1. Introduction

The concept of horizontal continuous casting had been introduced by Seller and Bessemer in the middle of the 19th century, and has been used to produce billets since the 1970's. Though there are far less horizontal casters in the world than curved or vertical-bending casters, they are widely used in the small-scale steel plants and nonferrous metallurgical plants like the continuous casting of copper, aluminum and their alloys. As shown in Fig. 1, during the horizontal continuous casting process, the molten metal enters the mold through outlets located at side wall and near the bottom of the tundish. The mold of the horizontal caster is a closed system and connected to the tundish body directly. Horizontal casters have both advantages and disadvantages, including:

- Less reoxidation from air at the mold region since there is no free surface;
- No mold flux thus less slag inclusions entrained;
- No natural meniscus at the beginning of shell formation reducing meniscus related problems;
- Rapid cooling from direct liquid metal contact with mold;
- No strand-bending helping avoid internal cracks;
- No mold lubrication possibly increasing the wear of the mold and sticking problems;
- No opportunity to remove inclusions once the metal enters the mold;
- Unsymmetrical solidification due to the gravitational segregation, which may be improved by using electromagnetic stirring.

Today it is well known that the continuous casting tundish has a far more important function as a continuous reactor than originally envisioned and it has evolved into a useful reactor for liquid steel refining. Thus, a modern day steelmaking tundish is designed to provide maximum opportunity for carrying out various metallurgical operations such as inclusion separation, flotation, alloy trimming of steel, calcium doped inclusion modification, superheat control, thermal and particulate homogenization. Turbulence inhibitors, dams, weirs and baffles (sometimes with inclined holes) have been widely used as flow modification devices in a conventional tundish in order to achieve high average residence time, to minimize the volume of severe turbulence, dead zone and short-circuiting, to maximize the volume of laminar flow, to improve inclusion growth by forced coagulation in suitable turbulent zones and floating of inclusions at other zones to be assimilated by cover slag, to avoid “open (red) eye” creating uncovered surface of molten steel contacting the atmosphere and air absorption, and to remove more inclusions from the molten steel.

For the horizontal continuous casting process, due to the direct and fixed connection between the mold and the tundish, the fluid flow conditions in the mold and the casting strand are remarkably different from those of other casting processes. The tundish in the horizontal casting process is of even more importance since it is the final opportunity to remove inclusions. Though numerous studies on fluid flow and inclusion removal in the conventional tundishes

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**Structure Optimization of Horizontal Continuous Casting Tundishes Using Mathematical Modeling and Water Modeling**

Shufeng YANG,1) Lifeng ZHANG,2) Jingshe Li3) and Kent PEASLEE2)

1) Formerly Visiting Scholar at Missouri University of Science and Technology. Now Ph.D Student at School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China.
2) Department of Material Science & Engineering, Missouri University of Science and Technology (Missouri S&T), 223 McNutt Hall, Rolla, MO 65409-0340, USA. E-mail: zhanglife@mst.edu
3) School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China.

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The configuration of a tundish for a two-strand horizontal continuous caster was designed and optimized using water modeling, mathematical modeling and industrial trials. Five designs were studied: the original tundish without flow control devices, the tundish with a turbulence inhibitor at the bottom, the tundish with a deep inlet launder and a tilted dam at the end of the inlet launder, the tundish with two dams with holes, and the tundish with a shallow inlet launder and a high dam in the main chamber. Water modeling was used to measure residence time and investigate dead zone fractions and fluid flow patterns. In the mathematical modeling, fluid flow, heat transfer and inclusion motion and removal were calculated. In industrial trials, the total oxygen, nitrogen pick-up, and inclusions in steel samples taken from the tundish and the billets were analyzed. The results indicated that the tundish with an inlet launder and a dam either at the end of the chamber or in the main chamber was the best design.

