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Effect of Turbulence Inhibitors on Molten Steel Flow in 66-Ton T-Type Tundish with Large Impact Area

Cheng Yao ¹, Min Wang ^{1,*} , Ruixuan Zheng ¹, Mingxu Pan ², Jinyuan Rao ² and Yanping Bao ¹

¹ State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China; 19801226790@163.com (C.Y.); zhengruixuan95@126.com (R.Z.); baoy@ustb.edu.cn (Y.B.)

² Daye Special Steel Co. Ltd., Huangshi 435000, China; wangqin019@163.com (M.P.); raojinyuan@163.com (J.R.)

* Correspondence: worldmind@163.com

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Abstract: A multiphase numerical simulation of the steel-slag flow was established by using the volume of fluid (VOF) model to study the effect of different turbulence inhibitors on the improvement of the steel-slag flow in the tundish. The steel-slag interface fluctuation was studied by vorticity magnitude and transient fluctuation change. A prediction model of residence time distribution (RTD) curve was established based on mathematical simulation and the error of prediction model can be controlled below 6% by comparing with the hydraulic results. The results show that jet flow into the tundish generated very different flow patterns. Case 1 produced a double-roll flow pattern and case 2 produced a four-roll flow pattern in the impact area. The ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 2.60% in case 1 and the ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 13.15% in case 2, which indicates case 2 increased the possibility of slag entrainment via the upward flow mechanism and shear layer instability. Surface velocity fluctuations in case 2 were much more severe near the ladle shroud. The thickness of the slag layer was 60 mm, the interface fluctuation towards surface in case 2 was close to 20 mm. Meanwhile, case 1 involved very small volume-fraction contours near interface. The turbulence inhibitor with internal ripples (case 1) showed a better optimization effect and the results could provide a theoretical basis for the selection of a suitable turbulence inhibitor for the 66-ton T-type tundish.

Keywords: multiphase numerical simulation; turbulence inhibitor; jet flow; turbulent kinetic energy; vorticity magnitude; transient fluctuation change

1. Introduction

Tundish, as the last procedure before solidification of molten steel, plays an important role for the removal of macro-inclusions, distribution of molten steel and homogenous of molten steel during continuous casting process. Tundish usually adopts many flow control devices, such as turbulence inhibitor, dam and weir, diversion wall, argon blowing and electromagnetic stirring, etc. [1–7]. The turbulence inhibitor installed in the impact area of tundish can eliminate eddies, reduce scour and alleviate injection flow impact.

Turbulence inhibitors can improve the flow state of molten steel, mainly in the following aspects [8–10]: turbulence inhibitors can (1) relieve the impact of molten steel on the bottom of tundish and reduce the involvement of gas and slag; (2) extend the average residence time of molten steel in tundish and reduce the dead area of flow; (3) reduce the erosion of molten steel on the bottom and wall of tundish and prolong the service life of tundish; (4) slow down the formation of confluence vortex and optimize the flow of molten steel.

Traditional tundish structure are summarized T-type, H-type and rectangle-type, etc. [11–13], and for most of steel plants, the proportion of impact area of tundish maintained generally 20–30%. As the development of tundish metallurgy, the large capacity T-type tundish with high proportion of impact area is gradually used in recent years. The researches on the impact area of tundish become important especially with the large capacity high proportion of impact area [14–18]. In the impact area, the turbulence inhibitor shows the most obvious effect on improving the flow state of molten steel.

