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MATHEMATICAL SIMULATION FOR EFFECTS OF FLOW CONTROL DEVICES IN TWO-STRAND SLAB TUNDISH

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Fluid flows in a two-strand tundish for slab continuous casting were performed with mathematical simulation methods. The molten steel flow velocity fields in the tundish with a turbulence inhibitor, dam, and weir were numerically calculated. Simulation results showed that the tundish with a turbulence inhibitor with no opened holes has similar flow characteristics to the tundish with dam and weir. These results are essential to optimizing the turbulence inhibitor, dam and weir parameters for slab continuous casting tundish.

Keywords: tundish, residence time, flow field, inhibitor

INSTRUCTION

Tundish that works as a distributor and reservoir joins the ladle and mold in continuous casting, which plays an important role in clean steel production by removing non-metallic inclusions in the molten steel. To improve the cleanliness of steel products [1, 2], many flow control devices, such as bubble curtains, dams, weirs, and turbulence inhibitors (TIs), have been proposed to separate inclusion particles from liquid steel in the tundish. Most of these devices can change the molten steel path lines to improve the molten steel average residence time. Different flow control devices in the tundish affect the molten steel flow. Therefore,.understanding the effect of the flow control devices is necessary to determine the optimum flow characteristics. Mathematical modeling has been widely used to illustrate this process

Mathematical modeling is a powerful method to study molten steel flow in tundish and investigate its flow characteristics. Chattopadhyay and Mazumdar present many studies on the physical and mathematical modeling of tundish operation in a review [3, 4]. Most of the investigations [5–9] examine the molten steel flow behavior in continuous casting tundish to understand the effect of different flow control devices. Therefore, understanding the phenomenon of fluid flow in detail is quite important. Numerous studies have been performed on continuous casting tundish by physical or mathematical simulation [10–15] to clarify molten steel flow behavior. Molten steel flow in tundish is further explored through the numerical simulation method.

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The purpose of the present study is to determine the influence of different flow control devices of tundish. The commercial CFD software FLUENT was used for the mathematical simulation. The simulation investigated the inhibitor in the tundish with and without the dam and wire to understand the role of a single turbulence inhibitor. The flow characteristic of the molten steel is determined by the flow control devices. Moreover, the residence time distribution (RTD) curves and the path of fluid flow in the tundish with the turbulence inhibitor are discussed in the numerical modeling. Finally, the tundish level velocity is discussed.

TUNDISH DESCRIPTION

The tundish in the present study is a trough-type slab continuous casting tundish with two nozzles and a nominal capacity of 60 t. The tundish is equipped with a turbulence inhibitor. Figure. 1 shows the schematic of a two-strand tundish. The geometrical dimensions of the tundish are described in Table 1. The tundish is equipped with a turbulence inhibitor located at its center bottom. The molten steel from the inlet shroud immersed in the liquid pours toward the inhibitor.

Table 1 **Parameters of slab tundish / m**

Parameters	D_1	D_2	H	L_1	L_2	W
Values	0,12	0,075	1,20	7,8	7,3	1,4

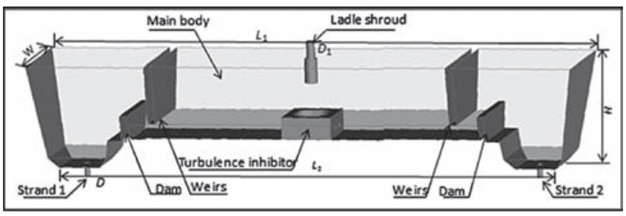

Figure 1 sketch of tundish

MATHEMATICAL MODEL

Continuity equation:

$$\frac{\partial(\rho\mu_j)}{\partial x_j}=0 \quad (1)$$

Momentum equation:

$$\rho\frac{\partial(u_i u_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}(\mu_{\text{eff}}\frac{\partial u_i}{\partial x_j})+\frac{\partial}{\partial x_i}\left(\mu_{\text{eff}}\frac{\partial u_j}{\partial x_i}\right)+\rho g_i+F \quad (2)$$

Turbulent kinetic energy and dissipation rate equation:

$$\rho\frac{\partial(u_i k)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu_{\text{eff}}+\frac{\mu_{\text{t}}}{\sigma_{\varepsilon}}\right)\frac{\partial k}{\partial x_i}\right]+G-\rho\varepsilon \quad (3)$$

$$\rho\frac{\partial(u_i\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu_{\text{eff}}+\frac{\mu_{\text{t}}}{\sigma_{\varepsilon}}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+c_1\frac{\varepsilon}{k}G-c_2\frac{\varepsilon^2}{k}\rho \quad (4)$$

$$G=\mu_{\text{t}}\frac{\partial u_j}{\partial x_i}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \quad (5)$$

Species transport equation:

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x_i}(u_i C)=\frac{\partial}{\partial x_i}(D_{\text{e}}\frac{\partial C}{\partial x_i}) \quad (6)$$

where

$$G=\mu_{\text{t}}\frac{\partial u_j}{\partial x_i}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \quad (7)$$

Effective viscosity:

$$\mu_{\text{eff }\mu}=\mu+\mu_{\text{t}}=\mu+\rho C\frac{k^2}{\varepsilon} \quad (8)$$

The effective mass-diffusion coefficient depends on the fluid flow field; this coefficient can be calculated as follows:

$$\frac{\mu_{\text{eff}}}{\rho D_{\text{e}}}\approx 1 \quad (9)$$

The constants of the k–ε two-equation turbulence model are C_1 = 1,44, C_2 = 1,92, C_μ = 0,09, σ_k = 1,0, and σ_ε = 1,3.

