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Modeling study on fluid flow and inclusion motion in 6-strand bloom caster tundishes

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Abstract: The behavior of fluid flow and particle motion in a 6-strand bloom caster tundish was investigated by a water model and numerical simulation. Compared with a device without flow control, the tundish with flow control has an important effect on the fluid flow pattern and inclusion removal. It is revealed that by non-isothermal process, which is real production condition, the fluid flow in tundish shows a strong buoyancy pattern, which drives particles to move upwards. The particle removal was quantitatively studied by mathematical and physical simulations.

Key words: physical and mathematical simulation; non-isothermal process; fluid flow; inclusion removal; multi-strand tundish

1 Introduction

For the past couple of decades, it has been recognized that the liquid steel in tundish has an important influence on the quality of cast steel product. Therefore, physical and mathematical simulations on tundish were extensively reported [1-6]. However, except a few considerations on the effect of natural convection on fluid flow [5, 6], most previous studies were under isothermal condition and with water model at room temperature. For a tundish with multi-strands, it is required not only to effectively control the inclusion motion and remove them to top slag, but also to uniform the temperature distribution for each strand. In this paper, the behaviors of the fluid flow, tracer diffusion and inclusion motion in a six-strand bloom tundish at Pangzhihua Iron and Steel Company were investigated by physical and mathematical simulations. At the same time, the effect of non-isothermal conditions with the flow control device and without the flow control device on fluid flow pattern and inclusion removal in the tundish was studied.

2 Research methods

2.1 Water model experiment

The main factors controlling the flow pattern in a tundish are gravity and internal force, the Froude similarity criterion ($Fr=gL/U^2$) is therefore considered for the water model. On the other hand, it was reported that if the average fluid flow velocity is less than 0.14 m/s, the natural convection can not be ignored [7]. For the current tundish, the average velocity is 0.067 m/s (the bloom section: 280 mm×380 mm; the casting speed: 0.8 m/min), thus the natural convection should be considered, and Tu similarity criterion ($Tu=\frac{\beta g L \Delta T}{U^2}$), standing for the relation between buoyancy and inertial force, therefore, should also be satisfied. According to the Froude similarity criterion ($Fr_m=Fr_p$),

The characteristic velocity: $U_m=\lambda^{0.5}U_p$;

The characteristic length: $L_m=\lambda L_p$;

The volumetric flow rate: $Q_m=\lambda^{2.5}Q_p$.

The temperature difference is determined by $(Tu)_p=(Tu)_m$, and the following equation is derived:

$$\Delta T_m=\frac{\beta_p}{\beta_m}\Delta T_p .$$

The temperature difference of liquid steel between the injection spot of the ladle and the lowest temperature in the tundish is 15-25°C [8], and $\beta_p=1.16\times10^{-4}$, $\beta_m=2.79\times10^{-4}$ [9], thus $\Delta T_m=10.75$°C, which means that in the hot water model of the tundish, the water temperature should be 10.75°C higher than that in the normal cold water model (room temperature) in order to simulate the hot steel flow pattern, namely, $T_{heat}=\Delta T_m+$ the cold water temperature.

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The water model experiment apparatus for this six-strand tundish is shown in **figure 1** schematically, which is 1/4 of the prototype and is made of plexiglass. The fluid flow pattern was obtained by executing the stimulate-response experiments known as the residence time distribution (RTD) curve, and the temperature distribution was obtained by analyzing the F curve (the dimensionless curve of temperature *versus* time) and the collected data. The flow field was revealed by tracer diffusion, injecting blue ink into the domain at the inlet and recording the color dispersion with time interval with camera. The two cases for the simulation are detailed in **table 1.**

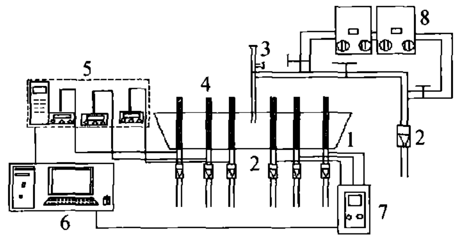
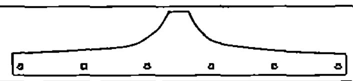
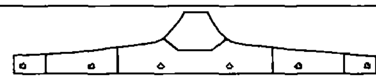


Figure 1 Schematic of water model experiments, 1— tundish; 2—flowmeter; 3—tracer inlet; 4—stopper; 5— RTD system; 6—computer; 7—temperature collection system; 8—heater.