Yang et al. [19–21] studied turbulence inhibitors with different structures, and analyzed the flow behavior, transfer behavior and inclusion field of molten steel by numerical simulation. The results showed that the square, round and straight shapes cannot affect the mixing dynamics of liquid steel, and the optimization effect of molten steel flow was not obvious. The turbulence inhibitor with internal ripples or partial closure could effectively dissipate the turbulent kinetic energy of liquid steel, reduce the impact on the steel-slag interface and improve the “open eye”. Merder et al. [9,22,23] combined the physical and numerical simulations to optimize the flow control devices such as turbulence inhibitor in tundish, simulated the flow field, velocity field and concentration field of molten steel, calculated the RTD curve by mass transfer equation, and analyzed the flow characteristics of molten steel. These studies mainly focused on the simulation of single-phase (molten steel) but ignored the study of the steel-slag interface fluctuation. The steel-slag interface fluctuation could be more closely related to the inspirations, spatter and slag entrainment of the jet flow. The steel-slag flow belonged to multiphase behavior and the results of multiphase numerical simulation were more reliable. At present, the research on the multiphase behavior of tundish mainly focused on the operation of ladle changing, argon blowing and steel filling [24–26] and the research on the effect of turbulence inhibitor on the steel-slag flow have not been introduced into the multiphase simulation.

This paper focused on a 66-ton T-type tundish of a Chinese special steel plant with large impact area. A long flow channel connects the impact area and casting area. The comparison of sections of the present T-type tundish and the traditional tundish are shown in Figure 1. For the experimental T-type tundish, two kinds of turbulence inhibitors, internal ripples type and partial closure type, were designed. According to the actual process conditions, a multiphase numerical simulation of steel-slag flow had been established to study the jet flow and turbulent kinetic energy of the tundish with two different turbulence inhibitors. At the same time, the fluctuation of steel-slag interface was studied by vorticity magnitude and transient fluctuation change. A human-defined virtual phase (tracer) was added to the VOF model to calculate the RTD curve. The results can provide a theoretical basis for selecting a suitable turbulence inhibitor for the experimental tundish.

Figure 1. The section of experimental tundish and traditional tundish: (a) T-type(experimental); (b) rectangle-type; (c) triangle-type; (d) T-type (traditional); (e) H-type.

2. Description of Numerical Simulation and Hydraulics Experiment Process

2.1. Numerical Simulation

2.1.1. Basic Assumptions

The actual fluid flow in tundish is very complicated turbulence and some basic assumptions in numerical simulation are prerequisite, as follows:

- (1) The fluid flow in the tundish is treated as steady state flow, and the fluid is considered as Newtonian and incompressible.
- (2) The effect of temperature on the density of the steel, slag and tracer are ignored. The density of the steel, slag and tracer are constant.
- (3) In the tundish, the steel, slag and tracer are treated as homogeneous medium.
- (4) The liquid-liquid interface is set to non-slip wall boundary, meaning that the velocity at the wall is 0, $k = 0$ and $\varepsilon = 0$.

2.1.2. Mathematical Models

The equations describing the mass transfer of molten steel in tundish included the momentum equation (Navier-Stokes equation), the k - ε equation, the continuity equation and the VOF model equation used to describe the free surface fluctuation. Here, it is assumed that the fluid flow in tundish was transient and the density (ρ) was constant.

- (1) Continuity equation could be expressed as follows:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

- (2) Momentum equation (Navier-Stokes equation) could be expressed as follows:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_{eff} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i \quad (2)$$

- (3) Standard k - ε model equations for turbulence [24,25]

The equations that describe the transport of the turbulent energy k and dissipation rate ε could be expressed as follows:

$$\rho u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\mu_{eff}}{\sigma_k} \times \frac{\partial k}{\partial x_i} \right) + G - \rho \varepsilon \quad (3)$$

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = \left(\frac{\mu_{eff}}{\sigma_\varepsilon} \times \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{C_1 \varepsilon G}{k} - \frac{C_2 \rho \varepsilon^2}{k} \quad (4)$$

where, G represents the generation of turbulence kinetic energy due to the mean velocity gradients, $\text{m}^2 \cdot \text{s}^{-2}$; ρ is the density of liquid steel, $\text{kg} \cdot \text{m}^{-3}$; u is the velocity, $\text{m} \cdot \text{s}^{-1}$; i and j represent the coordinate directions; μ_{eff} is effective viscosity, $\text{Pa} \cdot \text{s}$; μ_l is laminar viscosity, $\text{Pa} \cdot \text{s}$; μ_t is turbulent viscosity, $\text{Pa} \cdot \text{s}$; $C_1 = 1.43$, $C_2 = 1.93$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$ are the empirical constants of the k - ε model.

