

Numerical Simulation, Physical Modeling and Plant Trial on the Slag Entrapment Behavior in a Four-Strand Tundish

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Numerical Simulation, Physical Modeling and Plant Trial on the Slag Entrapment Behavior in a Four-Strand Tundish

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ABSTRACT

The continuous casting process yields more than 96% crude steel worldwide. Numerical simulation and physical modeling were employed to investigate the slag entrainment behavior during the final casting stage in a four-strand continuous casting tundish. It is demonstrated that the numerical and physical modelling results agree well. Vortex formation in the final casting stage can be divided into four distinct stages: surface rotation, vortex generation, vortex development, and vortex penetration, with significant variations in critical slag entrainment depths observed among different outlets. Increasing casting speed increases slag entrainment risks, while employing vortex inhibitors could reduce the critical slag entrainment height by up to 29%. Through optimized casting termination procedures in a plant trial, the tundish residual depth decreased from 400 to 200 mm; The tail-end billet cleanliness significantly improved to reach a normal billet quality level in the end billet range of 2–3 m. This study provides theoretical and technical support for reducing slag entrainment defects and improving steel cleanliness in continuous casting.

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1 Introduction

With the increasing performance demands on steel in modern industries, the controls over composition, cleanliness and properties of steel production have become stricter. While refining technologies have significantly improved steel quality in recent years, unsteady conditions during continuous casting, such as start-up, ladle changeover, and end of casting, remain critical challenges. Although these unsteady phases account for only 10%–15% of a tundish casting sequence [1,2], they significantly detriment steel cleanliness, which leads to unstable steel quality and billet defects [3,4]. To mitigate quality risks, steel plants usually downgrade or scrap the head and tail sections of billets. However, inconsistent criteria for determining downgrade/scrap lengths often result in misjudgments, further exacerbating product variability and yield costs. Thus, investigation of billet cleanliness during unsteady casting and precision control of head/tail sections is of profound industrial significance.

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The primary stages of steel quality fluctuation during continuous casting include: (1) Start-up stage: During initial pouring, the ladle slide gate is fully opened to rapidly fill the tundish, exposing molten steel to air and causing intense reoxidation [1]. Cleanliness only stabilizes after slag coverage is achieved. Additional contaminants include air aspiration [5,6] and refractory erosion [7]. Prolonged residence time and excessive heat exchange with the tundish also exacerbate temperature fluctuations. (2) End-of-casting stage: As the tundish liquid level drops, vortex formation at the outlet promotes slag entrainment [8]. These vortices may evolve into draining vortices, inducing severe slag/air entrainment and degrading tail slab quality [9–11]. Overly conservative vortex avoidance strategies, however, can increase residual steel volume and waste [8].

Studies demonstrate that optimizing tundish designs and end-of-casting protocols can effectively reduce billet downgrades [9,12–15]. For instance, Li et al. [14] achieved a significant reduction in tail slab scrap rates by implementing a speed-reduction strategy during final casting. The presence and geometry of stoppers also influence critical vortex height; elliptical stopper heads exhibit superior vortex suppression, and their synergy with vortex inhibitors further delays vortex penetration [15].

The current study investigates the multiphase flow of the slag entrapment process in a four-strand tundish. By combining numerical simulation, physical modeling, and plant trials, the slag entrapment process and the critical slag entrapment height under different structural and operational parameters were analyzed. Furthermore, plant trials optimization was conducted based on simulation results, which demonstrates a benefit on the metallurgical performance of the tundish.

2 Experiment and Analysis Methods

2.1 Numerical Model

To simulate the steel-slag behavior during the end of the casting stage and analyze vortex evolution, a numerical model of an industrial tundish was established to determine the critical slag entrainment depth under varying operational conditions. The model of the four-strand tundish is illustrated in Fig. 1a. Due to the symmetric nature of the tundish, the computational efficiency was enhanced by simulating only half of the computational domain.

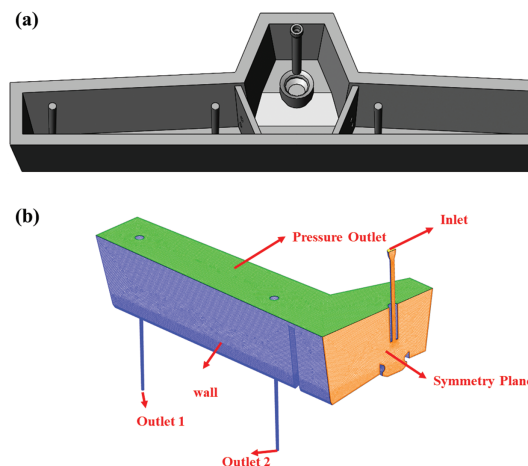


Figure 1: (a) Model of the tundish; (b) Mesh and boundary conditions of the tundish domain

The computational mesh and boundary conditions are shown in Fig. 1b. The whole domain was divided into approximately 800,000 polyhedral-hexahedral cells. Mesh refinement was applied to the

turbulence inhibitor and its adjacent regions to improve the accuracy of the flow pattern and ensure numerical convergence.

