Numerical simulation of convection and inclusion distribution during solidification in a heavy steel ingot

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Abstract. Inclusions content in the steel ingot is an important index for homogeneity, and it becomes more serious for heavy steel ingots which are used for major equipment. However, knowledge about the formation of inclusion in steel ingot is limited, and modeling of inclusion distribution is still challenging, so it is of great significance to research the behavior of inclusion. In this paper, fluid flow during solidification is numerically simulated based on the equilibrium equations of mass, momentum and energy, and then inclusion distribution is modeled according to the Lagrangian Stokes trajectory method. The results show that the inclusion distribution in the steel ingot is influenced by the flow pattern which is affected by the solidification pattern. Therefore, inclusion distribution could be controlled by the solidification front with the optimization of heat transfer condition such as the hot top design of steel ingot for the high quality steel production.

1. Introduction
Ingot casting is still commonly used for high alloying steel grades, e.g. tool steel. Non-metallic inclusion is a very serious defect because it may lead to problems that require expensive casting repairs or rejection. The mechanical properties of steel are controlled to a large degree by the volume fraction of inclusion, which acts as stress raisers. Similar pronounced property degradation caused by inclusion is observed in tests that reflect slow, rapid, or cyclic strain rates, such as creep, impact and fatigue testing [1]. Sometimes, inclusion causes voids which will induce cracks if larger than a critical value [2]. Large exogenous inclusion, which originates mainly from reoxidation of the molten steel, slag entrapment and lining erosion, also cause inferior surface appearance, poor polishability, reduced resistance to corrosion, and in severe cases, slag lines and laminations [3]. Larger inclusion has a more negative effect on the fatigue life than smaller ones [4]. So with the increasing demands on steel cleanliness, the study of inclusion formation and removal in the casting process has drawn more and more attention of the researchers and engineers [5-8]. Zhang and Thomas [9] presented methods to measure and detect inclusion in steel, and the causes of exogenous inclusion, the transport as well as entrapment of inclusion during fluid flow have been studied in detail. Ragnarsson et al. [10] have investigated the impact of flow pattern on inclusion removal in ingot during mold bottom filling with experimental and numerical modeling. It is well known that many negative effects are generated during solidification. However, further understanding about the distribution and removal of inclusion during the solidification after filling are comparatively limited.
The present work attempts to depict the effects of fluid flow on the movement of inclusion during the solidification of ingot by using the computational fluid dynamics method.

2. Model formulation

2.1. Governing Equations

The investigated ingot weighs 36 t with an average diameter of about 1.4 m and height of about 3 m. Figure 1 schematically shows the ingot system with sliced meshes. The inclusion’s trajectory coupled with heat transfer and fluid flow during whole solidification process after top filling is modeled with assumptions: (1) solidification starts after mold filling with an initial uniform temperature; (2) inclusions are uniformly distributed in the molten melt; and (3) convection is driven by thermal buoyancy and the residual fluid flow is not considered after filling.

A two-dimensional axial symmetrical heat transfer and turbulence linked model is applied to describe the unsteady transport phenomena of molten steel with solidification. Mass, momentum and energy conservation equations are as follows (k-ε equations turbulence model is omitted):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \cdot (\vec{\tau}) + \vec{F}_k
\]

\[
\frac{\partial \rho}{\partial t} (\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S
\]

where \( \rho \) is density, \( \vec{v} \) is fluid velocity; \( P \) is static pressure; \( \vec{\tau} \) is stress tensor; \( \vec{F}_k \) is interaction momentum per unit mass; \( H \) is enthalpy, and \( S \) is source term, which is related to thermal expansion coefficient \( \beta \).