- (4) Interface wave control equation

In order to accurately investigate the dynamic behavior of the steel and slag flow in the tundish, a multiphase VOF model was applied to calculate the behavior of the steel-slag interface. Since a

void region was not allowed in this model, the volume fractions of all phases sum to unity in each control volume.

$$\sum_{q=1}^n \alpha_q = \alpha_{\text{steel}} + \alpha_{\text{tracer}} + \alpha_{\text{slag}} \quad (5)$$

The fields for all variables and properties were shared by the phases and represented volume-averaged values, as long as the volume fraction of each of the phases was known at each location. Thus, the volume fraction average properties in any given control cell were computed in the following form, as for volume fraction average density (ρ) and viscosity (μ), which can be obtained by equations $\rho = \sum_{i=1}^n \alpha_i \rho_i$ and $\mu = \sum_{i=1}^n \alpha_i \mu_i$ respectively.

2.1.3. Boundary Conditions

According to the actual fluid flow in tundish, the boundary conditions of the mathematical model of tundish were treated as follows:

- (1) The velocity inlet boundary condition was applied for the computational inlet. The velocity of molten steel was calculated according to the volume flow of the inlet and the cross-section area of the ladle shroud. The turbulent kinetic energy and the turbulent energy dissipation rate of the inlet can be obtained by Equations. $k = 0.01v_{\text{inlet}}^2$ and $\varepsilon = \frac{2k^{1.5}}{D_{\text{inlet}}}$ respectively. Where, v_{inlet} is the inlet velocity, $\text{m}\cdot\text{s}^{-1}$, D_{inlet} is the inner diameter of ladle shroud, m.
- (2) The outflow boundary condition was applied for the computational outlet.
- (3) The top of the tundish was set as a free surface with shear force of zero.
- (4) No slip boundary condition at the wall and standard wall function near the wall has been applied.

For the numerical simulation of liquid steel in tundish, a mathematical model with the same size as the prototype was established. Initial basic setting of steel, slag and tracer are shown in Table 1.

Table 1. Initial basic setting of the fluid.

Physical Properties	Unit	Value
v_{inlet}	$\text{m}\cdot\text{s}^{-1}$	1.6949
k	$\text{m}^2\cdot\text{s}^{-2}$	0.0287
ε	$\text{m}^2\cdot\text{s}^{-3}$	0.1298
Density of steel/slag/tracer	$\text{kg}\cdot\text{m}^{-3}$	6950/3000/6950
Viscosity of steel/slag/tracer	$\text{pa}\cdot\text{s}$	0.0064/0.0560/0.0064
Interfacial tension of steel-slag	$\text{N}\cdot\text{m}^{-1}$	1.15
Interfacial tension of steel-tracer	$\text{N}\cdot\text{m}^{-1}$	0
Interfacial tension of slag-tracer	$\text{N}\cdot\text{m}^{-1}$	1.15
Height of steel level	mm	900
Thickness of slag layer	mm	60

2.1.4. Numerical Method

The test object is a six-strand continuous casting tundish with a nominal capacity of 66-ton, which is used in a Chinese special steel plant. In tundish, the depth of the casting area is greater than that of the impact area. The impact area and the casting area are connected by a flow channel with a certain slope. The volume of generalized impact area accounts for 1/3 of the total volume of tundish. The tundish with such design is to make sure more residence time of the liquid steel, which can be helpful to the homogenous of the chemical composition and the floating removal of inclusions. The basic structure of this tundish is shown in Figure 2a, and the dimensions are in millimeters.

Figure 2. Schematic diagram of (a) field prototype tundish structure and (b) numerical simulation tundish structure at 800 s.

