Effect of Feeding Modes of Molten Steel on the Mould Metallurgical Behavior for Round Bloom Casting

Haibo SUN and Jiaquan ZHANG

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, NO.30 Xueyuan Road, Haidian District, Beijing, 100083 China.

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Three kinds of modes for molten steel delivery have been studied in the paper for better understanding of their mould metallurgical effects during round bloom casting. The melt flow, free surface fluctuation, temperature field and solidification behavior in the mould region have been numerically analyzed upon the respective adoption of conventional straight single SEN, quad-furcated SEN with outlets in radial direction and a new type of quad-furcated SEN with outlets at tangential direction. For the latter, a strong horizontal swirling flow has been observed along with the upper and lower recirculation region in the mould. It is shown that the horizontal swirling flow in the mould can reduce the impingement depth of molten steel remarkably, inhibit the mould level fluctuation, and create an active bulk flow below the meniscus, which can also move the hot spot upward and promote superheat dissipation of the molten steel. Meanwhile, the temperature of molten steel near the free surface can be increased by 2.6 K to 4.4 K as compared with the two other normal nozzles. Moreover, compared with quad-furcated SEN with outlets in radial direction, the jet impingement on shell is much weaker, while the thickness of solidified shell at the cross-section of the mould is more even. Furthermore, the shell thickness at exit of the mould under the new type of SEN can reach approximately 18.6 mm, while that under quad-furcated SEN with outlets at radial direction is about 17.4 mm, which leave much allowance for the speed enhancement of present round bloom castings.

KEY WORDS: numerical simulation; continuous casting; round bloom; swirling flow; submerged entry nozzle; mould.

1. Introduction

In continuous casting, it is well know that the way in which the molten steel fed into the mould has a key effect on strand quality. At present, a submerged entry nozzle (SEN) with normal straight single outlet is widely adopted not only for billet castings but also for bloom castings. The impingement depth of the molten steel under the conventional SEN of single outlet is usually very large, which is not beneficial both to the flotation remove of non-metallic inclusions and the melting of mould powder at meniscus especially for bloom casting with big cross section. In recent years, quad-furcated SEN with outlets in radial direction has become of concern for bloom castings. The impingement depth of the fluid flow of liquid steel can be obviously weakened under the multi-outlets SENs. The local longitudinal shell-thinning regions, however, have been observed to some degree near the impingement zones due to the jet from the outlets. The distribution of solidified shell will be not uniform at the cross-section of the mould which may easily induce the formation of longitudinal depression or crack. Therefore, it is of basic important to create a reasonable and steady bulk flow in bloom mould for big bloom castings, which has received, in the recent years, increasing interests from steel producers in China.

Electromagnetic stirring (EMS), a well established technology as we know, is popularly used for round bloom casting to control the bulk flow pattern in the mould. EMS can generate horizontal swirling flow in the specified region of the mould through using the multi-phase induction coils to yield a rotating magnetic field in the mould. However, EMS has a limitation of controlling the flow pattern in the mould dynamically for predetermined results upon the variation of real-time casting conditions. Another way to control the bulk flow favorably is to modify the modes of steel delivery into mould. Yokoya et al. have devoted to inspecting the swirling flow created by fixing a swirl blade at the upper part of SEN with straight outlet for billet continuous casting. The behavior of the swirling blade, however, is hard to maintain because of the erosion from the high speed molten steel or adhesion of inclusions.

To address the difficulties above and well control the flow in the mould, we designed a quad-furcated SEN with outlets at tangential direction, which was based on the idea to control the melt flow pattern by changing the direction of jets from the outlets of SEN. This is the easiest way to apply swirling flow through a submerged entry nozzle itself for continuous casting without investment of additional facilities. In this paper, the effect of three possible types of SENs on the flow patterns, mould level and solidification behavior...
of molten steel in the mould cavity for round bloom castings has been studied by numerical simulation.

2. Models Description

Figure 1 shows the geometric schematic of three types of SENs for round bloom casting and Table 1 lists the detailed dimensions. A three-dimensional (3D) schematic of the top part of computational domain for the quad-furcated SEN with outlets in radial directions is given in Fig. 2 based on symmetry principle. A full geometrical model was taken for the computational domain of the case under quad-furcated SEN with outlets at tangential direction as shown in Fig. 3(c). The assumptions, governing equations and boundary conditions are specified below for the analysis of both fluid dynamics and heat transfer.