BOUNDARY CONDITION

The tundish wall is assumed to be the non-slip boundary condition. The liquid level of the tundish is taken as a free surface; the velocity gradient in the normal direction is set at zero. The average velocity at the inlet is assumed to be uniform in slab transversal section; it is obtained by the steel flow rate into the continuous casting mold. The outlet is set as the outflow boundary condition. The conditions of the tundish operation in the numerical simulations are given in Table 2.

The tundish grid is generated in the hexahedron element using the pre-processor of FLUENT, GAMBIT. The number of the whole cells is approximately 422 000. The turbulent kinetic energy of the entrance (k) and the dissipation rate (ε) are calculated according to Formulas (9) and (10). Other calculated boundary conditions are set as in Reference 8.

$$k_{\text{in}}=0{,}01u_{\text{in}}^2 \quad (10)$$

$$\varepsilon_{\text{in}}=2k_{\text{in}}^{3/2}/d_{\text{in}} \quad (11)$$

Table 2 **Simulation parameters**

Parameters	Values
Mass flow rate / t·min^{-1}	4,8
Density(steel) / kg·m^{-3}	7 200
Viscosity of liquid steel/ Pa·s	0,0055
Gravity / m·s^{-2}	9,81

NUMERICAL SOLUTION

In this study, the commercial software fluid dynamics calculation package FLUENT was adopted to solve the continuity, momentum, and turbulence equations. The second-order wind scheme was used to discretize these equations and ensure a high order accuracy. The convergence condition was the residual error less than 10^{-4}. The governing equations were solved based on the finite volume method (FVM) by the Semi-Implicit Method for Pressure-Linked-Equation (SIMPLE) algorithm. The usual grid-dependent tests were also performed. The results are discussed in the following sections.

RESULTS AND DISCUSSION

The tracer added into the tundish first flows toward the turbulence inhibitor. The molten steel flows from the turbulence inhibitor to the top surface when the turbulence inhibitor without opening holes was used as the only flow control device in the tundish. The RTD curves of strands 1 and 2 were measured in the numerical method for the two-strand tundish configuration; they are presented in Figure 2. The curves of the tracer concentrations from the two outlets as a function of time are significantly different in different tundish configurations, as shown in Figure 2. The short minimum residence, peak concentration, large average residence times, and small dead volume fraction were obtained for the two strands. Table 3 shows the molten steel flow parameters in the tundish outlets obtained from the RTD curves with different flow control devices. Cases 1 to 4 have different configurations: Case 1 combined the dam weir and turbulence inhibitor, Case 2 is the turbulence inhibitor with four holes with the dam, Case 3 is the turbulence inhibitor with four holes, and Case 4 is the

Table 3 **Flow characteristics for different tundish configurations**

Case	Strand	t_{min}	t_{max}	t_{av}	$V_{\text{d}}/V_{\text{i}}$
1	1	88	426	760	4,8
	2	104	582	748	6,3
2	1	98	205	693	14,0
	2	90	215	694	13,9
3	1	70	200	663	17,7
	2	80	210	694	13,9
4	1	95	310	764	7,4
	2	88	330	741	8,1

