Analysis and Research of Molten Copper Sloshing in Mould of Anode Based on VOF Method

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Abstract. In the production process of anode, the quality of anode is affected by the sloshing of molten copper caused by casting wheel during operation. Therefore, it is significant to study the sloshing of molten copper and the motion model of casting wheel for improving the quality of anode. Using VOF method and UDF to study the sloshing of molten copper and the motion characteristics of casting wheel. Establishing the \( \Delta H = a \) model through the method of FLUENT and MATLAB. The optimal motion model of casting wheel is S-model.

1. Introduction
The sloshing of copper liquid in the mould will be caused by the rotating process of casting wheel. Because the temperature of the mould is lower than that of the molten copper, when the molten copper sloshes, the molten copper will adhere to the mould and form copper, forming raised edge and burrs. When the raised edge is large or burr is much, the scrap anode is formed and recasted. The study of molten copper sloshing and motion characteristics of casting wheel is very important in the industry. It can improve the quality of anode, reduce the scrap rate and cost.

VOF refers to the volume function of the fluid, which is defined as the ratio of the volume of the target fluid to the volume of the grid in each grid of the flow field. As long as we know the value of this function on each grid, we can track the moving interface[1,2]. At present, many domestic scholars such as Yutai Huang[3] and Xicong Zou[4] have studied the fluid-solid coupling dynamics of aircraft fuel tank sloshing, Di Yu[5] and Zhuqing Cheng[6] have studied the liquid impact in automobile fuel tank, and analyzed the influence of fuel tank filling ratio and fuel tank baffle on liquid sloshing. The effect is well. However, there are few studies in the field of sloshing of molten metals. The software called ICEM CFD[7] has better mesh quality in fluid region, analysis and optimization of motion model using UDF[8], the sloshing of molten copper can be accurately traced by VOF.

2. Establishment of temperature-viscosity model of molten copper and its fluidity analysis
Molten copper is different from water. To analyze the sloshing of molten copper, it is necessary to study the viscosity characteristics of molten copper. The viscosity of molten copper is different at different temperatures. The type of mould and the average flow rate of molten copper will affect the fluidity of molten copper. The viscosity and fluidity affect the results of sloshing analysis.

2.1. Establishment of temperature-viscosity model of molten copper
The fluidity of molten copper is equal to the reciprocal of viscosity. The viscosity of molten copper affects the sloshing. In the industry, the main factor affecting the viscosity is temperature. The temperature of molten copper affects the sloshing. The relationship between viscosity and temperature:
In formula (1), \( \eta \) is the viscosity, \( B_0 \) is the coefficient and \( RT \) is the temperature in a certain range. The melting point of copper is 1083°C. The fluidity of molten copper is better when the temperature is 1200°C. The temperature of molten copper studied in this paper is 1083°C - 1350°C, which is converted to Kelvin temperature of 1356 K - 1623K.

Referring to literature [9], two viscosities at different temperatures were obtained: \( T_1 = 1373K, \eta_1 = 3.996 \times 10^{-3} \text{pa} \cdot \text{s} \); \( T_2 = 1573K, \eta_2 = 2.638 \times 10^{-3} \text{pa} \cdot \text{s} \).

The relationship between temperature and viscosity of liquid copper is obtained by substituting temperature into formula (1):

\[
\eta = 10^{1950/T-3.8186}
\]  

The relationship between viscosity and temperature of molten copper is shown in Fig. 1.

2.2. Fluidity analysis of molten copper in mould

Reynolds is a dimensionless number that can be used to represent fluid flow. The formula for calculating Reynolds number is:

\[
Re = \frac{\rho v d}{\eta}
\]  

Formula (3): \( \rho \) is density, \( v \) is velocity of fluid, \( d \) is length, \( \eta \) is viscosity.

The relationship between viscosity and temperature (2) is substituted into formula (3), and the Reynolds formula is obtained:

\[
Re = \frac{\rho v d}{(10^{1950/T-3.8186})}
\]  

In the simulation of molten copper sloshing, the length of mould \( d = 1140 \text{ mm} \). The density of molten copper \( \rho=8.920 \text{ g/cm}^3 \).

