Effect of the soft reduction of secondary cooling zone on the flow field of molten steel in the mold and the secondary cooling zone

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Abstract. In order to analyse the influence of the soft reduction of secondary cooling zone on the flow field of molten steel in the mold and the secondary cooling zone, a three-dimensional model including the submerged entry nozzle, the mold and the secondary cooling zone was established. The influence of the soft reduction of secondary cooling zone on the flow characteristics and the fluctuation of free surface in the mold and the secondary cooling zone is analyzed. The results show that: (1) There are two vortex regions in the mold and the secondary cooling zone, which are above and below the nozzle jet. Compared with the slab thickness of 52 mm, the vortex area above and below the nozzle jet is larger when the slab thickness is 72 mm. (2) The maximum height difference of free surface is 6 mm when the slab thickness is 72 mm, and 4.5 mm when the slab thickness is 52 mm. (3) Compared with the slab thickness of 52 mm, the maximum flow velocity of molten steel on the free surface is higher when the slab thickness is 72 mm.

1. Introduction

The technology of soft reduction of secondary cooling zone has become an important part of the continuous casting and rolling process of thin slab, and has been applied to production. The main functions include: (1) The reasonable matching of thin slab continuous casting and hot rolling in product specifications is solved. (2) The flexibility of the production process of thin slab continuous casting and rolling is increased. (3) The taper of sector section is adjusted online to adapt to the shrinkage of different steel casting under different production conditions, and the quality of the slab is improved.

Many investigations of fluid flow in the steel continuous casting nozzle and mold have been conducted using three-dimensional computational fluid dynamics (CFD) models. The most popular numerical approach is to assume steady state, single-phase flow, using a Reynolds Averaged Navier–Stokes (RANS) method, together with a turbulence model such as k-e, or k-omega SST, which is designed to estimate the average effect of turbulence, based on solving extra transport equations which depend on calibrated empirical parameters. Thomas compared four different methods for evaluating fluid flow velocities in the liquid pool in the mold region of a continuous caster of steel slabs, and the results show that each method has its own merits and disadvantages relative to the others, and can be a useful tool for investigating flow phenomena in processes with molten metal [1]. Shen conducted a full scale water modelling experiment to address the relationship between the instability of fluid flow and level...
fluctuation in the continuous thin slab casting mold with the particle image visualization, and the results show that the internal fluid flow and level fluctuation are unsteady and periodical [2]. Zarea simulated the fluid flow and heat transfer with solidification of a steel in the funnel type mold region of a thin slab steel continuous caster, and the fluid flow results indicate a special flow pattern in the caste for a tetra-furcated nozzle [3]. Calderón-ramos studied three different submerged entry nozzles with the same bore sizes but different ports including rectangular, square, and round shape at immersion depth of 185 mm, the results show that the port shape has great effects over the fluid dynamics of the liquid steel inside the slab mold [4]. Wang optimized the slag entrapment in 150×1270 mm slab continuous casting mold by CFD simulations, and the water modelling results were in good agreement with the numerical simulation results [5, 6].

In this study, the effect of the soft reduction of secondary cooling zone on the flow field of molten steel in mold and secondary cooling zone was investigated by computational fluid dynamics simulation, and the level fluctuation was analysed in detail.

2. Model and boundary conditions

2.1. Physical model
In order to investigate the influence of the soft reduction of secondary cooling zone on the flow field of molten steel in mold and secondary cooling zone, a three-dimensional model including the submerged entry nozzle, the mold and the secondary cooling zone was established. When the soft reduction is not used in the secondary cooling zone, the slab size is 72×1270 mm, and the slab size is 52×1270 mm when the soft reduction is used in the secondary cooling zone, the start and end position of soft reduction is show in Fig. 1.

![Figure 1](image-url)
2.2. **Boundary conditions**

During the simulation process, the effect of solidification and heat transfer on the molten steel flow is considered, and the boundary conditions of molten steel flow are as follows:

1. **Inlet:** Mass flow inlet, and its value is calculated by the casting speed and the slab size. In this study, the casting speed of slab is 4.5 m/min. The slab size is 52×1270 mm when the soft reduction is used in the secondary cooling zone, and the slab size is 72×1270 mm when the soft reduction is not used in the secondary cooling zone. In addition, the inlet temperature of molten steel is 1525 °C.

2. **Symmetry:** The velocity component perpendicular to the symmetry plane and the gradient of each physical along the normal direction of the symmetry plane is zero.

3. **Free surface:** The velocity component perpendicular to the symmetry plane and the gradient of each physical along the normal direction of the symmetry plane is zero.

4. **Wall:** The heat flux of wide surface of mold is 2.9 MW/m², and that of narrow surface of mold is 2.8 MW/m². The distribution of cooling intensity in secondary cooling zone is shown in **Fig. 2** and **Table 1**.

5. **Outlet:** Velocity outlet, its value is casting speed, 4.5 m/min.