2.1. Assumptions

In order to simulate the physical phenomena in round bloom mould, the following assumptions were made in the formulating of the models:

1) The molten steel flow in the mould is a steady-state, incompressible flow process.
2) The influence of mould oscillation and mould taper is ignored.
3) Flux or slag layer was considered on top of the molten metal free surface only for insulation.
4) The molten steel in mould is regarded as a homogeneous phase medium.

2.2. Governing Equations

2.2.1. Turbulent Model

According to the above assumptions, transport equations for incompressible and unsteady thermal flow are given in Cartesian coordinate as:

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \mathbf{V} \phi) = \nabla \cdot (\Gamma_{\phi} \nabla \phi) + S_\phi \quad \cdots \cdots \ (1)
\]

where the variable \( \phi \) represents mass, velocity, enthalpy, turbulent kinetic energy or turbulent energy dissipation rate. \( \Gamma_\phi \) and \( S_\phi \) are diffusion coefficient and source term for the variable \( \phi \) respectively. They are summarized in Table 2.

2.2.2. Solidification Model

To obtain a precise prediction of the temperature field

![Fig. 1. Schematic of the SENs. (a) A-type SEN. (b) B-type SEN and its section view at outlets. (c) C-type SEN and its section view at outlets.](image)

![Fig. 2. Top part of computational domain.](image)

![Fig. 3. FDM Meshes for 3D flow and heat transfer simulation of continuous casting mould with different types of SEN. (a) A-type SEN. (b) B-type SEN. (c) C-type SEN.](image)

![Table 1. Geometric parameters of various SENs.](image)

| Geometric parameters | SENs          | Normal straight single outlet SEN (type A) | Quad-furcated SEN with outlets in radial direction (type B) | Quad-furcated SEN with outlets at tangential direction (type C) |
|----------------------|--------------|-------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Inner diameter (m)   | 0.05         | 0.05                                      | 0.05                                                        | 0.05                                                        |
| External diameter (m)| 0.1          | 0.1                                       | 0.1                                                         | 0.1                                                         |
| Outlet angle (rad)   | –            | 15                                        | 15                                                          | 15                                                          |
| Outlet height (m)    | –            | 0.04                                      | 0.04                                                        | 0.04                                                        |
| Outlet width (m)     | –            | 0.02                                      | 0.02 (inside)                                               | 0.02 (inside)                                               |

* \( \mu_i = \rho C_{\mu_i} \frac{k^2}{\varepsilon} ; \ G = \mu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_i} ; \ \sigma_i = 1.0, \ \sigma_i = 1.3, \ C_1 = 1.44, \ C_2 = 1.92, \ C_3 = 0.09, \ \Pr_i = 0.9. \)
and solidification, the variable for enthalpy formulation in Table 2 can be derived by splitting the total enthalpy \( H \) into sensible enthalpy \( h \) and latent enthalpy \( \Delta H \).

\[
H = h + \Delta H \quad \text{(2)}
\]
\[
h = h_0 + \int_{p_0}^{p} C_p \, dT \quad \text{(3)}
\]
\[
\Delta H = f L \quad \text{(4)}
\]

Where \( C_p \) is specific heat of molten steel. \( L \) is latent heat of steel solidification. \( f \) is liquid fraction given by:

\[
f_L = 1 - f_s = \begin{cases} 
1 & T \geq T_i \\
\frac{T - T_i}{T_j - T_i} & T_i < T < T_j \\
0 & T \leq T_i
\end{cases} \quad \text{(5)}
\]

2.2.3. Effect of Phase Change on the Conservation Model

The source term of moment in Table 2, \( S_\rho \), which is called Darcy’s source term, is utilized to account for the effect of phase change on the convection and turbulence in the mushy region, which can be considered as porous medium.\(^{10}\) The Darcy’s source term is linearly proportional to the velocity difference between the liquid and solid subscribed small \( s \) and inversely proportional to permeability \( K \). The permeability \( K \) can be given in term of liquid fraction as follows.

\[
K = K_0 \frac{f_L^3 + \xi}{(1 - f_L)^3} \quad \text{(6)}
\]

Where \( K_0 \) is permeability coefficient, \( \xi \) is a very small positive number.