KEY WORDS: horizontal continuous casting; tundish; water modeling; mathematical modeling; fluid flow; inclusions.
have been carried out using water modeling and mathematical modeling, to the authors’ knowledge, little studies on the horizontal casting tundish have been reported. Heard studied the flow patterns in a two-strand 20 metric ton horizontal continuous casting tundish using a water model, and reported that the installation of dams parallel to the casting direction helps confine the incoming stream turbulence to a central region and achieve longer minimum residence times. Kam et al. investigated the fluid flow characteristics in a two-strand 5 metric ton horizontal continuous casting tundish under different dam configuration. Yan et al. studied the effects of liquid depth, immersed depth of the shroud nozzle, casting speed and flow control devices on the flow pattern in a water model of horizontal continuous casting of a billet.

In the current study, the redesigning and optimization of flow control devices for a 15 ton tundish for a horizontal caster were performed using water modeling, mathematical simulation and industrial trials. Using water modeling, the Residence Time Distribution (RTD) curves for four different designs of the tundish were measured, and the fluid flow patterns studied. Using mathematical simulation, five designs of the real tundish configuration were carried out and fluid flow, heat transfer and inclusion motion were calculated. During the industrials trials, cleanliness of steel samples from the tundish with different designs and the subsequent billets were analyzed. The five designs of the tundish are shown in Fig. 2, where case 1 is the original two-strand tundish with no flow control installed. Table 1 shows characteristics of the five designs and study methodology employed.

2. Water Modeling

2.1. Experimental Set-up

For the water modeling, geometrical and dynamic similarity were maintained between the model tundish and prototype. In the present work, the ratio of the geometrical dimensions between the model and the prototype was 1 : 1.5 (λ=0.67). Froude similarity criterion was used in order to satisfy the dynamic similarity: \( Fr_m = Fr_p \) thus:

The characteristic length:

\[
L_m / H_1 = L_p / H_1^{0.67}
\] ............................(1)

The characteristic velocity:

\[
U_m / H_1 = U_p / H_1^{0.82}
\] ..........................(2)

The volumetric flow rate:

\[
Q_m / H_1 = Q_p / H_1^{0.36}
\] ..........................(3)

In the industrial caster, the casting speed is 3 m/min and the diameter of the billet is 120 mm. The detailed tundish parameters are shown in Table 2. The experimental set-up is shown in Fig. 3. During each experiment, after reaching the steady-state flow condition, 200 mL of KCl-saturated solution was added into the tundish through the shroud nozzle as tracer, then the electric conductivity at two outlets were detected to achieve RTD curves. From RTD curves, the minimum residence time \( t_{min} \), the peak concentration time \( t_{max} \), and the mean residence time \( t_{av} \), were calculated. According to Sahai and Ahuja, the volume for the dead zone \( V_{dv} \), plug zone \( V_{pv} \), and mixed zone \( V_{mv} \) can be calculated by the following equations.

\[
V_{dv} = \frac{1 - \theta_{dv}}{H_1}..........................(4)
\]

\[
V_{pv} = \theta_{min} (mixed model)..........................(5)
\]

\[
V_{pv} = \frac{(\theta_{min} + \theta_{peak})/2 (modified model)}..........................(6)
\]

\[
V_{mv} = 1 - V_{dv} - V_{dpv}..........................(7)
\]

where dimensionless times are defined as follows:

![Fig. 2. Five designs of the tundish investigated in the current study.](image)

![Fig. 3. Schematic of the water modeling set-up.](image)

| Table 1. Methodology to study the five designs of the horizontal continuous casting tundish. |
|---------------------------------------------|
| Cases | Designs and flow control devices | Water model | Mathematical model | Industrial trial |
|-------|----------------------------------|-------------|--------------------|-----------------|
| Case1 | Original tundish (no flow control devices) | ✓ | ✓ | ✓ |
| Case2 | Using a turbulence inhibitor at the bottom | ✓ | ✓ | ✓ |
| Case3 | A deep inlet launder and a low dam behind the main chamber | ✓ | ✓ | ✓ |
| Case4 | Two dams with holes | ✓ | ✓ | ✓ |
| Case5 | A shallow inlet launder and a high dam in the main chamber | ✓ |