The molten copper velocity \( V \) is similar to the linear velocity \( v_1 \) of the mould, \( v = v_1 \). According to the production requirements of copper smelter, the production task of 18-mode single casting wheel is \( x=30 \text{ tons/hour} \). Taking 275 kg anode as an example, the weight of each anode is \( G=275 \text{ kg} \), the modulus of casting wheel is \( S=18 \), the diameter of casting wheel is \( D=10 \text{ m} \), and the time of casting process is \( C=15 \text{ s} \). The results show that the average velocity \( v_1 \) of each position is:

\[
v_1 = \frac{\pi D}{4t}
\]  

In formula (5), \( t \) is the time for mould to rotate a position:

\[
t = \frac{3600G}{1000x} - C
\]
The average flow velocity $v = v_1 = 0.097 \text{m/s}$ was obtained. The Reynolds formula was introduced to calculate the minimum value of the movement of molten copper in the mould, which was 309624.

3. The simulation of the molten copper sloshing

The diameter of the casting wheel is 10m. The velocity and acceleration of the outer ring is the highest, and the arc length of the outer ring is 1.74m. The rotational characteristics of casting wheel can be understood as the movement characteristics of the wheel.

3.1. The simulation model of molten copper level

It is necessary to understand the shape of molten copper in the mould to establish the simulation model. The specification of 275kg anode is shown in Fig. 2. $L_1=1140\text{mm}$, $L_2=1110\text{mm}$, $L_3=960\text{mm}$, $D_1=770\text{mm}$, $D_2=200\text{mm}$, $D_3=620\text{mm}$, $R_1=75\text{mm}$, $R_2=105\text{mm}$, $H=45\text{mm}$.

According to the specifications of anode, the shape of anode is about cuboid. Sloshing height is mainly caused by the tangential force of casting wheel, and the influence of centrifugal force is small. Therefore, the molten copper is simplified into rectangle, $H = 100\text{mm}$, $D = 770\text{mm}$, and the molten copper level is 45mm, as shown in Fig. 3.

3.2. Establishment of $\Delta H - a$ model and simulation

When the acceleration is $0 \text{m/s}^2$, the level of molten copper is 0 mm. According to the experience, the acceleration $a_1=0.1 \text{m/s}^2$ and $a_2=0.04 \text{m/s}^2$ are selected, and the maximum liquid level height in the mould under the action of $a_1$ and $a_2$ is calculated by FLUENT simulation. The $\Delta H - a$ model was established by MATLAB curve fitting.

The curves are shown in Fig. 4. The model equation is:

$$\Delta H = 8832 \times \left( \sin(a - \pi) \right) - 446.1(a - 10)^2 + 4.461 \times 10^4 \quad (7)$$

Formula $7\text{m/s}^2 < a < 0.1\text{m/s}^2$. When $\Delta H= 4\text{mm}$, the $a=0.056 \text{m/s}^2$. Under the condition that the casting wheel rotates for the shortest time, the maximum sloshing height is 4mm.
In order to verify the correctness of the \( \Delta H - a \) model, further simulation shows that when the acceleration is 0.056 m/s\(^2\), the maximum molten copper level is 49mm, and the height difference \( \Delta H = 4 \)mm, as shown in Fig. 5.

4. Establishment of moving model of casting wheel

4.1. Triangular motion model

The triangular motion model is shown in Fig. 6. The molten copper is accelerated in opposite direction, and the potential energy is transformed into kinetic energy. The level at 770 mm will exceed 49 mm. Therefore, the model does not meet the design requirements.

