Hydrodynamic and Mathematical Simulations of Flow Field and Temperature Profile in an Asymmetrical T-type Single-strand Continuous Casting Tundish

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To further remove mini-size nonmetallic inclusions and improve surface quality of stainless steel slab at No. 2 Steelmaking Plant of Shanxi Taigang Stainless Steel Company Limited, the flow field and temperature profile of molten stainless steel in an asymmetrical T-type single-strand continuous casting tundish with a capacity of 18–20 tons have been investigated by both hydrodynamic and mathematical simulations. The influences of height for low-wall of turbulence inhibitor, dam height, weir depth, distance between dam and weir, submerged depth of ladle shroud and casting speed on flow field in the tundish have been studied in a 1:3 reduced scale hydrodynamic model. The streamlines, velocity vector fields and temperature profiles are also mathematically simulated.

The hydrodynamic modelling results indicate that height for low-wall of turbulence inhibitor, dam height and weir depth are three important structural parameters on flow field of molten stainless steel in the tundish. The optimization of the three parameters can improve dispersed plug zone and reduce dead zone effectively. Changing casting speed can improve turbulent flow, and thus reduce dead zone of molten stainless steel in the tundish. As a result, five groups of optimized structural parameters of the tundish have been recommended, which can reduce volume fraction of dead zone down to 15–30 % and increase volume fraction of dispersed plug zone to more than 20 %. In addition, it is verified that the optimized groups of structural parameters of the tundish can maintain their advantage at different casting speeds in a narrow range.

The mathematical modelling results suggest that heat losses around the tundish must be considered in order to accurately simulate the streamline, velocity vector field and temperature profile. The calculated temperature drop of molten stainless steel between inlet and outlet of the tundish is about 4.4 K; the maximum temperature drop in the whole tundish is about 10 K. The modification of flow filed by changing structural parameters of the tundish can slightly affect temperature profile of molten stainless steel in the tundish.

KEY WORDS: hydrodynamic modelling; mathematical simulation; asymmetrical T-type single-strand continuous casting tundish; velocity vector field; temperature profile; range analysis; orthogonal tests.

1. Introduction

It is well known that proper structure of tundish is important for distributing molten steel with stable pressure and constant flow rate, keeping uniform both temperature and chemical composition of molten steel, increasing floatation capacity of dispersed plug zone to more than 20%. In addition, it is verified that the optimized groups of structural parameters of the tundish can maintain their advantage at different casting speeds in a narrow range.

The tremendous related studies indicate that the method of hydrodynamic modelling, which is based on computational fluid dynamics (CFD) by using various sophisticated softwares, is a useful method to investigate flow field and temperature profile of molten steel in various metallurgical reactors, such as tundish. To further improve surface quality and reduce mini-size nonmetallic inclusions content beneath slab surface of stainless steel slab at No. 2 Steelmaking Plant of Shanxi Taigang Stainless Steel Company Limited, both hydrodynamic and mathematical simulations have been carried out for an asymmetrical T-type single-strand continuous casting tundish with a capacity of 18–20 tons molten stainless steel in this study. In the hydrodynamic modelling, the influences of five structural parameters, i.e., height for low-wall of turbulence inhibitor, dam height, weir depth, distance between dam and weir, and submerged depth of ladle shroud (i.e., long nozzle of ladle) on flow field of molten stainless steel in the asymmetrical T-type single-

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strand continuous casting tundish have been investigated by analyzing residence time distribution (RTD) curves measured via orthogonal tests. In the mathematical simulation, the streamlines and velocity vector fields of molten stainless steel in the tundish have been simulated under isothermal and nonisothermal conditions, while the temperature profiles under nonisothermal conditions have also been calculated. The optimal structural parameters of the tundish are recommended according to results of hydrodynamic and mathematical simulations to fulfill the aim of increasing floatation ratio of mini-size nonmetallic inclusions in the tundish as well as improving surface quality of stainless steel slab.

2. Experiments of Hydrodynamic Modelling

2.1. Design of Hydrodynamic Model

It is well-known that similarity of flow field between two models of different scales is decided by Reynolds number $Re$, Froude number $Fr$, Weber number $We$ and so on, according to similarity principles.\(^1\) Considering the prototype size of the studied asymmetrical T-type single-strand continuous casting tundish (shown in Fig. 1) and limitation in laboratory-scale experiment, a 1 : 3 reduced scale plexiglass hydrodynamic model was applied in this study.

The $Re$ of molten stainless steel in the prototype tundish varies in a range of $6.22 \times 10^4$–$10.39 \times 10^4$ at different continuous casting speeds from 0.8 to 1.1 m/min with the corresponding $Re$ of water at ambient temperature as $1.04 \times 10^5$–$1.43 \times 10^5$. It has known\(^1\) that $Re$ number of both the prototype tundish and the model is in the range of $1 \times 10^4$–$1 \times 10^5$, simultaneously, the distributions of fluid velocity vectors and turbulent kinetic energy of the two systems are automatically similar without meeting the equality of $Re$, i.e., the fluid flow is in the second automatic simulation region. Therefore, the geometrical and operation parameters in the two systems can be decided by only keeping $Fr$ equal between the model and prototype,\(^17\) i.e.,

\[
Fr_m = Fr_p \quad \text{..................................(1)}
\]

where $m$ means hydrodynamic model, $p$ means the prototype tundish.