| Table 2. Parameters in the prototype tundish and the model tundish. |
|---------------------------------------------|
| Parameters | Prototype tundish | Model tundish (Case 1) |
|-------------|------------------|-------------------------|
| Liquid      | Molten steel    | Water                   |
| Number of strand | 2 strands       | 2 strands               |
| Flow volume per strand (L/h) | 4071 | 1477 |
| Flow velocity at the inlet (m/s) | 0.64 | 0.52 |
| Bath depth in the tundish (mm) | 1400 | 933 |
| Distance between two strands (mm) | 1200 | 800 |
| Submergence depth of the shroud nozzle (mm) | 350 | 230 |
| Length of upper longitudinal side (mm) | 1780 | 1186 |
| Length of lower longitudinal side (mm) | 1400 | 933 |
| Length of upper width side (mm) | 1180 | 787 |
| Length of lower width side (mm) | 640 | 427 |

![Fig. 3. Schematic of the water modeling set-up.](image)
where \( t_{\text{av}} \) is the mean residence time, \( s \); \( t_s \) is the theoretical residence time, \( s \); \( t_{\text{min}} \) is the minimum residence time, \( s \); \( V \) is the volume of water in the tundish, \( m^3 \); and \( Q \) is the flow rate, \( m^3/s \).

### 2.2. Measured Residence Time and Flow Pattern

The RTD curves and data measured in the water modeling experiment are shown in Fig. 4 and Table 3. The RTD curve in the original tundish had a very narrow peak indicating that the tracer quickly flowed out of the tundish outlet. Most of the tracer exited the tundish within the first 160 s. The residence time of the molten steel in the original tundish was short, with 10 s minimum residence time and 25 s peak concentration time. The original tundish design resulted in short-circuiting flow, thus inclusions may directly enter the mold. The dead zone volume fraction in the original tundish was over 40%.

Black ink was added into the tundish as a tracer to demonstrate fluid flow patterns and time lapse photos were captured by a digital camera. Any zone where the tracer does not disperse into after a long time can be considered as dead zone. In the current study, these ink dispersion time lapse photos were postprocessed, and re-drawn in Fig. 5. As a comparison, the original ink dispersion time lapse photos are shown in Fig. 6. It can be seen that the postprocessed figures more clearly show the dispersion of the ink, thus more clearly reveal the flow pattern in the tundishs.

In the original tundish (Case 1), the jet reached the bottom and then flowed around quickly to the four side walls. Part of the molten steel directly flowed out of the tundish from the outlets—short circuit flow, and the rest flowed upward. It is interesting that the jet is not straight but wavy towards the bottom, which will be discussed later in the paper. The dead zone was large in volume as shown in the last photo of Fig. 5.

For Case 2, a turbulence inhibitor was installed at the bottom of the tundish. Compared to the original tundish, the RTD curve of Case 2 changed more smoothly indicating that the liquid resided longer in the tundish. Table 3 shows that the average residence time for the tundish with the turbulence inhibitor increased about 10% compared to the original tundish. The minimum residence and peak concentration times were significantly larger than those of the original tundish and the dead zone volume decreased to 33% as shown in Table 3 and Fig. 5. After the jet reached the bottom, the flow changed direction upwards, diminishing the short circuiting flow.

For Case 3, an inlet launder was used to introduce the inlet jet, as shown in Fig. 2. The distance between the impingement location of the jet and the tundish outlets was longer. This generated a longer minimum residence time and peak concentration time and diminished the short circuiting flow. The RTD curve in the Case 3 had the lowest peak, indicating the highest mixing condition. The average residence time was larger than in Cases 1 and 2, partially due to the increase in the tundish volume. The dead zone
was around 33%. When the jet reached the bottom of the launder zone, the liquid changed direction and flowed upwards due to the tilted dam (Fig. 5). After reaching a certain height, the liquid began to flow downward. It can be imagined that the installation of the tilted dam is difficult, and there is a risk of eroding the dam due to the high impingement force of the incoming jet.