During solidification, inclusion distribution is modeled according to the Lagrangian Stokes trajectory method. Force equilibrium equation of inclusions in liquid steel is as follows:
\[ \frac{\partial u_p}{\partial t} = F_D (u - u_p) + \frac{g (\rho_p - \rho)}{\rho_p} + F \]  

(4)

where \( F_D \) is fluid resistance by unit mass of inclusion particles; \( u \) is the time average velocity; \( u_p \) is the speed of inclusion; \( \rho_p \) and \( \rho \) are the density of inclusion particle and liquid steel, respectively; \( g \) is acceleration of gravity; \( F \) is an additional acceleration term. \( F_D (u - u_p) \) is the drag force per unit particle mass and is given by:

\[ F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re}{24} \]  

(5)

where \( \mu \) is the molecular viscosity of the fluid; \( d_p \) is the particle diameter. \( Re \) is the relative Reynolds number, which is defined as:

\[ Re = \frac{\rho d_p |u_p - u|}{\mu} \]  

(6)

And \( C_D \) is the drag coefficient for the smooth spherical particles:

\[ C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \]  

(7)

For the formula (7), \( a_1, a_2, \) and \( a_3 \) are all constants [11]. Table 1 lists parameters used in calculation.

| Table 1. Parameters used in calculation. |
|------------------------------------------|
| Steel (ingot)                          |
| (kg·m\(^{-3}\))                        |
| 7000                                    |
| Mold                                    |
| (kg·m\(^{-3}\))                        |
| 7300                                    |
| Insulation material                     |
| (W·m\(^{-1}\)·K\(^{-1}\))              |
| 41                                      |
| Insulating brick                        |
| (W·m\(^{-1}\)·K\(^{-1}\))              |
| 2900                                    |
| \( \rho \) (kg·m\(^{-3}\))            |
| \( k \) (W·m\(^{-1}\)·K\(^{-1}\))      |
| 785                                     |
| \( Cp \) (J·kg\(^{-1}\)·K\(^{-1}\))    |
| 7.9                                     |
| \( \mu \) (kg·m\(^{-1}\)·s\(^{-1}\))   |
| 0.0056                                  |
| \( \beta \) (1/K)                       |
| 0.0002                                  |
| initial temperature (K)                 |
| 1830                                    |
| 500                                     |
| 1830                                    |
| 1000                                    |

2.2. Solution Procedures

FLUENT14.0 code is employed to solve the set of conservation equations along with initial and boundary conditions. The QUICK scheme [12] is utilized for all the space derivatives, and the pressure-velocity coupling is solved using the PISO algorithm [13]. In order to avoid the well-known problems due to checker-board oscillations, the Rhie-Chow algorithm [12] is applied. An adaptive time-stepping is used, which provides automatic control of the time-step (the maximum time step allowed is \( \Delta t < 6 \times 10^{-3} \) s), and at least 80 iterations are needed within each time-step to satisfy a strict convergence limit (all the scaled variable residuals are smaller than \( 5 \times 10^{-4} \)).

3. Results and discussion

The computational results about temperature field, fluid flow, solid fraction and inclusion distribution at times of 2 min, 26 min, 2 h and 10 h are shown in Figure 2 to Figure 5. Because of heat release, temperature decreases from the mold centerline to the mold outside (Figures 2(a) ~ 5(a)).

At the early solidification stage of time 2 min, liquid steel begins to flow and velocity increases gradually owning to the temperature gradient. It is seen that, solid fraction is very small and circulation forms in front of the solidifying shell. The liquid steel flows downwards along the mold...
side wall and upwards within the central region as indicated in Figure 2. At the same time, inclusion begins to move with liquid.

![Temperature distribution](image1)

![Fluid flow](image2)

![Solid fraction](image3)

![Inclusion distribution](image4)

**Figure 2.** Calculated temperature distribution (a), fluid flow (b), solid fraction (c) and inclusion distribution (d) at the time of 2 min.

At the time of 26 min, the whole liquid steel temperature decreases further, and the solid shell becomes apparent near the mold inside wall. The temperature gradient in front of solid shell becomes large and melt flow is strong. Most of inclusion in the liquid steel flows with melt and some are caught by the solid part as shown in Figure 3. At the same time, the two circumfluences beside the centerline become violent. With the increasing time, the solid shell thickness increases and more and more inclusions are caught by the solid shell.

![Temperature distribution](image5)

![Fluid flow](image6)

![Solid fraction](image7)

![Inclusion distribution](image8)

**Figure 3.** Calculated temperature distribution (a), fluid flow (b), solid fraction (c) and inclusion distribution (d) at the time of 26 min.