In the actual process, tundish slag thickness gradually increases due to the addition of tundish flux during continuous casting. To ensure accuracy, we investigated the actual production process in a steel plant, and it is shown that the tundish slag thickness should be around 50 mm during the steady casting process.

To mitigate slag entrainment during the end of casting stage, a vortex inhibitor was designed and integrated into the tundish outlet (Fig. 2), which aims to disrupt vortex formation and reduce the critical slag entrapment depth, thereby enhancing metallurgical performance (Table 1).

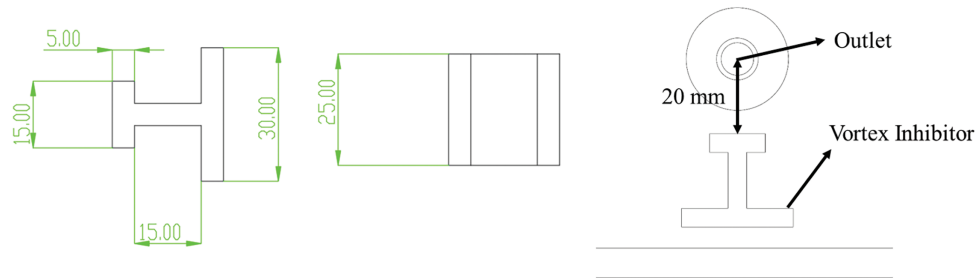


Figure 2: Structure and position of the vortex inhibitor (1:4 scaled-down, mm)

Table 1: Structural and process parameters of the tundish modeling

Parameters	Value
Ladle shroud submerged depth/(mm)	250
Height of steel bath/(mm)	600
Height of air/(mm)	100
Height of slag/(mm)	50
Casting speed/(m/min)	0.26
Density of air/(kg·m ⁻³)	1.225
Viscosity of air/(kg·m ⁻¹ ·s ⁻¹)	1.7894e-5
Density of steel/(kg·m ⁻³)	7020
Viscosity of steel/(kg·m ⁻¹ ·s ⁻¹)	0.006
Density of slag/(kg·m ⁻³)	3500
Viscosity of slag/(kg·m ⁻¹ ·s ⁻¹)	0.13
Density of oil/(kg·m ⁻³)	908.2
Viscosity of oil/(kg·m ⁻¹ ·s ⁻¹)	0.061
Density of water/(kg·m ⁻³)	998.2
Viscosity of water/(kg·m ⁻¹ ·s ⁻¹)	0.001
Tracer diffusion coefficient, m ² ·s ⁻¹	1.994e-9
Ink diffusion coefficient, m ² ·s ⁻¹	2.818e-10
Surface tension coefficient between steel and air/(N·m ⁻¹)	1.6
Surface tension coefficient between steel and slag/(N·m ⁻¹)	1.2

(Continued)

Table 1 (continued)

Parameters	Value
Surface tension coefficient between slag and air/(N·m ⁻¹)	0.58
Surface tension coefficient between oil and water/(N·m ⁻¹)	0.049

2.1.1 Governing Equations

The turbulence within the tundish was modeled using a Reynolds Averaged Navier Stokes (RANS)-based standard k - ε model, which is characterized by the continuity, momentum, and k - ε equations. The Volume of Fluid (VOF) model was employed to track the slag-steel interface, incorporating both continuity and volume fraction equations. These governing equations are presented as follows:

1. Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

2. Momentum Equation:

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \left[\mu_{\text{eff}} (\nabla \cdot \vec{v}) \right] + \rho g \quad (2)$$

where ρ is the density of liquid, kg/m³; $\vec{v}$ is the velocity, m/s; p is pressure, Pa; μ_{eff} is effective viscosity.

3. Standard k - ε Turbulence Model:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho v_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (3)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \rho \frac{\partial (\varepsilon v_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k + C_{2\varepsilon} \frac{\varepsilon^2}{k} \rho \quad (4)$$

in which G_k and μ_t can obtain by:

$$G_k = \mu_t \frac{\partial v_j}{\partial x_j} \left(\frac{\partial v_i}{\partial v_j} + \frac{\partial v_j}{\partial v_i} \right) \quad (5)$$

$$\mu_t = \rho C_u \frac{k^2}{\varepsilon} \quad (6)$$

in which $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ , σ_k , and σ_ε are constants 1.44, 1.92, 0.09, 1.0 and 1.3 [16].

