=0 and less than 3%.

Circle filling simulation. In this section, a filling process in the circle mould with core was calculated to validate the coupled flow and heat transfer of the current SPH model. The geometry we used refers to Schmid's work[5]. The AlSi8Cu3 is adopted as fluid material while the mould material we used is H13 steel. The filling speed and temperature of the fluid is set as 3m/s and 973K, respectively. Both the fluid and mould particle space is set as 1mm.

The calculating program is coded by Fortran language. The heat and flow coupled model used here works well and has enough precision to capture the behavior of the filling process. The simulation results are shown in Fig.2. Molten metal entered the mould cavity and directly impacted on the core, then split into two streams. Each stream strikes the outside of the mould and delivered as two sub-streams once again. At last, these sub-streams confluence together and form four hole around the core. During this process, the sub-streams which retrace back to the gate suffer a long period of heat transfer with the mould. This causes the temperature of these sub-stream significantly reduced.

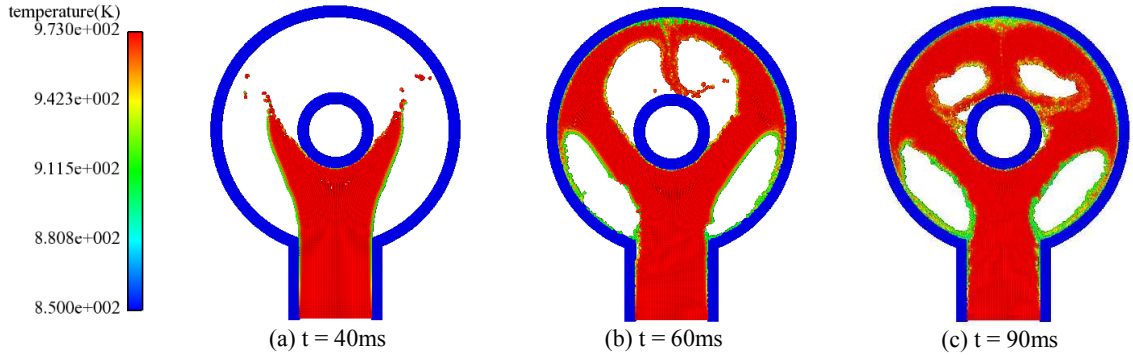


Fig.2 Temperature distribution of circle mould filling

Conclusions

The implementations of SPH method in liquid metal flow and heat transfer during the filling process are investigated. The temperature based thermophysical parameters are fitted and add into flow-heat coupling program. The temperature recovery method is included to consider the effect of latent heat.

The model of contact thermal conductions with one-dimensional case is calculated with analytic solution and numerical one. The comparison shows that the SPH results have good agreement with the analytical results. The maximum relative error occurred at x=0 is less than 3%. The circular part filling process is calculated with SPH method which considered latent heat and the flow-heat coupling. The SPH model used here works well and has enough precision to capture the behavior of the circle mould filling process.

Acknowledgements

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