The Froude number is defined as

\[
Fr = \frac{u^2}{gL} \quad \text{..................................(2)}
\]

thus, the main geometrical and operation parameters between model and prototype can be formulated with scale factor $\lambda$ as follows

\[
L_m/L_p = \lambda, \quad u_m/u_p = \lambda^{0.5}, \quad Q_m/Q_p = \lambda^2, \quad t_m/t_p = \lambda^{0.5} \quad \text{..................................(3)}
\]

2.2. Method and Criteria of Hydrodynamic Modelling

The experimental setup of hydrodynamic modelling is schematically illustrated in Fig. 2 with a reduced scale factor as 1 : 3. The stimulation-response method,\(^1\) in which a stimulus signal is added at the inlet and the output signal, i.e., response, is measured at the outlet for a non-ideal reactor as a black box, was applied to investigate flow filed of water in the hydrodynamic model, while the ambient temperature water was used to simulate molten stainless steel.

When water levels in both ladle and tundish in the hydrodynamic system were controlled stable simultaneously for more than 20 min, the saturated NaCl solution of 100 mL was injected as a pulse tracer at a side port mounted at the upper position of submerged ladle shroud, meanwhile, the conductivity of water at the submerged entry nozzle (SEN) of the tundish was on-line measured by a conductivity meter with time interval as 1 s. All the conductivity data were collected by a data acquisition system. Thus, the residence time distribution (RTD) curves of water can be obtained. The total time of data collection was chosen two times as long as theoretical average residence time $\tau$, suggested by Mazumdar et al.\(^18\) as follows

\[
\tau = V/Q_m \quad \text{..................................(4)}
\]

The average residence time $t_a$ can be calculated from the measured RTD curves as follows

\[
t_a = \int_0^\tau tC_{\tau}dt \approx \sum C_{\tau} \Delta t \quad \text{..................................(5)}
\]

According to the modified mixing model of flow,\(^5,18\) fluid flow in a tundish can be divided into three zones as dispersed plug zone, well-mixed zone and dead zone. The volume fraction of three zones in a tundish can be calculated by

\[
V_p = (\theta_{\text{mini}} + \theta_{\text{peak}})/2, \quad V_m = 1 - \theta_p, \quad V_a = 1 - V_p - V_m \quad \text{..................................(6)}
\]

The dimensionless time $\theta_{\text{mini}}$, $\theta_{\text{peak}}$ and $\theta_p$ are given by

\[
\theta_{\text{mini}} = t_{\text{mini}}/\tau, \quad \theta_{\text{peak}} = t_{\text{peak}}/\tau, \quad \theta_p = t_a/\tau \quad \text{..................................(7)}
\]

It is known that dead zone in a tundish is harmful for floating min-size nonmetallic inclusions and will increase heat losses. Hence, ideal configuration of a tundish should decrease dead zone, improve dispersed plug zone and keep...
2.3. Orthogonal Tests of Hydrodynamic Modelling

To find out the optimal integrated structural parameters of 5 factors, i.e., height for low-wall of turbulence inhibitor, dam height, weir depth, distance between dam and weir, and submerged depth of ladle shroud, 4 levels for each factor are considered in this study, shown in Table 1. The orthogonal tests designed for above-mentioned 5 factors with 4 levels are shown in Table 2 according to L₁₆(₄⁵) orthogonal array.¹⁹) The Case T₀ in Table 2 presents the structural parameters of 1 : 3 reduced scale model derived from the presently applied tundish. As shown in Table 3, the cross section of slab is 1 240 mm × 200 mm or 1 020 mm × 200 mm and casting speed changes from 0.8 to 1.1 m/min, so the corresponding water flow rate is determined in a range of 0.63–1.05 m³/h. In the orthogonal tests, the water flow rate was chosen as 0.96 m³/h, corresponding to 1 240 mm × 200 mm slab section at 1 m/min casting speed.

3. Mathematical Simulation

3.1. Governing Equations

The flow field and temperature profile of molten stainless steel in the tundish can be simulated by a developed mathematical model, including continuity equation, momentum balance equation, i.e., Navier–Stokes equation, the \( k – e \) two-equation model and the energy equation.¹⁴,²⁰,²¹) The continuity equation is given by

\[
\frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad \text{..............................................(8)}
\]

The Navier–Stokes equation is given by

\[
\frac{\partial}{\partial t} \left( \frac{\rho \mathbf{u}}{\rho} \right) + \nabla \cdot (\mathbf{u} \rho \mathbf{u}) = \nabla \cdot \left( 
\frac{\mu}{\rho} \nabla \mathbf{u} \right) + \mathbf{F} + \mathbf{S}
\]

Table 1. Factors and levels of designed orthogonal tests for 1 : 3 hydrodynamic model of the asymmetrical T-type single-strand tundish.

| Level | Dam height (mm) | Weir depth (mm) | Distance between dam and weir (mm) | Low-wall height (mm) | Submerged depth of ladle shroud (mm) |
|-------|----------------|----------------|-----------------------------------|---------------------|-------------------------------------|
| Level 1 | 87             | 253            | 100                               | 50                  | 35                                  |
| Level 2 | 115            | 280            | 135                               | 85                  | 70                                  |
| Level 3 | 145            | 280            | 167                               | 110                 | 100                                 |
| Level 4 | 175            | 305            | 200                               | 140                 | 130                                 |