4.2. Trapezoidal motion model

Aiming at the problem that the sloshing high in the deceleration stage of triangular model, the uniform phase is added in the middle period. The sloshing tends to be stable through the uniform phase. At the same time, the temperature of molten copper decreases continuously, the viscosity increases further, and the resistance to sloshing increases. Under the same acceleration, the level will decrease. The trapezoidal motion model is designed as shown in Fig. 7. The relationship between speed and time is as follows:

\[
 v = \begin{cases} 
   0.056t & (0 \leq t \leq 3) \\
   0.168 & (3 < t \leq 10.4) \\
   -0.056t & (10.4 < t \leq 13.4) 
\end{cases} \tag{8}
\]

4.3. The simulation of trapezoidal motion model

In order to study trapezoidal model, the time step is continuously lowered to increase the accuracy of simulation. The simulation results of acceleration section are shown in Fig. 8.
Curve a represents the level of molten copper before acceleration. Curve b represents the level at $t=0.5s$. Curve c represents the level at $t=1.165s$. Curve d represents the level at $t=2.445s$. and curve e represents the level after acceleration for 3s. The level reaches 48.5 mm. Considering the grid error, the maximum range is 48-49 mm, the range of the sloshing height is 3-4 mm, which meets the design requirements and production requirements.

Simulation results of the level in uniform speed range are shown in Fig. 9. When the time $t=4.195s$, there are burrs on the boundary, and the maximum height of burrs is 47.5mm. When the time $t=4.455s$, the level reaches the 47.7mm.

4.4. Optimizing the moving model of casting wheel

The trapezoidal motion model is further optimized in order to reduce the height of the sloshing edge and the number of burrs. During the operation of casting wheel, the burr is caused by the sloshing of molten copper caused by the sudden change of acceleration. In order to reduce the frequency of the sloshing, the curve optimization method is used to improve the sudden change of acceleration. The optimized model is S model, as shown in Fig. 10. The motion model formula is as follows:

$$v(t) = \begin{cases} 
0.056t, & 0 < t \leq 2 \\
-0.014t^2 + 0.112t - 0.056, & 2 < t \leq 4 \\
0.168, & 4 < t \leq 10 \\
-0.014t^2 + 0.28t - 1.232, & 10 < t \leq 12 \\
-0.056t + 0.784, & 12 < t \leq 13 \\
0.014t^2 - 0.42t + 3.15, & 13 < t \leq 15 
\end{cases}$$

(9)

4.5. Verification of simulation results

The simulation results of the first five seconds of the S-type motion model are shown in Fig.11. The sloshing state of molten copper in curves a, b and c at $t=2s$, 3s and 4s. Under the action of deceleration, the sloshing slows down. The sloshing condition of curve d and curve d at $t=4.48s$ and 5S respectively. The maximum height of the level is 46.4 mm, which is 1.3 mm lower than that of trapezoidal model, and the number of burrs is greatly reduced.

5. Verification and analysis of experimental results

T-type and S-type motion models are used to drive the rotation of casting wheel in a smelter. Fifty anode produced in each furnace were randomly sampled from five furnace to measure the height of sloshing edge and the number of burrs. As shown in Fig. 12, the proportion of anode with less than 40 burrs in S-type motion model increased significantly, and the proportion of anode with more than 40 burrs decreased from 70.2% to 15.6%.

Fig. 13, S refers to the serial number of the anode, and H refers to the height of the sloshing edge. The curve A above represents the height of sloshing edge of the anode produced under the trapezoidal motion model. The average height is 4.8mm. The maximum sloshing height of the anode is 5.8 mm. The curve
B represents the height of sloshing edge of the anode manufactured under the optimized S-type motion model. The average height is 3.6 mm. Maximum height of the sloshing edge is 4.2 mm. Compared with T-type model, the average height of sloshing edge decreases 1.2 mm, and the number of burrs decreases significantly.

6. Conclusion
When the acceleration is 0.056 m/s^2, the height of molten copper sloshing is 4 mm. The correctness is verified by FLUENT simulation. The motion model of casting wheel was analyzed and optimized. The sloshing caused by different motion models was compared by FLUENT simulation. The optimal motion model was S-type motion model. The experimental show that the average height of S-type model is 1.2 mm lower than that of T-type model, and the proportion of anode with more than 40 burrs decreases from 70.2% to 15.6%.

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