For Case 4, two dams with three holes parallel to the casting direction were used in the tundish, as shown in Fig. 2. The dams divide the tundish into three sections. The center section is to dampen the turbulence of the incoming stream and prevent short circuiting of flow to the mold. Figure 6 illustrates that the flow pattern is initially confined to the center region and first travels along the floor to the front and back walls before turning upward against the incoming stream. Only a little tracer goes through the holes to the mold because the incoming momentum of the stream is dissipated in this confined central region and the horizontal velocity of flow is nearly zero when it reaches the holes. According to the Fig. 4 and Table 3, the minimum residence time, average residence time, and peak concentration time are shorter than in Case 2 and Case 3, which may be because the dams are too low allowing the liquid to flow over the dam easily. Therefore, a higher dam may be better.

2.3. Asymmetry Flow Phenomenon

The RTD curves detected at the two outlet nozzles of the horizontal tundish are shown in Fig. 7. Case 1 has the best similarity between the two strands and Case 3 has the worst similarity. According to Table 3, the differences of the dead volume percent between two strands in cases 1–4 are 1.99%, 2.59%, 5.52% and 2.07%, respectively. It is reasonable that asymmetric flow phenomenon exists in the two-strand horizontal tundish. Two factors are responsible for this asymmetrical phenomenon: 1) non-fully developed and thus asymmetrical inlet flow and 2) turbulence itself. Turbulent flow is complex, unsteady, chaotic, and with eddies. In turbulent flow, the trajectory of any particular fluid cell is random. For turbulent flow, the flow parameters such as velocity and pressure at each point are described in terms of averages. The instantaneous velocity is obtained by combining the time-averaged velocity with the fluctuation velocity. Asymmetric flow is mainly induced by the fluctuation velocity. When the time-averaged velocity is much greater than the fluctuation velocity, asymmetric flow phenomenon will be less obvious. When the moving path of the tracer from the inlet to outlet is much shorter, the time-averaged velocity of a tracer at the outlet is much larger, and then the asymmetric flow phenomenon is less serious. For Case 1, the moving path of the flow is shortest, so the RTD curves of two strands are nearly identical. For Case 3, the distance from the inlet to the outlet is longer because of the use of a launder and low dam, resulting in the longest moving path for the fluid flow in these four cases. Therefore, the RTD curves of the two strands in Case 3 are noticeably different. Asymmetric fluid condition will exist in a continuous casting tundish.

2.4. Long Wavy Jet

The inlet jet was visualized using ink as tracer, as shown in Fig. 8. It is clear that the inlet jet was not straight but wavy towards the bottom for all the cases, especially for Case 1. The wavy but not straight jet should be related to the turbulent fluctuation feature and the asymmetrical situation of the fluid flow in the tundish. Case 1 had no flow control devices, thus the jet was very wavy downwards, while in the other three cases (Case 2–4) with control flow...
devices, the turbulent flow was confined and a wavy jet situation was not as serious as in Case 1. It should be noticed from Fig. 8 that when the inlet jet flowed downwards, part of the jet flows up and is dispersed along the ladle shroud nozzle bottom, as shown by the arrow in Fig. 8. This phenomenon is hard to explain and further investigation is needed.

2.5. Turbulent Fluctuation

The measured instantaneous electric conductivity ($C$) can be divided into two parts: the mean electric conductivity ($\bar{C}$) and the microscopic fluctuation of the electric conductivity ($C''$), as illustrated in Fig. 9. The mean electric conductivity at time $t$ can be obtained by averaging the value of the instantaneous electric conductivities between $(t-20)$ s and $(t+20)$ s. And then the microscopic fluctuation of the electric conductivity can be calculated by:

$$C'' = C - \bar{C} \quad \text{.................................(12)}$$

Fluctuation for the measured electric conductivity curves at the tundish outlet can then be classified into two types: macroscopic fluctuation and microscopic fluctuation. The macroscopic fluctuation is the fluctuation of the mean electric conductivity ($\bar{C}$) curve, as shown in Fig. 10, which is the sub-peak of the measured mean electric conductivity. The peak implies the occurrence of a sub-recirculation and this recirculation temporarily increases the local concentration of the solute. This kind of sub-recirculation may be in one large recirculation loop due to the macroscopic flow pattern or in small loops controlled by the large turbulent eddies. The macroscopic fluctuations occur several times during 300 s, and the time interval between the macroscopic fluctuations is not fixed.