Considering the symmetry of the tundish, half of the tundish was modeled for the numerical simulation. The control equation was solved by CFD software Fluent17.1 (Ansys Inc., Canonsburg, PA, USA). The PISO (Pressure Implicit with Splitting of Operators) algorithm was used for coupling the pressure and velocity terms [25]. To simulate the behavior of the steel-slag interface and turbulence inhibitor more accurately, local grid refinement technology was applied, and the meshes of the FLUENT computational domain included non-uniform grids with about 1,500,000 cells. Simultaneously, mesh refinement of the steel-slag interface and turbulence inhibitor were considered. The convergence criterion was established when the sum of all residuals for the dependent variable was less than 10^{-4} . Starting at time = 0 s, the VOF model was run for ~1100 s using a constant time step of 0.01 s. The flow was allowed to develop for ~800 s, and then a further ~300 s of data was used to draw the RTD curve, of which ~100 s was used to analyze the steel-slag interface fluctuations. In the process of drawing the RTD curve, the physical properties of the human-defined virtual phase (tracer) were the same as the steel, and at all the walls, zero concentration gradient was applied. The inlet boundary condition of the tracer mass fraction was stated as follows: when $t < 1$ s, the tracer mass fraction was set to 1, and when $t > 1$ s, the tracer mass fraction was set to 0. During this process, a monitor was set up at the outlets to continuously measure the instantaneous concentration of the

tracer as a function of time and then to use this information to plot the RTD curve. Figure 3 shows the details of the RTD curve simulation process. The initial setting of numerical model at 800 s was shown in Figure 2b. The top was slag, the interior was steel, and the inlet was tracer.

Figure 3. The details of the numerical simulation process.

Based on the basic characteristics of tundish, two kinds of turbulence inhibitor were designed. The working area of the turbulence inhibitor located at the bottom of the impact area of the tundish, and the center of the turbulence inhibitor faced the impact point. In this paper, case 1 installed a turbulence inhibitor with internal ripples; case 2 installed a turbulence inhibitor with partial closure. The basic structure and parameters of different turbulence inhibitors are shown in Table 2.

Table 2. The basic structure and parameters of different turbulence inhibitors.

Diagram	Characteristic	Symbol	Unit	Value
Case1 	Height	H1	mm	280
		H2	mm	208
		H3	mm	66
		H4	mm	72
	Length/Width	L1	mm	55
		L2	mm	100
		L3	mm	96
		L4	mm	140
		L5	mm	230
		L6	mm	205
Case2 	Height	L7	mm	235
		L8	mm	210
		L9	mm	300
	Length/Width	L10	mm	320
		H1	mm	120
		H2	mm	325
		H3	mm	380
		L1	mm	375
	Length/Width	L2	mm	425
		L3	mm	520
		L4	mm	600

2.2. Hydraulics Experiment

Based on the principle of similarity [27,28], a hydraulic model with ratio of 1:3 to the prototype was established, as shown in Figure 4a. The comparison between the main parameters of the prototype and the model is shown in Table 3. In the hydraulic experiment, the Froude number and Weber number of the model should be equal to those of the prototype and the ratios of velocity, flow rate and characteristic length between the hydraulic model and the prototype can be obtained by Equation (6), where F_{r_p} and F_{r_m} , v_p and v_m , L_p and L_m are the Froude numbers, velocities, and characteristic lengths of the prototype and the hydraulic model respectively. Then, $v_m = \sqrt{\lambda}v_p$, $Q_m = \lambda^{\frac{5}{2}}Q_p$, $t_m = \lambda^{\frac{1}{2}}t_p$ in the experiments can be calculated, where v_p and v_m , Q_p and Q_m , t_p and t_m are the velocities, capacity, and residence time of the prototype and the hydraulic model respectively.

$$\frac{v_p^2}{gL_p} = \frac{v_m^2}{gL_m} \quad (6)$$

Figure 4. (a) Schematic diagram of hydraulics experiment used for measuring residence time distribution (RTD) curve, (b) hydraulics experiment detailed procedure.