4. VOF Model:

5. One or more phases continuity equation is given by:

$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] = S_{\alpha_q} \quad (7)$$

where ρ_q is the density of the phase q , kg/m^3 ; α_q is the volume fraction of the phase q ; S_{α_q} is the source term. The volume fraction for the primary phase is calculated by:

$$\sum_{q=1}^n \alpha_q = 1 \quad (8)$$

6. The surface tension force was modelled using the Continuum Surface Force (CSF) approach, which effectively captures the interfacial effects within the multiphase flow.

2.1.2 Assumptions and Boundary Conditions

The multiphase behavior at the slag-steel interface was simulated by ANSYS Fluent. To address the computational complexity of the air-steel-slag multiphase flow system, the following reasonable assumptions were implemented:

- (1) Thermal effects were neglected, with isothermal conditions maintained throughout the simulation.
- (2) All fluids were treated as homogeneous and incompressible, with constant physical properties.
- (3) The slag layer above steel is assumed as liquid.

The boundary conditions of the computational domain (Fig. 1b) were specified as follows:

- (1) Inlet: Velocity inlet condition with magnitude determined by casting speed.
- (2) Free surface: Pressure outlet boundary condition is applied which allows the air phase escape from tundish.
- (3) Outlet: Outflow boundary is set for the tundish outlet.
- (4) The non-slip wall boundary condition was established for the wall of the tundish.

A pressure-based solver utilizing the PISO algorithm for pressure-velocity coupling was implemented, first establishing a steady-state flow field before simulating the transient slag entrainment process at the end of casting. The simulation was initialized with a 600 mm steel bath height and 50 mm slag layer thickness, tracking the complete casting process to determine the critical slag entrainment height. All relevant material properties and simulation parameters are detailed in Table 1.

2.2 Physical Model

This study also incorporated physical modeling (to be specific, hydraulic modeling) experiments to investigate the slag entrapment in the tundish and to obtain detailed flow characteristics of the steel-slag interface under different operating conditions. The hydraulic model is a widely accepted approach for studying fluid flow in metallurgical processes. While it does not account for heat and mass transfer processes of molten steel, it effectively captures the fundamental fluid dynamics, which have been verified by numerous studies [17–20]. As illustrated in Fig. 3, a scaled-down physical model of the tundish was constructed based on similarity principles, ensuring both geometric and dynamic similarity.

The geometric similarity between the prototype tundish and the model tundish was maintained through proportional relationships in corresponding geometric dimensions. In our study, the similarity ratio is established at 1:4.

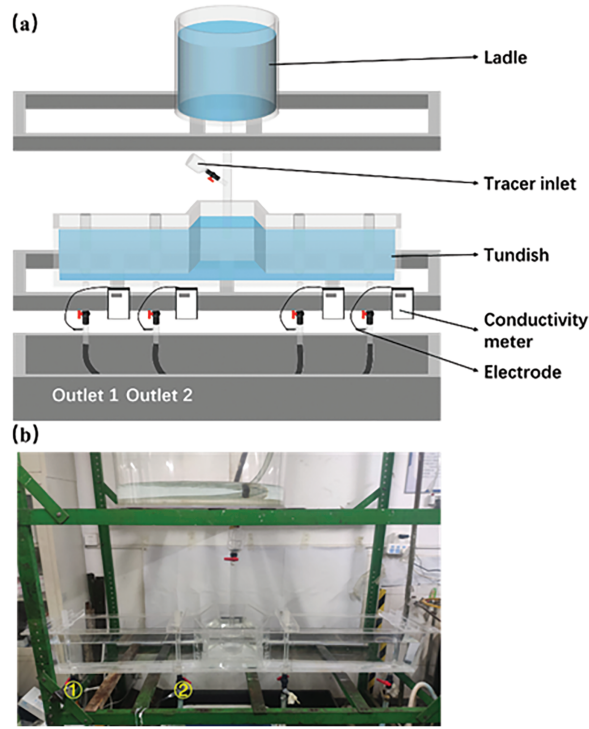


Figure 3: (a) Schematic and (b) Actual tundish model for hydraulic simulation

For dynamic similarity, it is important to match dimensionless numbers the Reynolds number (Re) and the Froude number (Fr) between the molten steel and the simulated liquids in the tundish physical simulation. However, the fluid flow in the tundish is independent of the Reynolds number due to the fluid flow in the second self-modeling zone. Therefore, ensuring equal Froude numbers between the prototype and model could achieve dynamic similarity. Consequently, water was chosen to simulate the molten steel within the tundish as it meets these criteria.