At the time of 3 h, temperature gradient in front of solid shell becomes small because more latent heat is released. The solidification rate decreases with the increasing solidifying shell, and the melt
flow thereby becomes gradually weak as shown in Figure 4. Therefore, inclusions in the liquid pool have enough time to float up to the top surface of melt instead of being captured by freezing steel.

Figure 4. Calculated temperature distribution (a), fluid flow (b), solid fraction (c) and inclusion distribution (d) at the time of 2 h.

At the time of 10 h, the solid shell changes the shape from U-type to V-type and it is more open to the riser. Therefore, fluid flows directly upwards, and inclusions are concentrated in the riser or the flux at the ingot top surface as indicated in Figure 5. It is estimated that the fluid flow and inclusion entrapment are related to the shape of solid shell according to Figure 4 and Figure 5.

Figure 5. Calculated temperature distribution (a), fluid flow (b), solid fraction (c) and inclusion distribution (d) at the time of 10 h.

In order to research the effect of solid shell shape on the inclusion removal rate, two cooling conditions are proposed with different riser insulation materials. Case 1 is traditional riser with heat
transfer coefficient of 60 W/(m²·K) and case 2 is improved strengthen insulation riser with heat transfer coefficient of 10 W/(m²·K). Inclusion removal rate is obtained after numerical computation for two cases.

Figure 6 compares the solid fraction of two cases. It is found that the solid shell shape is more like V-type and is more open to the riser at the late stage of solidification for case 1 compared to case 2.

![Figure 6](image)

**Figure 6.** Calculated solid fraction at time of 2 min (a), 26 min (b), 2 h (c) and 10 h (d) with traditional riser (case 1) and improved insulated riser (case 2).

Figure 7 compares the inclusion distribution of two cases. It is found that fewer inclusions are remained in the ingot body and more inclusions are concentrated in the riser or are captured in the flux for case 2 compared to case 1. It should be mentioned that the original inclusions number for the calculation is same for two cases and the inclusions in the flux is not shown in Figure 7, also not in Figure 2 ~ Figure 5.
Figure 7. Calculated inclusion distribution at time of 2 min (a), 26 min (b), 2 h (c) and 10 h (d) with traditional riser (case 1) and improved insulated riser (case 2).

Figure 8. Inclusion removal rate at different cooling conditions.

In order to investigate the effect of cooling conditions on the inclusion distribution in the ingot, the removal rate is applied, which means the percentage of inclusion entrapped in the flux to the initial amount. Figure 8 indicates the inclusion removal rate with solidifying time for two cases. In general,
inclusion removal rate increases especially at the early solidification stage for both cases. For a certain time, inclusion removal rate for case 2 is larger than that for case 1 and the difference between them becomes large with time. Because the heat transfer of riser is weaker for case 2 compared to that for case 1, the fully solidification time (i.e., 27 h) is longer than that of case 1 (i.e., 24 h). Along the ingot centerline, the solidification time at the neck of riser for case 2 is 14 h, while that for case 1 is 15 h. It can be found that the inclusion removal rate at the final solidification stage for case 2 and case 1 is 75% and 55%, respectively. When solidification starts in the riser, the inclusion removal rate for case 2 and case 1 is 70% and 50%, respectively. Therefore, the inclusion removal rate can be increased by optimization of the riser of ingot.

This is preliminary work coupling solidification and inclusion by use of CFD, further details of inclusion’s character should be awaited with a precise model.

4. Conclusions

According to the numerical simulation of solidification, fluid flow and inclusion distribution in steel ingot, conclusions are summarized as following:

1. Inclusion is easy to be entrapped at the early solidification stage because the solidification is quick and the fluid flow is against the solidifying front.
2. Inclusion is easy to be removed at the late solidification stage because the solidification is slow and the fluid in the liquid pool tends to flow upwards into the riser.
3. Inclusion removal rate increases with solidifying time.
4. Inclusion distribution and removal rate are influenced by the shape of solidification front. Inclusion is easy to be removed with V-type solid shell compared to that with U-type. The inclusion distribution can be improved with control of the heat transfer of ingot.

Acknowledgments

This work was financially supported by the National Basic Research Program of China (No. 2011CB012900) and the National Science and Technology Major Project of the Ministry of Science and Technology of China (2012ZX04012011).

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