Table 2. Results of orthogonal tests for 1 : 3 hydrodynamic modelling of the asymmetrical T-type single-strand tundish.

| Structural parameters of tundish | Results from RTD curves |
|----------------------------------|-------------------------|
| Case | Dam height (mm) | Weir depth (mm) | Distance between weir and dam (mm) | Low-wall height (mm) | Submerged depth of ladle shroud (mm) | \( t_{\text{ran}} \) (s) | \( t_{\text{peak}} \) (s) | \( t_a \) (s) | \( V_a \) (°) | \( V_p \) (°) | Prolongation ratio of \( t_{\text{ran}} \) (%) | Order based on \( t_{\text{ran}} \) (%) | Reduction ratio of \( V_a \) (%) | Order based on \( V_a \) (%) | Order based on \( t_{\text{ran}} \) and \( V_a \) (%) |
| T₀ | 87 | 253 | 167 | 83 | 100 | 52.0 | 78.5 | 266.0 | 0.3772 | 0.1533 | 0.00 | 12 | 0.00 | 17 | 29 |
| T₁ | 87 | 253 | 100 | 55 | 35 | 47.5 | 68.5 | 271.2 | 0.3630 | 0.1362 | -8.65 | 17 | 3.78 | 15 | 32 |
| T₂ | 115 | 280 | 133 | 85 | 35 | 52.0 | 79.0 | 277.7 | 0.3476 | 0.1539 | 0.00 | 12 | 7.85 | 14 | 26 |
| T₃ | 145 | 280 | 167 | 110 | 35 | 69.5 | 115.5 | 315.3 | 0.2593 | 0.2173 | 33.65 | 6 | 31.27 | 6 | 12 |
| T₄ | 175 | 305 | 200 | 140 | 35 | 65.0 | 140.5 | 359.9 | 0.1569 | 0.2414 | 25.00 | 7 | 58.42 | 1 | 8 |
| T₅ | 115 | 280 | 200 | 55 | 70 | 52.0 | 85.0 | 270.9 | 0.3637 | 0.1609 | 0.00 | 12 | 3.60 | 16 | 28 |
| T₆ | 87 | 305 | 167 | 83 | 70 | 50.0 | 91.0 | 308.7 | 0.2749 | 0.1656 | -3.85 | 16 | 27.14 | 10 | 26 |
| T₇ | 175 | 253 | 133 | 110 | 70 | 78.0 | 105.0 | 317.8 | 0.2555 | 0.2149 | 50.00 | 1 | 32.79 | 3 | 4 |
| T₈ | 145 | 280 | 100 | 140 | 70 | 72.7 | 111.7 | 316.3 | 0.2570 | 0.2165 | 39.81 | 4 | 31.87 | 5 | 9 |
| T₉ | 145 | 305 | 133 | 55 | 100 | 50.5 | 93.7 | 306.9 | 0.2790 | 0.1719 | -2.88 | 15 | 26.04 | 11 | 26 |
| T₁₀ | 175 | 280 | 100 | 83 | 100 | 62.3 | 93.5 | 293.6 | 0.3103 | 0.1850 | 19.71 | 9 | 17.75 | 13 | 22 |
| T₁₁ | 87 | 280 | 200 | 110 | 100 | 57.5 | 106.0 | 295.2 | 0.3066 | 0.1920 | 10.58 | 11 | 18.73 | 12 | 23 |
| T₁₂ | 115 | 255 | 167 | 140 | 100 | 75.5 | 110.0 | 314.1 | 0.2621 | 0.2179 | 45.19 | 3 | 30.55 | 8 | 11 |
| T₁₃ | 175 | 280 | 167 | 55 | 130 | 70.7 | 104.0 | 310.6 | 0.2704 | 0.2052 | 35.96 | 5 | 28.32 | 9 | 14 |
| T₁₄ | 145 | 253 | 200 | 83 | 130 | 77.5 | 107.5 | 315.1 | 0.2598 | 0.2173 | 49.04 | 2 | 31.13 | 7 | 9 |
| T₁₅ | 115 | 305 | 100 | 110 | 130 | 59.0 | 114.0 | 357.0 | 0.2084 | 0.2052 | 13.46 | 10 | 44.77 | 2 | 12 |
| T₁₆ | 87 | 280 | 133 | 140 | 130 | 62.5 | 120.0 | 317.7 | 0.2556 | 0.2144 | 20.39 | 8 | 32.76 | 4 | 12 |

Note: T₀ represents structural parameters of the presently used tundish.