Furthermore, in the tundish, the flow behavior of molten steel and slag is significantly affected by surface tension force, requiring the Weber number (We) to be equivalent between the model and the prototype tundish [21]. As shown in Eq. (9), to achieve this, corn oil was used to simulate the slag [21]. Properties of the oil used are given in Table 1, the We of the model and prototype are 34.49 and 37.92.

$$We = \frac{v_{\text{steel}}^2 \rho_{\text{steel}}}{[\sigma_{\text{steel-slag}} g (\rho_{\text{steel}} - \rho_{\text{slag}})]^{\frac{1}{2}}} = \frac{v_{\text{water}}^2 \rho_{\text{water}}}{[\sigma_{\text{water-oil}} g (\rho_{\text{water}} - \rho_{\text{oil}})]^{\frac{1}{2}}} \quad (9)$$

where ρ is the density of liquid, kg/m^3 ; v is the velocity, m/s ; σ is the surface tension, N/m .

It should be noted that the composition, property and thickness of tundish flux change over time in a casting sequence. The physical and numerical models may not precisely simulate all practical details. The tendency obtained in modelling is generally reliable and can provide effective guidance for continuous casting practices.

During the experiments, the cameras were positioned at each outlet to capture the slag entrainment process. To ensure experimental accuracy, each test condition was repeated 2–3 times.

2.3 Model Validation

To validate the accuracy of the numerical simulations, both the residence time distribution (RTD) characteristics and flow patterns under typical operating conditions (casting speed: 0.26 m/min) were compared with the hydraulic model.

The RTD curve was measured by a stimulus-response method, where a saturated KCl solution was injected as a tracer through the ladle shroud inlet while conductivity meters continuously monitored the tracer concentration at each outlet. Due to the inherent symmetry of the tundish model, only the RTD curves of strands 1 and 2 were recorded. As demonstrated in Fig. 4, a good agreement was observed between the experimentally obtained RTD curves and numerical simulation results. To quantitatively demonstrate the level of agreement, the RMSE and R^2 analysis between numerical and hydraulic models RTD curves was conducted. The RMSE and R^2 values between numerical and hydraulic models RTD curves were 0.085, 0.91 (outlet 1) and 0.10, 0.84 (outlet 2), respectively, confirming the reliability of the computational model in predicting flow characteristics.

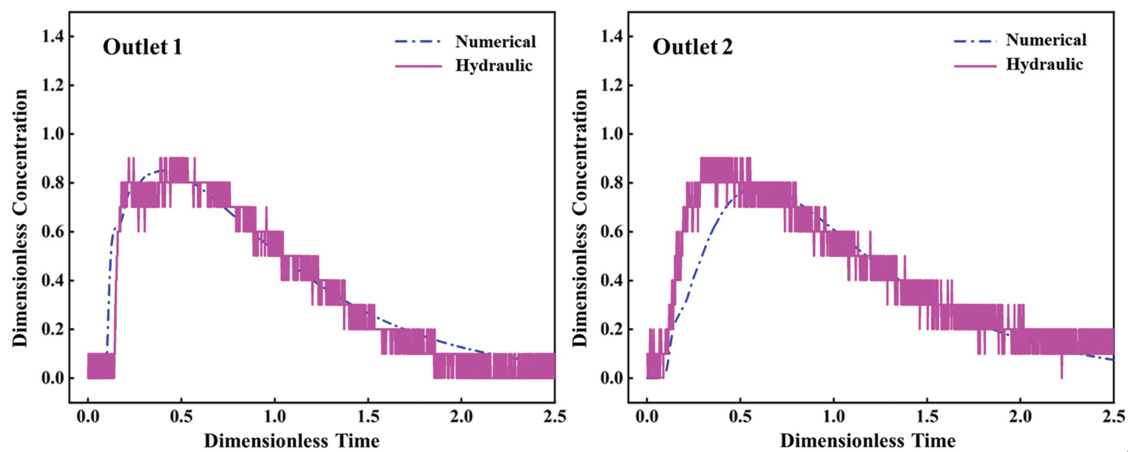


Figure 4: RTD curves comparison between numerical and Hydraulic model

The flow visualization experiment was also conducted by injecting ink through the ladle shroud inlet, which enabled direct observation of the fluid dispersion patterns within the tundish. Fig. 5 presents a typical sequence of ink dispersion profiles, which exhibit significant consistency with corresponding numerical simulations at various time stamps.

3 Results and Discussion

3.1 Multiphase Behavior during Slag Entrapped Process

A comprehensive investigation of the entire vortex formation and evolution process during the final stage of tundish casting was analyzed by numerical simulation. As illustrated in Fig. 6, the entire process can be systematically categorized into four distinct phases: surface rotation, vortex generation, vortex development, and vortex penetration.