The hydraulics experiment process can be described as 4 stages and potassium chloride (250 mL KCl) was used for the measurement of residence time distribution (RTD curve). Figure 4b shows the details of the hydraulic experiments and the numbers in square brackets in figure indicates the following stages. The first stage (Stage (1)) was the process of storage and appeared from $t = t_0$ to $t = t_1$, the second stage (Stage (2)) was the process to regulate flow instruments and appeared from $t = t_1$ to $t = t_2$, the third stage (Stage (3)) was the experiment time to simulate steady casting and occurred from $t = t_2$ to $t = t_3$ and the fourth state (Stage (4)) was the process to drain away water and occurred after

$t = t_3$. When $t = t_1$, the liquid level of tundish reached a predetermined height of 900 mm, and the flow instruments were adjusted to stabilize the liquid level for more than 10 min. When $t = t_2$, the saturated KCl solution of 250 mL was injected into the water stream flowing by the tracer adding device on the ladle shroud. Meanwhile, the conductance electrodes at the outlets began to measure the instantaneous concentration of the tracer as a function of time and then the collected information was continuously transmitted to the data acquisition and analysis system so that it could be used to plot the residence time distribution (RTD) curve. The time of hydraulics experiment was about 2.5 times the average residence time, and the experiment time ended at $t = t_3$.

Table 3. The comparison between the main parameters of the prototype and the model.

Casting Condition	Unit	Prototype	Model
Inlet flow	$L \cdot min^{-1}$	448.8	28.8
Single outlet flow	$L \cdot min^{-1}$	74.8	4.8
Height of molten steel	mm	900	300
Inner diameter of ladle shroud	mm	75	25
External diameter of ladle shroud	mm	130	43.3
Submergence depth of ladle shroud	mm	270	90

3. Results and Discussion

3.1. Model Validations and Analysis of Response Time

The RTD curves were measured using the hydraulic model system and numerical model system; and the reliability of numerical model system is verified by comparing with the error of RTD curves between the two models results. In this experiment, the response time (t_{min}) of each strand in the hydraulic model was measured and converted into the response time (t_p) of the actual size of the tundish by the conversion formula. Compared with the response time (t_a) of the numerical simulation, the authenticity of the result of the numerical simulation was verified. Conversion formula and error formula can be obtained by Equations (7) and (8), where $E(\%)$ is the error result. The tundish was symmetrical, so it was assumed that the “ t_a ” at the symmetric strand was the same in the numerical simulation. Generally, the flow state of molten steel was evaluated by comparing the actual mean residence time ($\bar{t}$), the standard deviation (S) of the response time (t_{min}) of each strand, the proportion of dead zone volume, etc. under different flow control devices. As the object of this experiment is a large-capacity tundish, the actual average residence time of molten steel is long, and the proportion of dead zone volume is small, which are not used as a criterion in this experiment. The standard deviation formula can be obtained by Equation (9), where S is the standard deviation, $\bar{x}$ is the arithmetic mean value of the variable and λ is the similarity factor between the model and the prototype.

$$t_{min} = \lambda^{0.5} \cdot t_p \quad (7)$$

$$E(\%) = 1 - \sqrt{\frac{\sum_{i=1}^n t_a}{\sum_{i=1}^n t_p}} \quad (8)$$

$$S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}} \quad (9)$$

The RTD curve of three strands on a half side of case 1 and case 2 are shown in the Figure 5a, the response time of case 1 and case 2 are shown in the Figure 5b and the main flow field indicators are shown in the Table 4. The results show that the error between the hydraulics experiment and the mathematical simulation was less than 6%, which indicates the correctness of the results of the VOF model. At the same time, the “ S ” under case 1 was 23.54, which was similar to 29.98 under case 2. The two cases had similar flow paths. Therefore, it was difficult to determine a more suitable

turbulence inhibitor for the experimental tundish. A new reliability numerical simulation method was provided which had been verified by comparing the RTD results, and then some important indicators in the numerical simulation of case 1 and case 2 are discussed and analyzed in the following sections.

Figure 5. (a) RTD curve comparison between hydraulic model and numerical model; (b) the response time of case 1 and case 2.