Table 3. Calculated water flow rate and theoretical resident time of 1 : 3 hydrodynamic model from prototype tundish at different casting speeds for two kinds of slabs.

| Parameter | 1020mm × 200mm | 1240mm × 200mm |
|-----------|----------------|-----------------|
| Casting speed of prototype tundish (m/min) | 0.8 | 1 | 1.21 | 1.34 | 0.66 | 0.82 | 1 | 1.1 |
| Flow rate of molten steel for prototype tundish (m³/h) | 9.792 | 12.24 | 14.88 | 16.368 | 9.792 | 12.24 | 14.88 | 16.368 |
| Water flow rate in hydrodynamic model (m³/h) | 0.63 | 0.78 | 0.96 | 1.05 | 0.63 | 0.78 | 0.96 | 1.05 |
| Theoretical resident time of hydrodynamic model (s) | 646.74 | 517.39 | 425.7 | 386.81 | 646.74 | 517.39 | 425.7 | 386.81 |
\[
\frac{\partial (\rho u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu_\text{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + \rho \beta \Delta T \theta_i
\]

The effective molecular and turbulent thermal conductivity of molten stainless steel \( K_\text{eff} \) defined in Eq. (11) can be calculated by

\[
K_\text{eff} = \frac{K}{\sigma_T} + \frac{\mu_\text{eff}}{\sigma_T} \quad \ldots \quad (14)
\]

The five constants\(^{21}\) appearing in the \( k-\varepsilon \) two-equation model defined in Eq. (10a) and Eq. (10b) and two constants defined in Eq. (14)\(^{21}\) take the values as follows

\[
C_1 = 1.43, \quad C_2 = 1.92, \quad C_\mu = 0.09,
\]

\[
\sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3, \quad \sigma_T = 1.0, \quad \sigma_{\text{eff}, T} = 0.9 \quad \ldots \quad (15)
\]

The following assumptions and boundary conditions are applied in the mathematical simulation of molten stainless steel in the tundish.

1. Molten stainless steel is treated as three-dimension steady incompressible viscous fluid, and the flow in the tundish is turbulence.
2. The surface fluctuation of molten stainless steel in the tundish is turbulence.
3. Solid walls, transversal walls, the bottom and free surface of the tundish are taken as 3.2, 3.8, 1.4 and 15 kW/m\(^2\)\(^\circ\)C respectively.
4. The average vertical velocity of molten stainless steel at the inlet from submerged ladle shroud into the tundish at the outlet of the tundish into SEN is assumed to be uniform through cross sections, meanwhile, the average vertical velocity at the other two Cartesian coordinates are assumed to be zero.

### 3.3. Numerical Solution Procedure

About 500,000 mixed tetrahedral grids for the full scale tundish, i.e., prototype, are generated by GAMBIT software, in which different mesh spacings for different portions of the tundish is applied. The commercial CFD software FLUENT of 6.3 version is used to calculate flow field and temperature profile of molten stainless steel in the tundish. The numerical simulation is carried out on a personal computer with a 2G RAM memory and 3.40 GHz CPU. The converged solutions can be obtained after 200 to 500 iterations in about 60 min. The following three aspects are studied in this mathematical modeling:

1. Streamlines and velocity vector fields of molten steel in the prototype tundish with original structural parameters have been simulated under isothermal condition at 1773 K.
2. Velocity vector fields of molten steel in the tundish with recommended structural parameters from hydrodynamic modelling studies have been simulated under non-isothermal conditions at 1773 K, 1823 K and 1873 K, respectively.
3. Temperature profiles of molten steel with recommended and original structural parameters in the tundish have been calculated at 1773 K, 1823 K and 1873 K, respectively.

### 4. Results and Discussion of Hydrodynamic Modelling

#### 4.1. Results of Orthogonal Tests

The results of measured RTD curves from orthogonal tests in hydrodynamic modelling are summarized in Table 2. The results of orthogonal tests show that volume fraction of dead zone \( V_d \) is about 38\%, and the minimum break-through time \( t_{\text{min}} \) is 52 s in Case T0 with the corresponding \( t_{\text{min}} \) in the prototype about 90 s. According to sum of order based on both prolongation ratio of \( t_{\text{min}} \) and reduction ratio of \( V_d \) as shown in Table 2, the optimal integrated tundish structural parameters can be found in Case T4, Case T7, Case T8, Case T12 and Case T14 as the top 5 cases, in which \( t_{\text{min}} \) can be increased by 25.00\%, 39.39\%, 45.19\% and 49.04\%, while \( V_d \) can be decreased by 58.42\%, 39.39\%, 40.39\% and 31.13\%, respectively, compared with those in Case T0. Obviously, the currently applied tundish with structural parameters shown in Fig. 1 does not behave perfectly for flow field of molten stainless steel.

#### 4.2. RTD Curves of Tundish with Optimal Structural Parameters

The comparison of measured RTD curves in Case T4, Case T7, Case T8, Case T12 and Case T14 with that in Case T0 is shown in Fig. 3, respectively. Obviously, in the above 5 cases, the minimum breakthrough time \( t_{\text{min}} \) can increase by 25.00\%, 39.39\%, 45.19\% and 49.04\%, as described in Sec. 4.1, time of attaining peak conductivity \( t_{\text{peak}} \) can increase by 62.35\%, 23.53\%, 48.24\% and 30.59\% and 28.24\%, while the peak conductivity \( C_{\text{peak}} \) can decrease...
by 42.57%, 29.79%, 30.45%, 28.61% and 27.01%, respectively. In addition, the tails of RTD curves are a little bit shorter in the 5 optimal cases than that in Case T0. Therefore, the currently applied tundish parameters should be modified to optimize flow field of molten stainless steel in the tundish.