**Figure 2.** The schematic of cooling system in the secondary cooling zone.

**Table 1.** The distribution of cooling intensity in the secondary cooling zone.

| Item | Cooling intensity /L·min⁻¹ | Item | Cooling intensity /L·min⁻¹ |
|------|-----------------------------|------|-----------------------------|
| 1.0  | 321                         | 4.2  | 314                         |
| 2.0  | 1659                        | 5.0  | 310                         |
| 3.0  | 972                         | 5.1  | 128                         |
| 3.1  | 414                         | 5.2  | 138                         |
| 3.2  | 175                         | 6.0  | 227                         |
| 4.0  | 912                         | 6.1  | 103                         |
| 4.1  | 397                         | 6.2  | 123                         |

The interaction between slag and molten steel is considered in the simulation process, and the surface tension coefficient between slag and molten steel is set as 1.2 N/m. The physical parameters of molten steel in the simulation process are shown in **Table 2**.
Table 2. The physical parameters of molten steel used in calculation

| Item                                      | Value                      |
|-------------------------------------------|----------------------------|
| Density/\(\text{kg} \cdot \text{m}^{-3}\) | 7020                       |
| Viscosity/\(\text{Pa} \cdot \text{s}\)   | 0.0065                     |
| Thermal conductivity/\(\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}\) | \(\lambda = 133.44 - 0.276T + 4.49e^{-4}T^2 - 4.95e^{-7}T^3 + 2.81e^{-10}T^4 - 5.94e^{-14}T^5\) |
| Capacity/\(\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}\) | \(C_p = 486.1789 + 0.1008T\) |
| Latent heat/\(\text{J} \cdot \text{kg}^{-1}\) | 270000                     |
| Solidus temperature/\(^\circ\text{C}\)   | 1426                       |
| Liquidus temperature/\(^\circ\text{C}\)  | 1490                       |
| Superheat/\(^\circ\text{C}\)              | 35                         |

3. Results and discussion

Figure 3 shows the effect of soft reduction on the velocity vector distribution of molten steel in the wide surface of mold. It can be seen that the flow velocity of molten steel in the vortex area above the nozzle jet is higher obviously when the slab thickness is 72 mm than when the slab thickness is 52 mm, because the flow velocity of molten steel at the inlet is higher when the slab thickness is 72 mm.

![Figure 3](image-url)

**Figure 3.** Effect of soft reduction on the velocity vector distribution of molten steel in the wide surface of mold.

Figure 4 shows the effect of soft reduction on the stream of molten steel in the wide surface of mold. It can be seen that in the mold and the secondary cooling zone, there are two vortex regions, which are located above and below the nozzle jet. Compared with the slab thickness of 52 mm, the vortex area above and below the nozzle jet is larger when the slab thickness is 72 mm, which is due to the larger mass flow rate at the nozzle inlet when the slab thickness is 72 mm.

![Figure 4](image-url)
Figure 4. Effect of soft reduction on the stream of molten steel in the wide surface of mold.

Figure 5 shows the effect of soft reduction on the fluctuation of free surface in the wide surface of mold. It can be seen that compared with the slab thickness of 52 mm, the fluctuation of free surface is greater when the slab thickness is 72 mm. Moreover, the maximum height difference of free surface can reach 6 mm when the slab thickness is 72 mm, and the maximum height difference of free surface is 4.5 mm when the slab thickness is 52 mm.

Figure 6 shows the effect of soft reduction on the velocity distribution of free surface in the wide surface of mold. It can be seen that the maximum flow velocity of molten steel on the free surface is higher when the slab thickness is 72 mm than when the slab thickness is 52 mm. In addition, the position of the maximum flow velocity of molten steel on the free surface is basically the same when the slab thickness is 72 mm and 52 mm.
Figure 6. Effect of soft reduction on the velocity distribution of free surface in the wide surface of mold.

4. Conclusions
In order to analyse the influence of the soft reduction of secondary cooling zone on the flow field of molten steel in the mold and the secondary cooling zone, a three-dimensional model including the submerged entry nozzle, the mold and the secondary cooling zone was established. The influence of the soft reduction of secondary cooling zone on the flow characteristics and the fluctuation of free surface in the mold and the secondary cooling zone is analyzed. The results show as follow:

1) There are two vortex regions in the mold and the secondary cooling zone, which are above and below the nozzle jet. Compared with the slab thickness of 52 mm, the vortex area above and below the nozzle jet is larger when the slab thickness is 72 mm.

2) The maximum height difference of free surface is 6 mm when the slab thickness is 72 mm, and 4.5 mm when the slab thickness is 52 mm.

3) Compared with the slab thickness of 52 mm, the maximum flow velocity of molten steel on the free surface is higher when the slab thickness is 72 mm.

References
[1] Thomas, B., Yuan, Q., Sivaramakrishnan, S., Shi, T., Vanka, S.P., Assar, M. (2001) Comparison of Four Methods to Evaluate Fluid Velocities in a Continuous Slab Casting Mold. ISIJ International, 41: 1262–1271.
[2] Shen, B.Z., Shen, H.F., Liu, B.C. (2007) Instability of Fluid Flow and Level Fluctuation in Continuous Thin Slab Casting Mould. ISIJ International, 47: 427–432.
[3] Zarea, M.H., Meysami, A.H., Mahmoudi, SH., Hajisafari, M., Mazratabaki, M. (2013) Simulation of Fluid Flow and Solidification in the Funnel Type Crystalizer of Thin Slab Continuous Cast. Oriental Journal of Chemistry, 29: 1325-1337.
[4] Calderon, I., Morales, R.D., Servin-castaneda, R., Perez-alvarado, A., Garcia-hernandez, S., Barreto, J., Arreola-villa, S.A. (2019) Modeling Study of Turbulent Flow in a Continuous Casting Slab Mold Comparing Three Ports SEN Designs. ISIJ International, 59: 76–85.
[5] Wang, Y., Feng, J., Yang, S.F., Li, J.S. (2020) Measurement of Surface Velocity in a 150 mm×1270 mm Slab Continuous-Casting Mold. Metals, 428: 1-9.
[6] Wang, Y., Yang, S.F., Wang, F., Li J.S. (2019) Optimization on Reducing Slag Entrapment in 150×1270 mm Slab Continuous Casting Mold. Materials, 1774: 1-13.