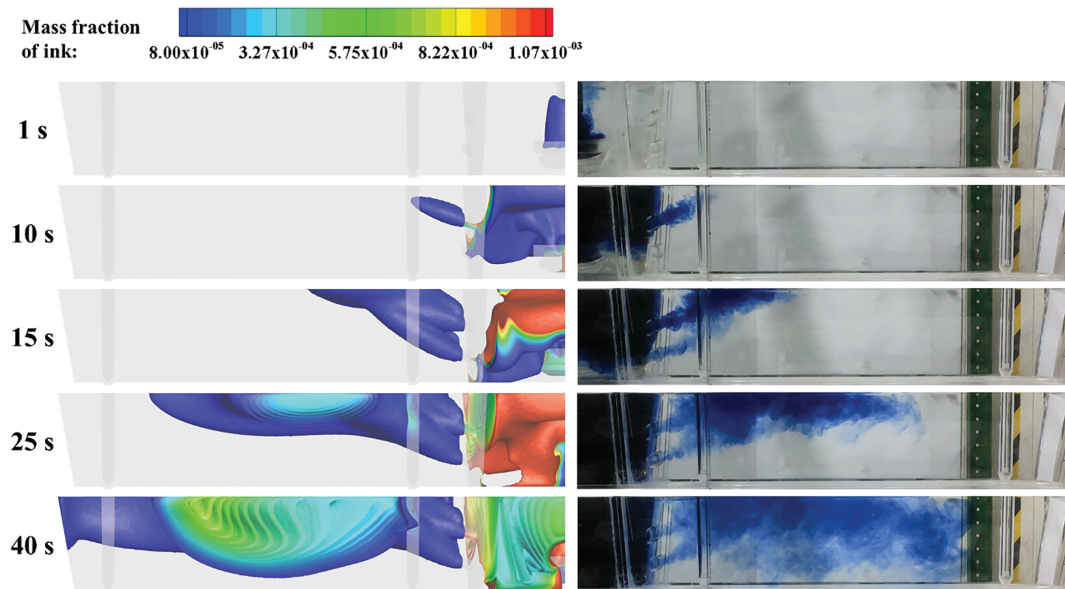


Figure 5: Comparison of ink dispersion profiles between numerical and hydraulic models

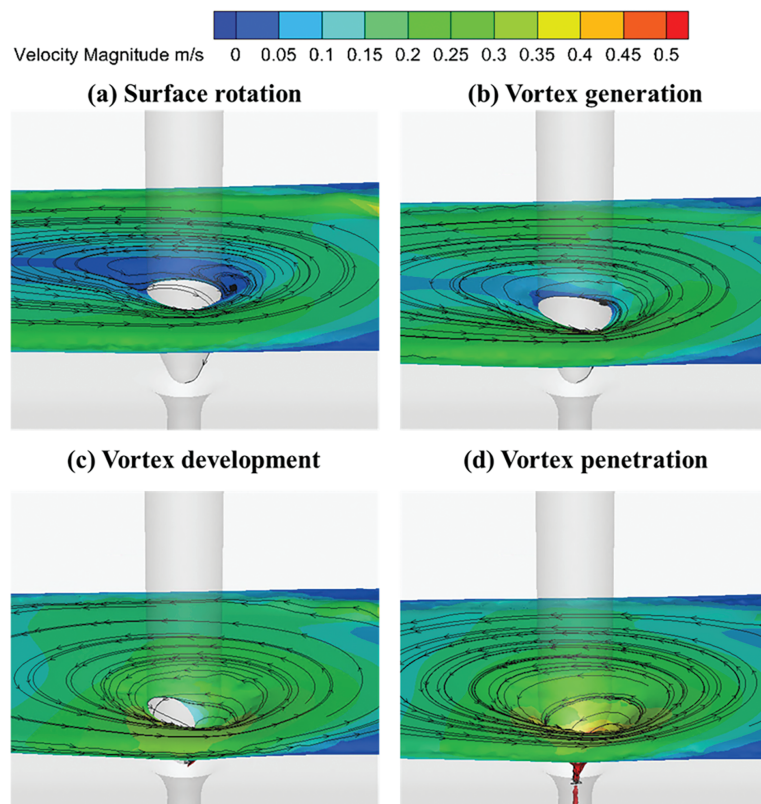


Figure 6: The formation and development process of vortex (a–d)

During the initial stage, as the steel liquid level gradually decreases, molten steel above the outlet begins to exhibit rotational motion, though at this stage the rotation remains relatively slow and the liquid surface maintains its horizontal profile (Fig. 6a). When the liquid level descends to a critical height (Fig. 6b), the rotational motion centered above the outlet intensifies significantly, forming a distinct concave depression on the steel-slag interface. This marks the onset of vortex generation and represents the critical slag entrapment height where the risk of slag capture becomes imminent.