### 4.3. Contribution of Structural Parameters of Tundish

The range $R$ analysis is one helpful method to find the key factors and choose the optimal operation and structural parameters in a complex system. As a criterion, the greater range of one factor is, the more important the factor is. Choosing $t_a$, $t_{\min}$, $V_d$ and $V_p$ as four criteria, the range analysis results for all runs of orthogonal tests are summarized in Table 4. It should be emphasized that $V_d$ can be calculated from $t_a$, hence, the range orders of 5 parameters for $V_d$ and $t_a$ as two criteria make no difference. Therefore, the sum of range order of 5 parameters bases on $t_a$, $t_{\min}$ and $V_p$ as three criteria is also listed in Table 4.

#### 4.3.1. Effect Tendency

The effect tendency of 5 structural parameters, i.e., submerged depth of ladle shroud, height for low-wall of turbulence inhibitor, dam height, weir depth, and distance between dam and weir on the above 4 criteria are illustrated in Fig. 4, respectively, based on range analysis results shown in Table 4. It can be observed from Fig. 4 that:

1. Increasing height for low-wall of turbulence inhibitor can lead to increasing $t_a$ from 290 to 327 s, improving $t_{\min}$ from 58.5 to 67.4 s, decreasing $V_d$ from 0.282 to 0.248, and expanding $V_p$ from 0.187 to 0.21.

*Note: Result of range $R$ means the difference between the maximum and the minimum based on a same criteria.*

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**Table 4.** Range ($R$) analysis results of orthogonal tests for 1 : 3 hydrodynamic model of the asymmetrical T-type single-strand tundish.

| Factor                        | $R$ order based on | $t_a$ ($s$) | $t_{\min}$ ($s$) | $V_d$ | $V_p$ |
|-------------------------------|--------------------|-------------|------------------|-------|-------|
| Range analysis on $t_a$       | Level 1 Level 2 Level 3 Level 4 $R$ | Level 1 Level 2 Level 3 Level 4 $R$ | Level 1 Level 2 Level 3 Level 4 $R$ | Level 1 Level 2 Level 3 Level 4 $R$ | Level 1 Level 2 Level 3 Level 4 $R$ |
| Dam height                   | 288.197 299.038 313.415 320.223 22.026 | 3 54.375 59.625 67.55 68.987 14.612 | 3 0.259 0.259 0.264 0.248 0.208 0.151 | 3 0.177 0.184 0.206 0.212 0.233 0.053 | 2 6 |
| Weir depth                   | 304.55 299.945 299.39 327.887 28.497 | 2 69.625 63.225 61.565 56.123 13.5 | 3 0.289 0.289 0.287 0.23 0.067 | 2 0.197 0.192 0.194 0.196 0.065 | 5 10 |
| Distance between dam and weir | 304.523 305.053 312.188 310.028 7.665 | 5 60.362 60.75 64.425 65 6.063 | 5 0.289 0.283 0.267 0.272 0.038 | 5 0.185 0.189 0.201 0.203 0.018 | 4 14 |
| Low-wall height              | 289.895 298.788 316.322 326.769 36.873 | 1 55.175 60.438 66 68.925 13.75 | 2 0.319 0.298 0.257 0.232 0.087 | 1 0.169 0.18 0.207 0.223 0.054 | 1 4 |
| Submerged depth              | 305.788 303.412 302.470 320.103 17.433 | 4 56.500 63.175 61.438 67.425 8.925 | 4 0.282 0.287 0.289 0.248 0.041 | 4 0.187 0.189 0.192 0.21 0.225 | 3 11 |

**Fig. 3.** Comparison of measured RTD curves for the asymmetrical T-type single-strand tundish during hydrodynamic modelling experiments in Case T4, T7, T8, T12 and T14 by choosing Case T0 as reference, respectively.
Certainly, the optimal structural parameters to the prototype tundish should be reasonably chosen and decided because all of them have strong interaction effects.

4.3.2. Range Comparison

The contribution or range of 5 structural parameters on 4 criteria of \( t_{fa} \), \( V_p \), \( V_d \) and \( V_t \) is shown in Fig. 5, respectively. As above-mentioned, \( V_j \) is calculated from \( t_{fa} \), the independent criteria are \( t_{fa} \), \( t_{fa} \), \( V_p \) and \( V_d \). It is indicated that: 1) for the three independent criteria, the parameters in decreasing order of importance are height for low-wall of turbulence inhibitor, then dam height, weir depth, submerged depth of ladle shroud and the last is distance between dam and weir; 2) the range of height for low-wall of turbulence inhibitor for \( t_{fa} \), \( V_p \) and \( V_d \) as criteria is 36.87 s, 0.087 and 0.054, respectively, each of them is greater than range of other four structural parameters for the same criteria. Meanwhile, the range of height for low-wall of turbulence inhibitor for \( t_{fa} \) as criteria is 13.75 s, which is comparable with that of dam height and weir depth, while larger than that of another two parameters. This result is in well agreement with result from Fig. 4 stated in Sec. 4.3.1 that increasing height for low-wall of turbulence inhibitor can change 4 criteria significantly. Hence, it can be induced that a higher low-wall of turbulence inhibitor can abate turbulence extent in pouring zone, expand volume of dispersed plug zone, and consequently extend floating time of mini-size nonmetallic inclusions in the tundish; 3) the ranges of dam height and weir depth for \( t_{fa} \), \( t_{fa} \), \( V_p \) and \( V_d \) as 4 criteria are 22.026 s, 14.612 s, 0.051 and 0.035, and 28.5 s, 13.5 s, 0.067 and 0.005, respectively. They are obviously larger than those of submerged depth of ladle shroud and distance between dam and weir for the same 4 criteria. This implies that properly integrated dam and weir arrangement can play a significant role in changing flow direction, improving flow and removal of mini-size nonmetallic inclusions and expanding of resident time of molten steel in the tundish; 4) The ranges of submerged depth of ladle shroud for \( t_{fa} \), \( t_{fa} \), \( V_p \) and \( V_d \) as 4 criteria is 17.63 s, 8.925 s, 0.041 and 0.023, respectively. Each of them is a little higher than range of distance between dam and weir as 7.665 s, 6.06 s, 0.018 and 0.018, respectively. In other words, submerged depth of ladle shroud and distance between dam and weir make a less contribution to flow field optimization of molten stainless steel in the asymmetrical T-type single-strand tundish than other three structural parameters.