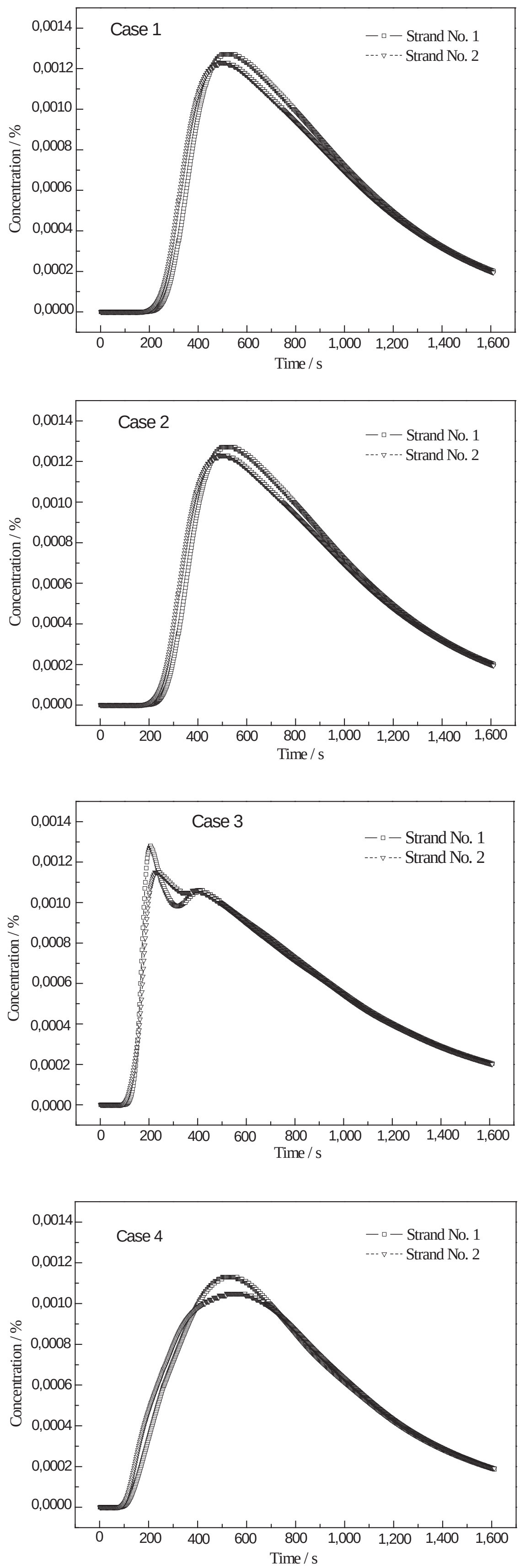

Figure 2 RTD curves for different cases

turbulence inhibitor without any hole. As shown in Table 3, t_{min} is the minimum residence time (s), t_{max} is the peak concentration time (s) obtained from the RTD curve, and t_{av} is the average residence time (s). The dead

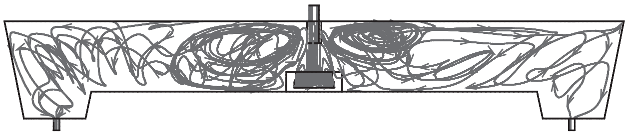

Figure 3 Pathlines for tundish with turbulence inhibitor without holes

volume fraction V_d/V_i and t_{av} are calculated as in Reference 8.

The RTD curves of strands 1 and 2 are very similar for cases 1 and 4. Thus, the flow characteristics in these two strands are almost the same with each other. Table 1 shows the flow characteristics, such as minimum residence, peak concentration, and average residence times. Large differences exist between the flow characteristics of the two outlets, as shown in Table 3. The minimum residence and peak concentration times are small, and the dead volume fractions are large in Case 4. Case 3 has short minimum residence and peak concentration times and a large dead volume fraction in strands 1 and 2; small differences in flow characteristics also exists between strands 1 and 2. The path lines of fluid in the seven-strand tundish are given in Figure 3. These path lines can reflect the flow characteristic in the tundish. The path lines adhering to the strands are similar. Thus, the molten steel flowing out of the outlet is similar.

Figure 4 shows the horizontal velocity distribution of the molten steel in the tundish level. The tundish level velocity is different in Case 4, the turbulence inhibitor without holes; its level velocity is larger than that of Case 3, the turbulence inhibitor with four holes. The maximum velocity value is 0,123 m/s. Thus, this value will not affect the level slag entrapment. The above results indicate that the turbulence inhibitors can control the fluid flows in the impact zone of the tundish, as well as improve the flow characteristic in the area far from the turbulence inhibitors for a tundish. The effect on flow control becomes weak as the distance to the turbulence inhibitor increases. However, the flow control effect is also effective in the tundish with only a turbulence inhibitor and without opening holes. Cases 1 and 4 have lower dead volume fractions compared with the other

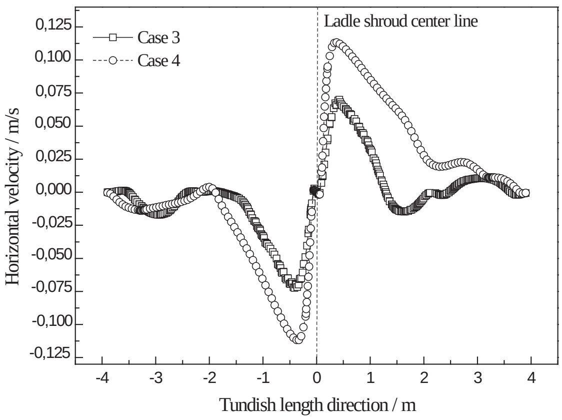

Figure 4 Horizontal velocity for tundish level

cases; their minimum residence times and their two strands are also more uniform. Therefore, Case 4 is considered to be the optimum configuration to save cost.

CONCLUSIONS

Fluid flow behavior in slab continuous casting tundish with a turbulence inhibitor was investigated using FLUENT commercial software, and the simulated results were tested by industrial experiments. The different flow control device configurations of the tundish have a significant effect on the fluid flow performance in terms of the minimum residence and peak concentration times. Turbulence inhibitors can effectively control and improve the fluid flow in two-strand slab continuous casting tundish. Turbulence inhibitors can also be used without other flow control devices, such as weirs and dams, to effectively improve the flow characteristics in the tundish considering production costs.

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Note: The responsible translator for English language is X. Z. Wang - School of Mechanic Engineering, Anhui University of Technology, Ma’ anshan, China