As the liquid level descends continuously, the developing vortex extends downward toward the outlet (Fig. 6c). The vortex turns into a pronounced conical shape with further liquid level reduction. Ultimately, when the liquid surface approaches the bottom of the tundish (Fig. 6d), the vortex fully penetrates through the outlet, forming a continuous channel that allows slag entry into the mold directly. When vortex penetration occurs, slag is directly introduced into the casting product, which is regarded as the most critical contamination.

Moreover, as demonstrated in Fig. 7, the simulation results reveal that vortex generation at different times for each outlet: the vortex at outlet 2 is observed at 172 s, whereas the vortex at outlet 1 is formed at 186 s, which may be due to differences in the vortex generation processes at each outlet. At outlet 2, strong tangential forces are generated in the vicinity of outlet 2 as molten steel flows through the guide hole, which significantly promotes vortex formation. Consequently, in actual production operations, priority should be given to closing outlet 2 during the final casting stage to mitigate quality risks. However, for outlet 1, the driving force from the guide hole is much smaller, resulting in a delayed surface rotation stage compared to outlet 2.

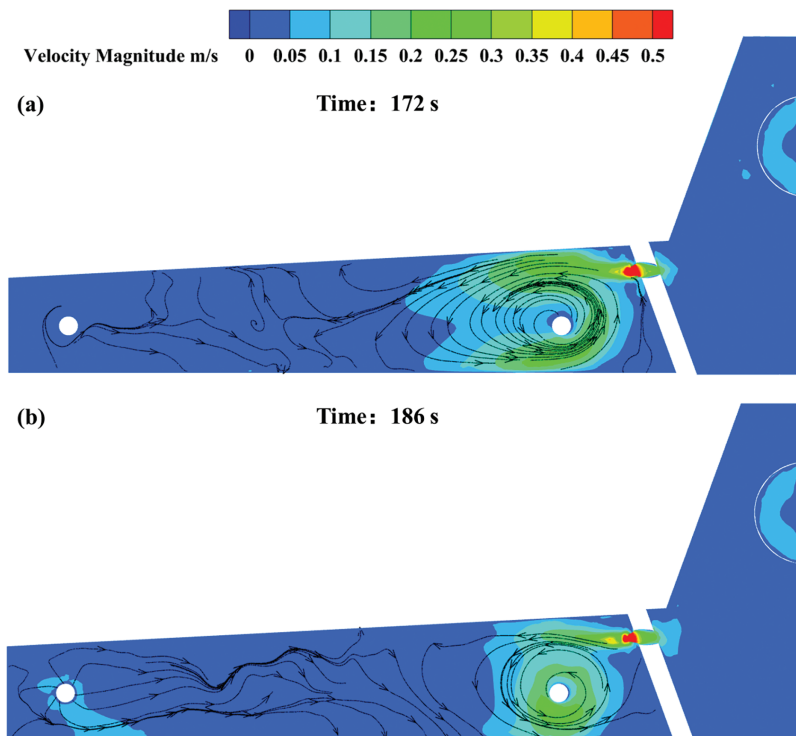


Figure 7: Velocity contour and streamlines at the steel-slag interface during vortex generation (a) Outlet 1; (b) Outlet 2

Fig. 8 presents the density contour on vertical cross-sections at different outlets during vortex formation. In alignment with the proposed mechanism, the outlet 2 is observed to exhibit a higher critical slag entrapment height than the outlet 1, as a consequence of the tangential flow forces being amplified in its vicinity.

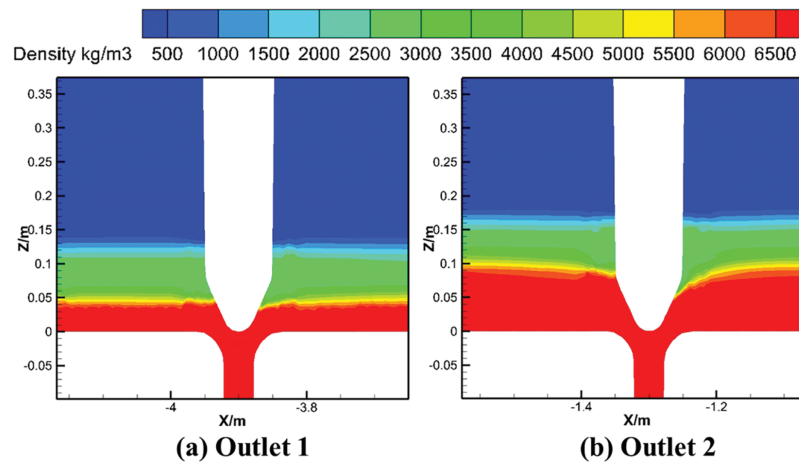


Figure 8: Density contour on vertical cross-sections at the outlet during vortex formation (a,b)

3.2 Critical Slag Entrapment Height under Different Conditions

To systematically evaluate the critical slag entrapment height under various operating conditions, this study employed hydraulic modeling to investigate the effects of different outlet opening degrees (50%, 75%, and 100%) and the presence of vortex inhibitors. The critical slag entrapment height was defined as the height that the slag begins to flow into outlet, with cameras positioned at each outlet; the snapshot can be captured to determine the specific value.