The measured microscopic fluctuation is shown in Figs. 11 and 12. The feature of the microscopic fluctuation should be controlled by the turbulent fluctuation. The existence of the microscopic fluctuation may be the main reason for the wave style of the long jet discussed in Sec. 2.4. In order to achieve a good plug flow condition, the microscopic fluctuation should be as small as possible. It is noticed that Case 3 has the smallest microscopic fluctuation and all the microscopic fluctuations are under 5 $\mu$S/cm. It is because the inlet launder decreases the turbulence energy in the main chamber. Cases 2 have too large microscopic fluctu-

![Fig. 9. Definition of instantaneous electric conductivity, mean electric conductivity, and fluctuation of electric conductivity.](image)

![Fig. 10. Macroscopic fluctuation of RTD curves measured in the water modeling.](image)

![Fig. 11. Microscopic fluctuation of RTD curves measured in the water modeling.](image)

![Fig. 12. Distribution of microscopic fluctuation of the measured electric conductivity.](image)
modeling will indicate that the design of Case 5 is also good.

### 3. Mathematical Modeling on the Fluid Flow, Heat Transfer and Inclusion Motion in the Molten Steel in the Horizontal Continuous Casting Tundishes

#### 3.1. Mathematical Formulation, Parameters and Boundary Conditions

For the 3-dimensional steady state simulation of the fluid flow and heat transfer of the molten steel in the tundish, the following equations were involved: continuity equation and Reynolds-averaged Navier–Stokes equations for incompressible Newtonian fluids; $k$–$\varepsilon$ equations to simulate the turbulence; and the energy transport equation to calculate the temperature distribution. Inclusions trajectories can be calculated using the Lagrangian particle tracking method, which solves a transport equation for each inclusion as it travels through a previously calculated velocity field. To obtain significant statistics, the trajectories of 12,000 individual inclusions each size were calculated in the current study, using different starting points. The trajectory of each inclusion can then be calculated incrementally by integrating its local velocity, $u_p$ (in m/s), which can be derived from the force balance between the drag force and the gravitational force, as follows:

$$ \frac{du_p}{dt} = \frac{3}{4} \frac{1}{d_p \rho_p} \frac{\rho}{\rho_p} C_D (u_p - u) \frac{u_p}{d_p} (\rho_p - \rho_p) g \frac{d}{d_p} $$

where $\rho$ and $\rho_p$ are density of molten steel and inclusions respectively, kg/m$^3$, $C_D$ is the drag coefficient as a function of inclusion Reynolds number, $u$ is the velocity of the liquid steel, m/s. The effect of the turbulent fluctuation on the motion of inclusions can be modeled crudely from a $k$–$\varepsilon$ flow field by adding a random velocity fluctuation at each step, whose magnitude varies with the local turbulent kinetic energy level. The instantaneous fluid velocity can be represented by

$$ u = \bar{u} + u' = \bar{u} + \xi \frac{2k}{3} $$

where $u$ is the instantaneous fluid velocity, m/s, $\bar{u}$ is the mean fluid phase velocity, m/s and $u'$ is the random velocity fluctuation, m/s. This is the so-called random walk model.

#### 3.2. Distribution of the Fluid Flow Velocity

The calculated velocity field of the molten steel in the tundishes is shown in Fig. 13, and discussed below.