2.3. Calculation Domain and Boundary Conditions

To ensure flow can be fully developed, the length twice over that of real mould has been taken as the length of the computational domain. FDM meshes employed to simulate the 3D flow and heat transfer in the round bloom mould under three different types of SENs are shown in Fig. 3. The fine meshes are applied to the interface region of free surface for better description of the local physical phenomena. The governing equations above is solved by the commercial software package Fluent\(^{3}\), where the PISO algorithm algorithm was chosen for the velocity iterations and the PRESTO for pressure. Moreover, under-relaxation factors were 0.15, 0.7, 0.15, 0.15, 0.15, and 0.8 for moment, pressure, \( K \), \( \varepsilon \), and energy. The criterion for convergence was established when the residuals for all variables above was less than \( 10^{-5} \). Calculations for these models under three different types of SENs took approximately 3 h 20 min, 3 h 10 min and 8 h 40 min respectively by PC with an Intel 3.4 GHz processor.

The geometrical parameters and operating conditions of the caster are summarized in Table 3, where the SEN submergence depth is calculated from the free surface to top boundary of the outlet of SEN. Table 4 lists the thermal physical properties of molten steel of grade CL60 (a kind of railway wheel steel in China) and air, which are supposed to be temperature independent in the computational models.

For the boundary conditions of fluid flow computation, the inlet velocity of the SEN is fixed as an only component along the casting direction (positive \( z \)), which can be determined through casting speed. The components in \( x \) and \( y \) directions at the inlet are taken to be zero. The outlet of the domain strand has been supposed to share the same mass flowrate with that from the inlet of SEN. The turbulent parameters \( k \) and \( \varepsilon \) are described by formula \( k=0.01v^2 \) and \( \varepsilon=2k^{3/2}/D\) respectively, where \( D \) is turbulent scale diameter.

For the boundary conditions of heat transfer computation, it is assumed that the normal gradients of temperature for both the inlet of SEN and outlet of the domain are zero. The adiabatic condition is used at the free surface and the wall of SEN. The heat flux density \( q \) as given in Eq. 7, is adopted for the description of the boundary adjacent to mould wall.

\[
q = 2670 - 330 \sqrt{60 \times \frac{v}{\nu}} \quad \text{(7)}
\]

Table 3. Parameters and the operating conditions.

| Parameter                  | Value          |
|----------------------------|----------------|
| Mould diameter, m          | 0.45           |
| Mould Length, m            | 0.78           |
| Casting speed, m/s         | 0.00833 (0.5 m/min) |
| Inlet temperature, K       | 1783           |
| SEN submergence depth, m   | 0.1            |
| Darcy coefficient, kg/(m³) | 1.016 × 10⁶   |
| Calculation length, m      | 1.56           |

Table 4. Thermal physical properties of molten steel and air.

| Parameter                  | Molten steel | air |
|----------------------------|--------------|-----|
| Density, kg/m³             | 7020         | 1.225 |
| Viscosity, Pa/s            | 0.0062       | 1.789 × 10⁻⁵ |
| Thermal conductivity, J/(mKs) | 31           | 0.0242 |
| Specific heat, J/(kgK)     | 700          | 1.006 |
| Solidus temperature, K     | 1663         | –    |
| Liquidus temperature, K    | 1753         | –    |
| Latent heat, J/kg          | 300 000      | –    |

3. Results and Discussions

3.1. Flow Pattern

The mode of delivery of molten steel into mould has a great influence on the flow pattern in the mould. Figure 4 shows the velocity contour and vector distribution at the symmetric y-z planes (x=0) under the three different types of SENs. The molten steel, supplied by A-type SEN, passes straight down with a high speed and then turns upward with a decayed speed approaching to the mould wall. The center of vortex flow is at about \( Z=0.8 \) m below the meniscus, which means that the stream penetration is quite deep, and the flow jet from outlet of this SEN travels a long distance before flowing upward to the meniscus. Under this situation, the removal possibility of inclusions involved in the molten steel solidification, the variable for enthalpy formulation in Table 2 can be derived by splitting the total enthalpy \( H \) into sensible enthalpy \( h \) and latent enthalpy \( \Delta H \).