Fig. 9 presents the critical slag entrapment heights for each outlet without vortex inhibitors, revealing two key findings: (1) the critical height increases proportionally with larger opening degrees (e.g., at outlet 2, the height rises from 19 mm at 50% opening to 28 mm at 100% opening), and (2) outlet 2 consistently demonstrates greater probability to slag entrapment than outlet 1, which demonstrates agreement with the above numerical results. These results indicate that higher casting speeds significantly increase the risk of slag entrapping into the mold, and are detrimental to steel quality at the end of a casting sequence.

The implementation of vortex inhibitors shows promisingly improved performance, as shown in Fig. 10. The inhibitors effectively reduce critical slag entrapment heights across the two outlets, with outlet 2 exhibiting a 29% decrease from 28 to 20 mm. This improvement is attributed to the inhibitor's benefit to suppress tangential flow forces and disrupt rotational motion near the outlets, thereby delaying vortex formation. The comparative results demonstrate that while operational parameters (opening degree) influence slag entrapment tendencies, proper flow control devices like vortex inhibitors can significantly mitigate these risks by altering fundamental flow characteristics during the final casting stage.

3.3 Plant Trial

The combined numerical and experimental evidence strongly suggests that operational parameters during the final casting stage significantly affect the critical slag entrapment height. Thus, plant trials

were conducted at a Chinese steel plant where the original termination procedure-maintaining 400 mm tundish residual steel and determining the casting termination procedures based on strand length requirements-was found to contribute to both steel contamination and scrap.

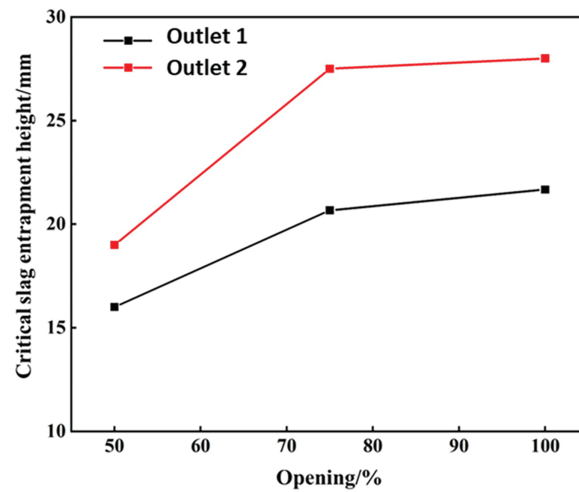


Figure 9: Effect of opening degree on the critical slag entrainment height

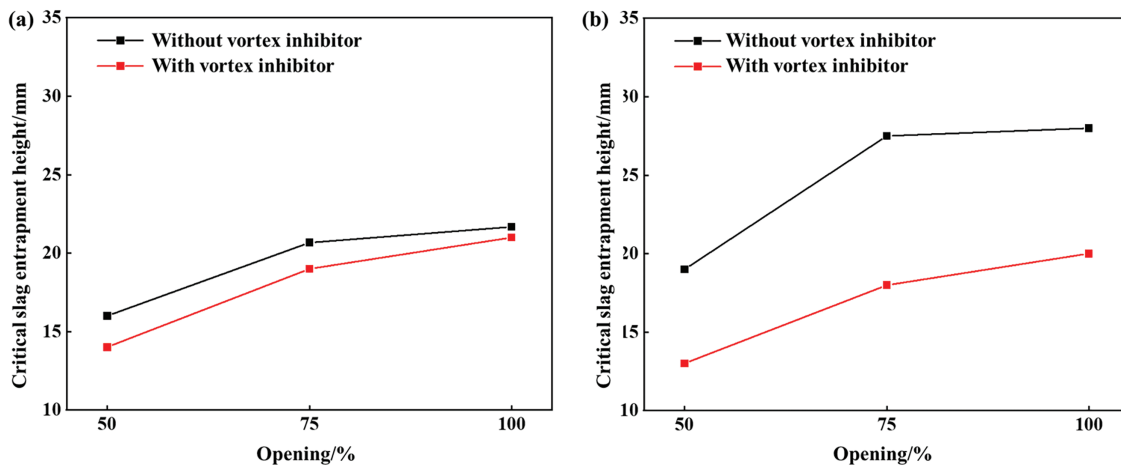


Figure 10: Critical slag entrainment heights at each tundish outlet with/without vortex inhibitors (a) Outlet 1; (b) Outlet 2

During our plant trials, based on observed outlet-dependent differences in critical slag entrainment heights (Outlet 2 > Outlet 1), we implemented a new termination procedure to enhance end billet quality. Initially, we prioritize closing higher-risk outlets (2 and 3) when the tundish level decreases to approximately 350 mm to mitigate slag entrapment risk. Then, outlets 1 and 4 are closed at tundish levels between 150–200 mm. The height of 350 mm corresponds to the upper guide hole of the wall, while the range of 150–200 mm is based on the lower guide hole height.