Table 4. Main flow field indicators in case 1 and case 2.

	t	Outlet1	Outlet2	Outlet3	Outlet4	Outlet5	Outlet6	S	E(%)
case 1	$t_{\min}(s)$	115	89	88	86	89	114		
	$t_p(s)$	199	154	152	149	154	197	23.54	5.87
	$t_a(s)$	188	144	141	141	144	188		
case 2	$t_{\min}(s)$	117	88	84	81	91	123		
	$t_p(s)$	203	152	145	140	158	213	29.98	4.17
	$t_a(s)$	199	145	138	138	145	199		

3.2. Jet Flow and Turbulent Kinetic Energy in Two Cases

Because of the irregular shape of turbulence inhibitor and tundish, the viscosity of molten steel and the existence of boundary layer on the wall, the internal flow is mostly swirling. Through the jet flow and turbulent kinetic energy, we can directly observe the flow trend of molten steel and the velocity difference in the tundish. Jet flow and turbulent kinetic energy are the most common and direct way to describe liquid steel flow.

The installation of turbulence inhibitor had obvious effect on the flow of molten steel. Jet flow into the tundish generated very different flow patterns with the two different turbulence inhibitor, as shown in Figure 6. The change of velocity was most obvious in the impact area, which was the focus of this section and had been marked with dotted black box in the Figure 6. Case 1 produced a double-roll flow pattern and case 2 produced a four-roll flow pattern in the impact area, as the high-spreading jet impinged first onto the bottom of turbulence inhibitor, and deflected upward to impinge into the wall of turbulence inhibitor. The velocity was fully dissipated in the turbulence inhibitor and then a more complex flow was formed due to the mixture and collision between the rising flow and the jet flow near the ladle shroud. Some molten steel flowed into the flow channel after forming circulation in the impact area, while others directly impacted the steel-slag interface, resulting in slag entrapment risk. Case 2 had two vortices under the turbulence inhibitor, which was its unique feature and could cause some molten steel to directly impact the steel-slag interface along the tangential direction of the

vortices. High risk existed during the process of strong impact on the steel-slag interface due to the inspirations, spatter and slag entrainment. Fortunately, the turbulence inhibitor could fully consume the energy of molten steel both in case 1 and case 2, so that the surface velocity of the steel-slag interface was only 10% of the initial velocity at the inlet, which was in an optimum range, effectively avoiding the surface instability caused by high surface velocity.

Figure 6. Flow field and velocity field of (a) case 1 and (b) case 2 at 850 s.

Meanwhile, the flow of molten steel in tundish was turbulent (random, three-dimensional, diffusive and dissipative). Turbulent steel strongly flow at the slag-steel interface may push or drag the slag via shear, leading to the entrainment of slag droplets into the flowing steel. With the use of turbulence inhibitor, most of the turbulent kinetic energy of molten steel was dissipated before reaching the steel-slag interface, as shown in the Figure 7. The initial turbulent kinetic energy of molten steel at the inlet is $0.28728 \text{ m}^2/\text{s}^2$, and the turbulent kinetic energy at the steel-slag interface decreased to about 20% of the initial value at the inlet. The effect of turbulence inhibitor on dissipation of turbulent kinetic energy was obvious

Figure 7. Turbulence distribution of (a) case 1 and (b) case 2 at 850 s.

Lower surface velocity and turbulence decreased the possibility of slag entrainment via the upward flow mechanism, and shear layer instability. The turbulence inhibitor played a significant role. Firstly, the negative pressure pumping effect of the injection flow was weakened, and the risk of slag entrapment was decreased; secondly, the flow state of the liquid steel in the impact area was optimized, and the strong erosion of the liquid steel on the refractory material was weakened; thirdly, the impact strength of the rising flow on the steel-slag interface was weakened, which was more conducive to the stability of the steel-slag interface. The fluctuations of the steel-slag interface and slag stability in two cases would be studied in the following sections.