\[
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\[
q = 2670 - 330 \sqrt{60 \times \frac{v}{\nu}} \quad \text{(7)}
\]

Where \( z \) is the distance from the meniscus, \( v \) is casting speed.
steel will be reduced, and the molten steel below the meniscus might be stagnant. For B-type SEN, the bulk flow leaving the outlets impinges on the mould wall and are split into two opposite directions. The upper circulation is confined by the meniscus and walls. The lower one is formed by mould wall and the return flow near the center of the mould. The centers of the upper and lower circulation locate at approximately 0.75 m and 0.27 m below the meniscus respectively. Compared with A-type SEN, a remarkable shift upward of the lower circulation center is observed, which will be in favor of inclusions floatation and removal. However, the upper circulation near the meniscus may increase the chance of slag entrapment. For C-type SEN, a strong horizontal swirling flow has been observed along with the upper and lower recirculation zones in the mould. Figure 4(c) has shown velocity distribution on the horizontal planes, positioned at the 0.05 m, 0.125 m, 0.3 m, 0.5 m and 0.65 m below the meniscus. Clearly, we can read from the figure that the horizontal swirling flow has been formed even far away from the exit of the mould. Moreover, as compared with the situation under B-type SEN, the central position of the upper recirculation produced in the mould is increased by 0.02 m below the meniscus, and the location of the lower recirculation is decreased by the same amount, which will be beneficial to the stability of meniscus and the inclusion removal. Furthermore, compared to the Yokoy’s nozzle6) with the ceramic blade that produces the swirling flow in the center pore of the nozzle, the swirling flow is only created at the exit of the outlets under present nozzle as shown in Fig. 4(c). For this reason, the present SEN can reduce the impingement depth of molten steel which is beneficial to the inclusion through floatation.

From the flow patterns described above, it is shown that using the C-type SEN will reduce the impingement depth of molten steel, inhibit the turbulence at the free surface, accelerate the inclusion floatation and produce a strong horizontal swirling flow in the whole mould as compared with the other two types of SENs.
3.2. Mould Level and Flow Condition Below the Meniscus

Figure 5 shows the free surface profiles of the moulds under the three different types of SENs. It is observed that the free surface profiles strongly depend on the flow condition of molten steel below the meniscus. Under A-type SEN, the molten steel level decreases slightly along the radial direction because of the stagnant fluid state below the meniscus. Under the case of type B and C, the molten steel of the free surface has a wave crest near the wall of mould, which should be produced from the ascending flow of the upper recirculation roll. Yet the magnitudes of mould level under the three different types of SENs are all in range from −0.8 mm to 1 mm, which means that a calm mould level is always present under the given SENs during the steady casting process for round bloom shapes.

To get better understanding of flow conditions below the meniscus, Fig. 6 shows the radial and tangential velocity components of molten steel at 0.003 m below the meniscus on the y-z planes (x=0 m) under the three different types of SENs. With A-type SEN, the maximum value of the radial and tangential velocity is about 0.0021 m/s, which means an inactive state of molten steel below the meniscus. With B-type SEN, the maximum radial velocity component of molten steel can reach 0.12 m/s, which may cause the occurrence of the mould flux entrapment. However, the maximum tangential velocity component is only about 0.005 m/s, which means that there should be no valid horizontal swirling flow present in the molten steel below the meniscus. For C-type SEN, the maximum radial velocity component of molten steel is about 0.05 m/s, about half of the counterpart from B-type SEN. Moreover, the variation curve of tangential velocity shows that the horizontal swirling flow has been formed near the SEN wall immediately below the meniscus. Therefore, compared with other two types of SENs, using the type C of SEN can build an active and steady bulk flow below the meniscus in the mould.