In summary, longer residence time, higher floatation possibility of mini-size nonmetallic inclusions and more reasonable flow field of molten stainless steel in the tundish can be achieved by modifying height for low-wall, dam height and weir depth. Therefore, choosing reasonable integrated structural parameters is more effective than adjusting a single parameter to optimize flow field of molten stainless steel in the tundish.

4.4. Effect of Casting Speed

To assess the effect of casting speed on flow filed of molten stainless steel in the tundish, the hydrodynamic modelling tests were carried out in Case T4, Case T7, Case 12, Case T14 and Case T0 with water flow rate at 0.63, 0.78, 0.96 and 1.05 m\(^3\)/h, while the corresponding casting speed is 0.8, 1.0, 1.2, 1.34 m/min for 1 020 mm ×200 mm slab, and 0.66, 0.82, 1.0, 1.1 m/min for 1 240 mm ×200 mm slab, respectively, as shown in Table 3.

The effect of increasing water flow rate from 0.63 to 1.05 m\(^3\)/h on \( t_{fa} \), \( t_{fa} \), \( V_p \) and \( V_d \) as criteria are illustrated in Fig. 6, respectively, with Case T0 as reference. It is shown from Fig. 6(a) that increasing water flow rate from 0.63 to 1.05 m\(^3\)/h in four optimal cases, i.e., Case T4, Case T7, Case T12 and T14) can not largely affect prolongation ratio of \( t_{fa} \). In addition, the prolongation ratio of \( t_{fa} \) in Case T4 is larger than those in other three cases at the same water flow rate, and the maximum of \( t_{fa} \) can be found at water flow rate as 0.96 m\(^3\)/h.

It can be observed from Fig. 6(b) that the prolongation ratio of \( t_{fa} \) shows a visible decrease tendency with an increasing of water flow rate from 0.63 to 1.05 m\(^3\)/h in four cases, while the prolongation ratio of \( t_{fa} \) reduces from 68.18 to 5.77% in Case T4 as an example. Although a large prolongation ratio of \( t_{fa} \) can be obtained at a low water flow rate, the results of prolongation ratio of \( t_{fa} \) at higher casting speed are more interesting when considering continuous casting production efficiency. From the viewpoint of comprehensively considering \( t_{fa} \) and casting efficiency, the optimal water flow rate should be at 0.96 m\(^3\)/h, i.e., corresponding casting speed at 1.21 m/h for 1 020 mm ×200 mm slab or casting speed at 1.0 m/h for 1 240 mm ×200 mm slab. Generally speaking, the larger prolongation ratio of \( t_{fa} \) can be achieved in Case T7, Case T12 and Case T14 than that in Case T4.

The reduction ratio of \( V_p \) has close relation with turbulence intensity. An increase of reduction ratio of \( V_p \) can be observed in Fig. 6(c) with an increasing of water flow rate from 0.96 to 1.05 m\(^3\)/h with Case T0 as reference. Obviously, the greatest reduction ratio of \( V_p \) is in Case T4...
among the cases. When water flow rate further increases from 0.96 to 1.05 m³/h, no obvious increase of \( V_d \) can be observed in four optimal cases. Therefore, from the viewpoint of reduction of \( V_d \), the optimal water flow rate should be set at 0.96 m³/h with structural parameters given in Case T4.

A modest reduction tendency of increasing ratio of \( V_p \) can be observed from Fig. 6(d) with an increasing of water flow rate from 0.63 to 1.05 m³/h. However, a peak of \( V_p \) can be found at water flow rate as 0.96 m³/h in each four cases, in which the maximum peak is found in Case T4. Comprehensive considering slab production efficiency and increasing ratio of \( V_p \), the optimal water flow rate is once again recommended at 0.96 m³/h with structural parameter adopted in Case T4.

Conclusively, the optimal water flow rate is suggested at 0.96 m³/h, and the optimal structural parameters of the tundish is in Case T4.

5. Results and Discussion of Mathematical Simulation

5.1. Comparison of Measured and Calculated Streamlines in the Tundish

The calculated streamlines of molten steel in Case T0 at 1873 K under isothermal condition at different time are schematically illustrated in Fig. 7(a), respectively, and the photographed streamlines in Case T0 in the hydrodynamic modelling by injecting black ink as color tracer are shown in Fig. 7(b). The streamlines of both molten steel and ambient temperature water in the tundish show that, the low-wall of turbulence inhibitor and sidewall of the tundish lead molten steel to disperse and flow upwards and then come to the main zone via the weir-dam arrangement, while some remaining molten steel will mix with the new molten steel in the turbulence inhibitor zone, and then flow to the main zone of the tundish. The weir-dam combination has the flow guide function for molten steel: a weir can make all molten steel flow horizontally along the tundish bottom, and a dam can lead some molten steel flow to SEN of the tundish directly and some other flow to the upper region in the main zone. As illustrated in Fig. 7, one part of molten steel can flow along the tundish surface after over the dam, then reach the left wall and form a small circulation flow region, and finally discharge from the tundish via SEN, while some molten steel can discharge from the tundish directly via SEN in the main zone.