Case 1: In the original tundish, the jet from the inlet impinges the tundish bottom directly with a very large velocity and high turbulent energy. Then the fluid quickly flows along the bottom and is separated into two parts. The first part flows out from outlets directly causing short-circuit flow. Such flow may cause serious erosion at the tundish bottom, which generates large exogenous inclusions. The other fluid, after flowing along the bottom, flows upwards along the back wall. After reaching 1/3 of the tundish height, the flow begins to flow downwards with the incoming stream from inlet jet because the velocity and energy are consumed by the bottom and the walls of the tundish. The flow velocity of the molten steel in the top region of the tundish is very slow, which may generate the dead zone. As shown in Figs. 13(a) and 13(b), two loops are formed at the lower part of the tundish along the side walls. The looping flow is detrimental for the removal of inclusions since inclusions may recirculate there and thus are difficult to be removed. Figure 13(c) indicates an obvious short-circuit flow at the bottom. In summary, the original tundish has the following problems:

- Too large of a velocity at the bottom causing serious erosion of the lining refractory;
- Obvious short-circuit flow;
- Lower loop flow retarding inclusion removal;
- Too low of a velocity at the upper part of the tundish causing a dead zone and a low temperature region.

Case 2: The turbulence inhibitor was used for Case 2. The incoming momentum energy of the jet is well confined inside the turbulence inhibitor. Except for the inhibitor re-
Fig. 13. Distribution of velocity vectors and streamline in the tundishes (Case 1, Case 2, Case 3, Case 5 from upper to lower).

Fig. 14. Distribution of shear stress and temperature on walls of the tundishes.
3.3. Distribution of Shear Stress and Temperature on Walls

The distribution of the shear stress and temperature on the walls and the bottom of each tundish design is shown in Fig. 14. The larger the shear stress and wall temperature, the greater the erosion potential for the lining refractory. The original tundish (Case 1) has significant area with a large shear stress at the bottom and side walls, especially around the outlets. In the industrial steel casting trials, the erosion of the original lining refractory was very serious, as shown in Fig. 15. The shear stress regions in the simulation match well with the erosion in the industrial tundish. For Case 2, the large shear stress is confined inside the turbulence inhibitor. In Case 3, the large shear stress is confined in the launder bottom, which is far from the outlet. The outlet is about 10°C.

3.4. Motion and Removal of Inclusions

Figure 16 shows the inclusion removal fraction to the top surface. All sizes of inclusions can be removed more than 40%. Almost all of the inclusions larger than 150 μm can be removed for Case 3. For Cases 1 and 2, around 5% of the 300 μm inclusions enter the mold and become final defects. Thus, from the point of inclusion removal, the Case 3 tundish is much better than Case 1 or 2. For Case 5, <75 μm inclusions can be removed more than Case 3. However, compared to Case 3, >75 μm inclusions can be less removed in Case 5. The removal fraction is larger than 70%.

4. Industrial Trial Investigation of Inclusions in the Molten Steel

The steel in the industrial trials was 39Mn2V steel with composition of C: 0.38, Si: 0.22, Mn: 1.5, V: 0.12, Al: 0.035, S: 0.02, P: 0.02, Cr: 0.3. Steel samples were taken from the tundish and billets for three continuous cast heats (Case 1, Case 2 and Case 3). The total oxygen (T.O.) and nitrogen of the steel samples were analyzed. Inclusions in the steel were evaluated using an optical microscope, SEM. Inclusions over 50 μm were extracted from the large billet samples (~2 kg each) using the method of Slimes. The measured total oxygen and nitrogen are shown in Table 5.

The removal fraction of the T.O. in the tundish can be calculated by

\[ \eta = \frac{(\text{T.O. at tundish inlet} + \text{oxygen pickup from tundish to billet}) - \text{T.O. in billet}}{(\text{T.O. at tundish inlet} + \text{oxygen pickup from tundish to billet})} \times 100\% \]

\[ \text{......................................... (14)} \]
The oxygen pickup from the air absorption at tundish can be estimated from the nitrogen pickup between the tundish and the billet using the following equation.\(^{12}\)

\[
\Delta [O] = \frac{100 M_O \cdot k_R \left( P_{O_2} - P_{O_2(G-F)} \right)}{\rho RT k_R [N]_E} \cdot \ln \frac{\left( [N]_E + [N]_B \right) \cdot \left( [N]_E - [N]_F \right)}{\left( [N]_E - [N]_B \right) \cdot \left( [N]_E + [N]_T \right)} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 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The combination of the launder and low dam (Case 3) can about 10%, and decrease the dead zone volume to 33%. Short circuit flow, increase the average residence time by small of a velocity at the upper part of the tundish. The ad-