3.3. The Fluctuation of Steel-Slag Interface in Two Cases

3.3.1. Analysis of Vorticity Magnitude

The vorticity of the flow field in the impact area is randomly distributed and consists of fluctuating vorticity of various scales. Vorticity is usually used to measure the size and direction of a vortex, which is defined as the curl of the velocity. As long as “vorticity source” existed in the molten steel, vorticity could be generated. Vorticity is mainly used to characterize the rotation of the fluid element

and reflect the information of the turbulent of the steel. In general, the rotation of small-scale vortex is stronger than that of large-scale vortex due to the limitation of tundish size and surrounding liquid steel. The velocity is one of the important properties of fluid, that was named $v_{ec} = (v_x, v_y, v_z)$,

and the vorticity is the curl of the velocity vector, namely $v_{oc} = \nabla \times \vec{v} = \begin{pmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ v_x & v_y & v_z \end{pmatrix}$, which is $(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}, \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}, \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y})$. Compared with the velocity field, vorticity field can directly and concisely show the possibility of the fluctuation of steel-slag interface.

The vorticity magnitude of the steel-slag interface of two cases in the transient numerical calculation of 850 s is shown in Figure 8a,b. The region near the ladle shroud and the region in the generalized impact area are the two study regions in this section, as shown in Figure 8a, where the turbulence was the most serious and the behavior of molten steel was closely the inspirations, spatter and slag entrainment. The value of vorticity magnitude in the study regions is shown in Figure 8b. The value of the vorticity magnitude represents the state of steel-slag flow and includes four gradients. The value above 1.00 s^{-1} means that the fluctuation of steel-slag interface is very volatile, which is easy to cause the inspirations, spatter and slag entrainment. The value under 0.10 s^{-1} means that vertical velocity of the molten steel is small, which cause the steel and slag to be not sufficiently connected and the inclusions are difficult to remove. The value between $0.10\text{--}0.55 \text{ s}^{-1}$ means the steel-slag flow state is suitable, the fluctuation of steel-slag interface is not volatile, and the turbulent kinetic energy can be effectively consumed.

Figure 8. At 850 s, vorticity distribution in (a) case 1 and (b) case 2; (c) the ratio of vorticity magnitude in different study regions.

By comparing the results, we can conclude that the vorticity distributions of the generalized impact area in two cases were very close. The ratio of vorticity magnitude between $0.10\text{--}0.55 \text{ s}^{-1}$ in the generalized impact area was 89.89% in case 1, the ratio of vorticity magnitude between $0.10\text{--}0.55 \text{ s}^{-1}$ in the generalized impact area was 88.06% in case 2 and the difference between the two ratios is less than 2%, which could be ignored. However, the vorticity distributions near the ladle shroud in two cases present obvious differences. The ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 2.60% in case 1, the ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 13.15% in case 2 and this ratio in case 2 is five times that in case 1, which indicates case 2 increased the possibility

of slag entrainment via the upward flow mechanism and shear layer instability. Therefore, case 1 had better steel-slag flow state and slag entrainment may not strongly occur during interface change.

3.3.2. Analysis of Transient Interface Change

Interface fluctuation is related to vorticity magnitude in the steel-slag interface, and it depends on transient flow near the steel-slag interface. Transient velocity changes continuously even during nominally steady-state casting conditions. To carry out analysis, correlated signals were fetched from the simulation results at key location points inside the section of turbulence inhibitor, as shown in Figure 9a. Point p1 is located near the ladle shroud, point p2 is located in the middle position, and point p3 is located near the wall. During the period of 800–900 s, the change of Y velocity of characteristic points was counted every 5 s, as shown in Figure 9b. Level fluctuations were very likely associated with this velocity change behavior. Taking point p1 as an example, the maximum surface velocity of case 2 was almost three times that of case 1, and surface velocity fluctuations were much more severe. Taking point p2 and point p3 as an example, the surface velocity fluctuation both two cases were gentle. The results indicated that slag entrainment may mainly occur near the ladle shroud.

Figure 9. (a) Points' location for fetching the correlated signals; (b) wave height of point p1, point p2 and point p3 in 800–900 s.