Implementation results demonstrated significant improvements, including a 1.5 m reduction in scrapped tail length per strand and decreased tundish melt residual to 200 mm, which saves approximately 8 t steel per casting sequence.

To quantitatively assess the impact of process optimization on the quality of the end billet, we conducted cleanliness and macrostructure analysis of the end billet of several steel grades. The total oxygen (T.O) and nitrogen ([N]) in steel samples obtained from this 2–3 m of the 40Cr end billet were analyzed. Table 2 presents the detailed analysis results, which shows that the T.O in the optimized end billet are consistently below 20×10^{-6} , and [N] are below 60×10^{-6} , which meets the quality requirements for the specific steel grades studied.

Table 2: O and [N] of 40Cr steel sample in the end billet

Position	T.O, $\times 10^{-6}$	[N], $\times 10^{-6}$
1 m of end billet	14	51
2 m of end billet	12	49
3 m of end billet	12	50

Macrostructure analysis is a widely-used method for analyzing the macrostructure and defects in billet; we performed the tests on the end billet using acid etching methods and evaluated the macro defects according to the Chinese Standard YB/T 153-2015.

As depicted in Fig. 11, the comparison of the macrostructure before and after optimization demonstrates advantage of new termination procedure in improving macrostructure quality. The grade 1 shrinkage cavity was observed at 2.5 m end billet which was produced by original progress. However, after process optimization, the macrostructure exhibited no severe defects, with only minor center porosity rated below grade 1.

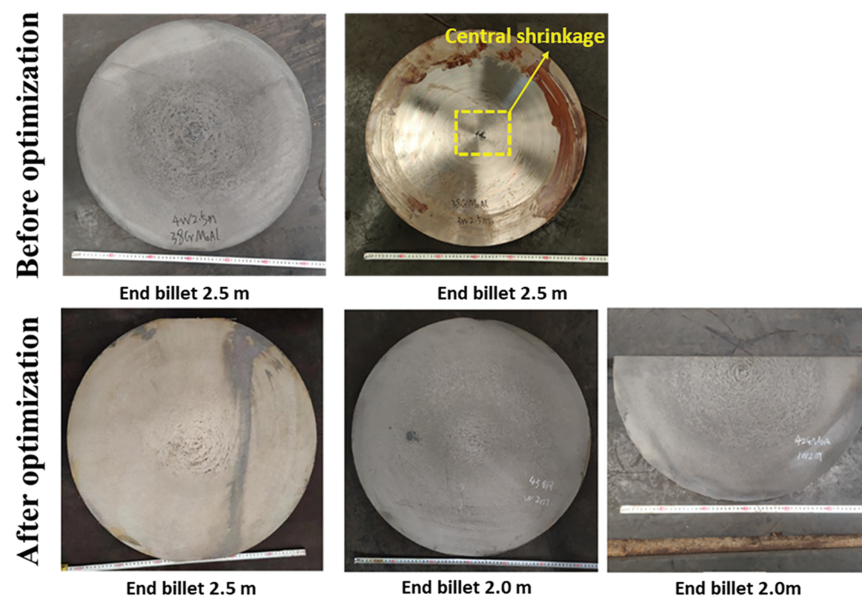


Figure 11: Comparison of macrostructure snapshots for tail billets before and after process optimization

4 Conclusions

Through integrated numerical simulation, physical modeling, and industrial trials, this study investigated slag entrainment behavior during the final casting stage in a typical four-strand tundish.

- (1) Numerical analysis revealed that vortex formation evolves through four distinct phases: surface rotation, vortex generation, vortex development, and full penetration. In addition, the critical slag entrainment depth varies by outlet due to differences in steel flow pattern.
- (2) Operational parameters significantly influence entrainment risks, as higher casting speeds significantly increase critical slag entrainment heights, while vortex inhibitors demonstrate remarkable effectiveness by reducing these heights up to 29%.
- (3) Optimized casting termination procedures successfully decreased tundish melt residuals to 200 mm while simultaneously improving both cleanliness and macrostructure in tail-end sections of various steel grades.

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Availability of Data and Materials: The authors confirm that the data supporting the findings of this study are available within the article.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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