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**Table 7.** Inclusions (>80 μm) in steel samples extracted by the Slime method.

| Heat of sample (kg) | Weight of inclusions (mg) | Inclusions amount |
|---------------------|---------------------------|------------------|
| Case 1-1            | 1.49                      | 10.06            |
| Case 1-2            | 1.33                      | 9.09             |
| Case 1-3            | 1.58                      | 4.43             |
| Case 2-1            | 1.73                      | 16.18            |
| Case 2-2            | 1.80                      | 5.55             |
| Case 2-3            | 1.21                      | 3.99             |
| Case 3-1            | 1.88                      | 4.10             |
| Case 3-2            | 1.82                      | 3.95             |

where \( \Delta [O] = 2.030.2 \times \ln \frac{(403 + [N]_B - [N]_T)}{(403 - [N]_B - (403 + [N]_T))} \) \( ... (16) \)

5. Conclusions

The configuration of the tundish for a two-strand horizontal continuous caster were designed and optimized through water modeling, mathematical modeling and industrial trials. Five designs of the tundish were studied. The following conclusions can be derived:

(1) The original tundish has the following problems:
(1) Too large velocity at the bottom causing serious erosion of the lining refractory, (2) obvious short-circuit flow, (3) lower loop flow retarding inclusion removal, and (4) too small of a velocity at the upper part of the tundish. The addition of a turbulence inhibitor (Case 2) can weaken the short circuit flow, increase the average residence time by about 15%, and decrease the dead zone volume to 33%. The combination of the launder and low dam (Case 3) can generate a longer minimum residence time and peak concentration time and diminish the short circuit flow. The average residence time of Case 3 is far larger than in Cases 1 and 2.

(2) The original tundish (Case 1) has a large area with a large shear stress at the bottom and side walls, especially around the outlets. The location of the large shear stress in the simulation matches well with the erosion in the industrial tundish. For Case 2, the large shear stress is confined inside the turbulence inhibitor. In Case 3, the large shear stress is confined to the launder bottom, which is far from the tundish outlets. The maximum temperature is at the inlet, 1888 K and the minimum temperature is 1876 K for Case 1, 1872 K for Case 2, and 1875 K for Case 3. The temperature difference between the inlet and the outlet is about 10°C.

(3) The simulation results show that over 40% of inclusions of all sizes can be removed and almost all inclusions larger than 150 μm can be removed for Case 3. For Cases 1 and 2, around 5% of the 300 μm inclusions enter the mold and become final defects. Thus, from the point of inclusion removal, the Case 3 tundish is much better than Case 1 or 2.

(4) Though no water modeling and industrial trials are studied for Case 5 (shallow inlet launder and a high dam in the main chamber), the mathematical simulation indicates that this design is at least as good as Case 3, while is easier for the installation of the dam than Case 3.

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**Nomenclature**

\( t_{min} \): The minimum residence time (s)
\( t_{av} \): The mean residence time (s)
\( V_{max} \): The maximum residence time (s)
\( V_{mv} \): Volume percent of mixed zone (%)
\( d_p \): Particle diameter (mm or μm)
\( t \): Time (s)
\( u_p \): Particle velocity at direction (m/s)
\( C_D \): The dimensionless drag coefficient
\( k \): The local level of turbulent kinetic energy (m²/s²)
\( R_e_p \): Particle Reynolds number (\( R_e_p = \rho u_p d_p / \mu \))
\( t_{max} \): The peak concentration time (s)
\( t' \): Theoretical residence time (s)
\( V_{inter} \): Volume percent of dead zone (%)
\( u \): The mean fluid phase velocity (m/s)
\( u' \): Random velocity fluctuation (m/s)
\( \rho \): The density of the molten steel (kg/m³)
\( \rho_i \): Inclusion density (kg/m³)
\( \xi \): The random number
\( \mu \): The viscosity of the molten steel (kg/(m · s))
\( \nu_i \): The velocity components of the fluid flow (m/s)

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