3.3. Temperature Field and Solidification

Figure 7 shows the temperature field of steel in mould at the horizontal y-z planes (x=0 m) under the three different types of SENs. It is shown that the temperature distribution is closely related to the flow pattern of molten steel in the mould. Under A-type SEN, the strong jet of molten steel from the SEN carries superheat into the deep part of mould, which will inhibit the nucleation and growth of equiaxed...
crystals. At the free surface, the superheating degree of molten steel is even below zero (around –0.6 K at 0.003 m below the meniscus). For type B and C of SENs, however, the superheating degree of molten steel below the meniscus is around 2 K and 3.8 K respectively due to the upward movement of the hot spots.

To study the superheat dissipation of molten steel in the mould under the three different types of SENs, we list comparatively, in Table 5, the molten steel superheating degree at three central locations in the mould, which are positioned at 0.3 m, 0.5 m and 0.68 m respectively below the meniscus. It is shown that the superheating degree of molten steel is decreased downward along the mould central axis under the three types of SENs. Meanwhile, it is also shown that the molten steel temperature located at 0.3 m and 0.5 m along the mould central axis below meniscus under C-type SEN is lower than that under B-type due to the upward movement of the low circulation zone. Additionally, under A-type SEN, the temperature of molten steel at the exit of mould decrease by 10.6 K as compared with that at the inlet. The decrease of temperature under type B and C SENs, however, can reach 28.7 K and 28.6 K respectively, which indicates that the latter two SENs help the superheat dissipation of molten steel much well.

Figure 8 shows the liquid fraction distributions at the various cross sections of the x-y planes under the three different types of SENs. In this paper, liquid fraction of 0.33 is defined as solidification front. Figure 9 shows the growth of solidification shell thickness at the horizontal y-z planes (x=0 m) along the casting direction for the three different types of SENs. The results show that the solidifying shell increases gradually and uniformly along the casting direction under A-type SEN due to no flow impingement on the shell. The thickness of solidified shell can reach 19.3 mm at the exit of the mould. With the other two types of SENs, local longitudinal shell-thinning regions have been observed to some degree near the impingement zones due to the jet from the outlets, which will lead the uneven solidified shell distribution at the cross-section of the mould. However, compared with B-type SEN, the jet impingement on shell can be weakened and the solidified shell distributes uniformly at the cross-section of the mould owing to horizontal swirling flow generated by C-type SEN. Besides, the thickness of solidified shell at the exit of mould can be increased by 1.2 mm. These results suggest that thinner shell caused by the jet of side outlet could be one of limiting factors for higher speed casting. To improve the strand quality, however, the application of C-type will leave much allowance for the increase of casting speed for round bloom semi-products.

### 4. Conclusions

The effect of the modes of molten steel delivery on flow pattern, temperature field, free surface fluctuation and solidification behavior in the mould of round bloom castings was calculated and compared by 3D FDM models. The conclusions are summarized as follows:

1. Under the quad-furcated SEN with outlets at tagen-

| Location | Nozzle A-type SEN | B-type SEN | C-type SEN |
|----------|-------------------|------------|------------|
| 0.3 m    | 28.2 K            | 14.8 K     | 10.7 K     |
| 0.5 m    | 24.6 K            | 6.9 K      | 4.4 K      |
| 0.68 m   | 19.4 K            | 1.3 K      | 1.4 K      |

Fig. 8. Liquid fraction distributions at the various cross sections of x-y plane for the three different types of SENs. (a) A-type SEN. (b) B-type SEN. (c) C-type SEN.

Fig. 9. Shell thickness distributions at the horizontal y-z plane (x=0 m) along the casting direction for the three different types of SEN.
tial direction, a strong horizontal swirling flow has been produced along with the upper and lower back flows in the mould, which can reduce the impingement depth of the molten steel, inhibit the mould level fluctuation, accelerate the inclusion floatation, move the heat spot upward and increase the steel activity below the meniscus.

(2) Compared with conventional single outlet SEN or quad-furcated SEN with outlets in the radial directions, the temperature of molten steel below the meniscus can be increased by 4.4 K and 2.6 K respectively under the new SEN, which has been proven to be quite beneficial to the superheat dissipation of molten steel.

(3) Compared with the quad-furcated SEN with outlets in radial directions, the local shell thinning due to the impingement of jet flow is depressed obviously under the new SEN we presented.

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