5.2. Streamlines in the Tundish with and without Low-wall of Turbulence Inhibitor

It has been confirmed from above-mentioned results of the hydrodynamic modelling that low-wall of turbulence inhibitor have an important effect on the flow pattern of molten steel in the tundish. The calculated streamlines of molten steel in the tundish at 1873 K with and without low-wall of turbulence inhibitor are illustrated in Fig. 8, respectively. It can be found by comparing Fig. 8(a) and Fig. 8(b) that low-wall of turbulence inhibitor can obviously reduce the turbulent flow zone in the input zone under submerged

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Most molten steel will flow upwards. Circulation regions can be formed on both sides of the weir. Isothermal condition represented in Fig. 9(b) show that no tundish through the third circulation region, finally to SEN. The velocity fields of molten steel in the main zone can improve absorption of momentum transfer must be coupled with heat transfer in the tundish, otherwise, inaccurate results of velocity fields could be generated. However, the hydrodynamic modeling under isothermal condition is still a greatly effective and low-cost method to quantitatively evaluate effect of various flow-controlling devices in a tundish, although it neglects heat transfer.

5.4. Effect of Structural Parameters on Velocity Fields under Nonisothermal Condition

The velocity vector fields of molten steel in the tundish with studied structural parameters have been simulated at 1773 K, 1823 K and 1873 K under nonisothermal condition for all cases listed in Table 2. As representatives, the velocity vector fields in Case T4, Case T7, Case T8, Case T12 and Case T14 on longitudinal plane of y as 322 mm are illustrated in Fig. 9(b) under isothermal and nonisothermal condition in Case T0.

The velocity vector fields in Case T0 shown in Fig. 9(b), it can be summarized: 1) The calculated velocity vector fields in Case T12 and Case T14 are similar with that in Case T0. No obvious circulation flow can be formed. The height for low-wall of turbulence inhibitor and dam height increase by 170 mm and 85 mm respectively in Case T12 compared with those in Case T0, hence the similar velocity vector fields can be obtained in Case T12 and Case T0. The dam height and distance between dam and weir improve by 175 mm and 100 mm respectively in Case T14 compared with those in Case T0, so the small circulation flow, more or less, can be formed in a small range in the main zone. 2) Both dam height and low-wall height increase, while submerged depth of ladle shroud reduces in Case T4, Case T7 and Case T8 comparing with those in Case T0, hence, stronger turbulent and circulation flow will be formed in input region, region between dam and weir, and in the main region. Thus, less dead zone and well-mixed zone can be formed in Case T4, Case T7 and Case T8, which is benefit for floating of nonmetallic inclusions. It should be emphasized that strong circulation flow must not exceed reasonable limit, otherwise, more top slag will be entrapped into molten steel as well as violent erosion for inner wall by forceful circulation flow. 3) Slight differences of velocity vector fields can be observed in the tundish with various optimal structural parameters at different molten steel temperatures under nonisothermal condition. In addition, changing molten steel...
temperature in a range of 1773 to 1873 K can not bring large change to velocity vector fields of molten steel in the tundish. The mathematical calculation by computer can bring some errors compared with theoretical solving results, however, the same converge criteria have been adopted in all calculations. Therefore, the same system calculation error can not change velocity vector fields as illustrated in Fig. 10 at the same converge criteria. This means the small discrepancy of calculated velocity vector fields at different initial temperatures is not caused by calculated error, but mainly from intrinsic flow characteristics affected by physical properties of molten steel, such as density coupled with temperature profiles in the tundish at three initial temperatures.

5.5. Effect of Structural Parameters on Temperature Profile

Temperature profiles of molten steel in the tundish in all tested cases have been calculated in this study at three temperatures as 1773 K, 1823 K and 1883 K. As representatives, the temperature profiles of molten steel in the tundish on surface and on the longitudinal plane of y as 322 mm and 1053 mm are shown in Fig. 11 in Case T4, Case T7, Case T8, Case T12 and Case T14 at 1773 K, 1823 K and 1873 K, respectively.

In 6 simulated cases at different input molten steel temperatures, the higher the input molten steel temperature is, the greater drop of the surface temperature can be obtained, since molten steel at higher temperature has more heat losses into ambient atmosphere.

According to temperature profiles at a fixed temperature, the 6 cases can be classified into two groups by similarity: group one includes Case T0, Case T12 and Case T14; group two covers Case T4, Case T7 and Case T8. In group one, heat exchange between the newly input molten steel from ladle and remaining molten steel in the tundish will make temperature drop inside the low-wall to some extent. Temperature of molten steel rapidly reduce after flowing over dam-weir arrangement until to main zone because of heat losses from walls of the tundish. The calculated lowest temperature of molten steel near the left inner wall of the tundish is 1863 K, 1813 K and 1763 K, while temperature of molten steel at SEN is 1868.5 K, 1818.5 K and 1768.5 K at three input temperatures as 1873 K, 1823 K and 1873 K, respectively.