The change in the direction of Y velocity represents the material and energy exchange between steel and slag. From 825 s to 830 s, case 1 and case 2 had the same velocity direction and the range of velocity change was obvious. Therefore, it is of practical significance to study the change of interface fluctuation change in this stage. Figure 10a,b are the slag fraction contours of case 1 at 825 s and 830 s

respectively. Figure 10c,d are the slag fraction contours of case 2 at 825 s and 830 s respectively. In order to show the changing trend of steel-slag interface more clearly, the steel-slag interfaces at different times of the same case are coupled into a diagram, as shown in Figure 11. The study region shown in Figure 11 is consistent with the region marked in Figure 10 by dotted black box. In Figure 11, the red region represents the interface level only belonging to 825 s, the blue region represents the interface level only belonging to 830 s, and the purple area represents the interface level overlapped at two times.

Figure 10. The slag fraction contours of case 1 at (a) 825 s and (b) 830 s; the slag fraction contours of case 2 at (c) 825 s and (d) 830 s.

The steel-slag interface level for both two cases showed a strong curvature, due to surface tension. The turbulence inhibitor shape greatly affected the profile of the steel-slag interface level and its time variations. The interface curvature in case 2 was most obvious near ladle shroud and had an obvious change, which is marked in black round frame in Figure 11. The thickness of the slag layer was 60 mm, and the interface fluctuation towards surface was close to 20 mm, which could cause surface instability and slag entrapment. The height of the interface fluctuation continued to increase, which may cause open eye. The open eye is a critical product quality problem because it allows both reoxidation of the steel, and carbon pickup from the slag layer. Case 1 involved very small volume-fraction contours near the ladle shroud, which indicates that case 1 more not closely related to the inspirations, spatter and slag entrainment and case 1 is more suitable for the 66-ton T-type tundish with large impact area.

Figure 11. The change of steel-slag interface in two cases from 825 s to 830 s.

4. Conclusions

Due to the high temperature of the continuous casting process and the opacity of the tundish, the VOF model has been used to establish a multiphase numerical simulation of the steel-slag flow to study the steel-slag flow with or without a turbulence inhibitor, and the results were compared and verified with the physical simulation. The obtained conclusions are summarized as follows:

- (1) A human-defined virtual phase (tracer) with the same properties as steel is introduced to calculate the RTD curve of each strand through the VOF model, and the error was less than 6% compared with the numerical simulation result, which could prove the reliability of the numerical simulation results.
- (2) Jet flow into the tundish generated very different flow patterns. Case 1 produced a double-roll flow pattern and case 2 produced a four-roll flow pattern in the impact area. The turbulence inhibitor can fully consume the velocity and turbulence of molten steel both in case 1 and case 2. However, case 2 had two vortices under the turbulence inhibitor, which could cause some molten steel to directly impact the steel-slag interface along the tangential direction of the vortices and slag entrainment may occur during the process.
- (3) The ratio of vorticity magnitude between $0.10\text{--}0.55\text{ s}^{-1}$ (in this range, steel-slag flow state is the best) in the generalized impact area in case 1 and in case 2 were close. However, the ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 2.60% in case 1, the ratio of vorticity magnitude above 1.00 s^{-1} near the ladle shroud was 13.15% in case 2 and this ratio in case 2 is five times that in case 1, which indicates case 2 increased the possibility of slag entrainment via the upward flow mechanism and shear layer instability.
- (4) Near the ladle shroud, the maximum surface velocity of case 2 was almost three times that of case 1, and surface velocity fluctuations were much more severe. The thickness of the slag layer was 60 mm, and the interface fluctuation towards surface in case 2 was close to 20 mm, which can cause surface instability and slag entrapment. Case 1 involved very small volume-fraction contours in this region.

- (5) The turbulence inhibitor with internal ripples (case 1) had more obvious optimization effect, which can provide a theoretical basis for selecting suitable turbulence inhibitor for the 66-ton T-type tundish with large impact area.

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