In group two, the highest, lowest temperature and temperature at SEN are almost the same as those in group one, though the temperature distributions are different as the structural parameters change. Since low-wall height of the tundish in group two is greater than that in group one, molten steel can mix more uniformly, hence, a more uniform temperature profile can be obtained with wider high-temperature zone in the tundish. No obvious temperature decrease can be observed in zone of turbulence inhibitor. A little decrease of temperature will occur after molten steel flowing over dam-weir arrangement and further in the main zone.

In addition, temperature of molten steel in input zone is greater than that in the main zone in the tundish in all cases. The greatest temperature drop in the tundish is about 10 K, the largest temperature drop between submerged ladle shroud and SEN is about 4.4 K. It should be emphasized that the calculated temperature drop is, more or less, different with in situ measured because the assumed heat losses have some deviation compared with the in situ applied tundish.

6. Conclusions

The flow field and temperature profile of molten stainless steel in an asymmetrical T-type single-strand tundish with capacity of 18–20 tons have been investigated in a 1:3 hydrodynamic model coupled with a mathematical modelling. The main conclusions can be summarized as follows:

(1) The results of 1:3 hydrodynamic model show that currently applied structural parameters of the tundish at No. 2 Steelmaking Plant of Shanxi Taigang Stainless Steel Company Limited are not as good as wished, such as, the fraction of dead zone is 38%, the minimum breakthrough time of measured RTD curve is about 50 s corresponding to minimum breakthrough time of the prototype tundish as about 90 s. According to results of orthogonal tests, five groups of modified structural parameters of the tundish have been recommended, in which can reduce volume fraction of dead zone to 15–30%, and increase volume fraction of dispersed plug zone to more than 20%, and prolong the minimum breakthrough time of determined RTD curves to 70–90 s. Improving casting speed can not largely deteriorate the effect of recommended structural parameters on modifying flow field of molten stainless steel in the tundish.

(2) The results of hydrodynamic modelling show that height for low-wall of turbulence inhibitor, dam height and weir depth are three important structural parameters of the asymmetrical T-type single-strand tundish on flow field of molten stainless steel. Increasing height for low-wall of turbulence inhibitor, improving dam height and expanding weir depth in the investigated range can effectively improve
dispersed plug zone and reduce dead zone. Improving casting speed will improve turbulent flow, certainly reduce dead zone of molten stainless steel in the tundish.

(3) The calculated temperature profiles of molten stainless steel in the tundish under nonisothermal condition in the recommended optimal cases show that heat losses around the tundish must be considered to accurately calculate temperature profiles. The calculated temperature drop of molten stainless steel at submerged ladle shroud and submerged entry nozzle of the tundish is about 4.4 K, the maximum temperature drop of molten stainless steel in the tundish is about 10.0 K. The modification of flow filed by improving cast- ing speed will improve turbulent flow, certainly reduce dead zone of molten stainless steel in the tundish.

Nomenclature

\( q \) : Acceleration of gravity (9.8 m/s^2)
\( G \) : Generation rate of turbulence kinetic energy (m^2/s^3)
\( k \) : Turbulent kinetic energy (m^2/s^2)
\( K_{\text{eff}} \) : Effective thermal conductivity (kg/(m · s · K))
\( L \) : Characteristic length (m)
\( p \) : Pressure (kg/(m · s^2))
\( Q \) : Volumetric flow rate (m^3/h)
\( Re \) : Reynolds number (—)
\( t \) : Time (s)
\( T \) : Temperature (K)
\( \Delta t \) : Time step (s)
\( \bar{t}_q \) : Average residence time (s)
\( \bar{u} \) : Flow velocity (m/s)
\( V_p \) : Volume fraction of dispersed plug zone (—)
\( V_d \) : Volume fraction of dead zone (—)
\( V_w \) : Volume fraction of well-mixed zone (—)
\( \bar{V} \) : Water volume in hydrodynamic plexiglass model (m^3)
\( x_i, x_j \) : i-th or j-th Cartesian space coordinate (m)

Greek symbols

\( \beta \) : Coefficient of volumetric thermal expansion of molten steel (K^-1)
\( \varepsilon \) : Dissipation rate of turbulent kinetic energy (m^2/s)
\( \theta_{\text{av}} \) : Dimensionless average residence time (—)
\( \theta_{\text{min}} \) : Dimensionless time of minimum breakthrough of conductivity (—)
\( \theta_{\text{peak}} \) : Dimensionless time of attaining peak conductivity (—)
\( \lambda \) : Geometrical scale factor (—)
\( \mu \) : Molecular viscosity (kg/(m · s))
\( \mu_{\text{eff}} \) : Effective viscosity (kg/(m · s))
\( \mu_t \) : Turbulent viscosity (kg/(m · s))
\( \rho \) : Density of molten steel (kg/m^3)
\( \sigma_k, \sigma_\varepsilon \) : Schmidt number for \( k \) and \( \varepsilon \) (—)
\( \sigma_f, \sigma_{\varepsilon,f} \) : Laminar and turbulent Prandtl number (—)
\( \tau \) : Theoretical average residence time (s)

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