Table 1 Two cases for simulation

Case	1—without the flow control device	2—with weir and dams
Schematic		

In the current water model, the polystyrene plastic particles were used to simulate inclusions in steel. The selection of particle size in the water model is based on the following similarity criterion [9]:

$$\frac{R_{\rm m}}{R_{\rm p}}=\lambda^{0.25}\left[\frac{\left(1-\frac{\rho_{\rm p}}{\rho_{\rm l}}\right)}{\left(1-\frac{\rho_{\rm m}}{\rho_{\rm w}}\right)}\right]^{0.5} \quad (1)$$

where λ is the proportion coefficient, 0.25; $\rho_{\rm w}$ the density of water, 1.0 g/cm^3; $\rho_{\rm l}$ the liquid steel density, 7.035 g/cm^3; $\rho_{\rm p}$ the density of inclusions in steel, around 2.5-3.4 g/cm^3; $\rho_{\rm m}$ the density of polystyrene plastic particles, 0.995 g/cm^3. Thus the polystyrene plastic particles of 0.72 mm in water, as shown in **figure 2**, correspond to the inclusions of 90-100 μm in steel. The removal ratio is defined as $\eta=(1-W_{\rm g}/W_{\rm e})\times100\%$.

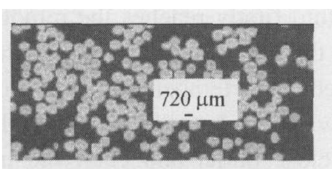


Figure 2 Particle morphology in water model.

2.2 Mathematical simulation

Three-dimensional fluid flow in the current tundish was simulated, the k-ε two equation model [5] was used to model turbulence. The particle trajectory was calculated by integrating its velocity, which was obtained by considering the drag force and gravitational force. No slip boundary condition was used at walls, and zero flux condition was employed at the free surface. The effect of top slag on the fluid flow was ignored. The domain was divided into 300000 fine meshes in order to get accurate results. The particles were assumed to escape when reaching the top surface, outlets and to be reflected at solid walls.

3 Results and discussion

3.1 Fluid flow behavior

The residence time, flow pattern and the RTD curves by water model for two cases in table 1 are shown in **tables 2** and **3** and **figure 3**, respectively. Without flow control devices, obviously, a short flow and a recirculation flow take place near the first outlet. The inclusions, therefore, have little time to float out to the top surface and tend to flow away from the outlets, and meanwhile the dead volume reaches 26%, and the plug flow zone is only 2.3%. Several peaks are found in the RTD curves (figure 3). C/C_0 and t/t_0 stand for the dimensionless concentration and dimensionless time in figure 3. With flow control devices, however, the previous short flow and recirculation flow are eliminated and the vigorous turbulence is controlled in the inlet zone, the flow pattern is therefore improved. At the same time, the average residence time of the liquid is prolonged 8% compared with that without the flow control devices, and the dead zone decreases to 28%, the piston flow zone increases to 8.4 times, the liquid, therefore, gets a better mixing before entering the continuous casting mold.

The velocity vector distributions of the calculated fluid flow along some faces for case 1 and case 2 are shown in **figure 4**. With flow control, the fluid flow in the inlet zone (the zone circled by the weir) becomes much more vigorous than that without flow control. Due to some holes on the weir, there are some places above the close outlet have a little larger velocity than that without flow control. The calculated turbulent energy dissipation rate in the inlet zone and other zone is 1.534×10^{-3} and 2.823×10^{-5} m^2/s^3 respectively for the tundish with flow control devices. But without flow control, the turbulent energy dissipation rate in the inlet zone and other zone is 1.142×10^{-3} and 1.281×10^{-5} m^2/s^3 respectively. The result shows that the vigorous turbulence is well controlled in the inlet zone with flow control devices. This can increase the inclusion collision probabilities, favor the inclusion growth, thus improve the inclusion removal.

Table 2 Measured residence time for hot water model experiments s

Case	τ_1	τ_2	τ_3	$\bar{\tau}_1$	$\bar{\tau}_2$	$\bar{\tau}_3$	$\bar{\tau}$	$\bar{S}$
1	4	10	24	377.1	391	431	400	27.98
2	17	21	41.5	420	436	457	438	18.56

Table 3 Measured flow patterns for hot water model experiments

Case	Close outlet / %			Middle outlet / %			Remote outlet / %		
	V_d	V_m	V_P	V_d	V_m	V_P	V_d	V_m	V_P
1	30.00	68.15	0.90	27.42	69.06	1.76	19.94	75.98	4.08
2	21.91	64.77	13.32	18.97	55.97	25.06	14.99	58.84	26.18

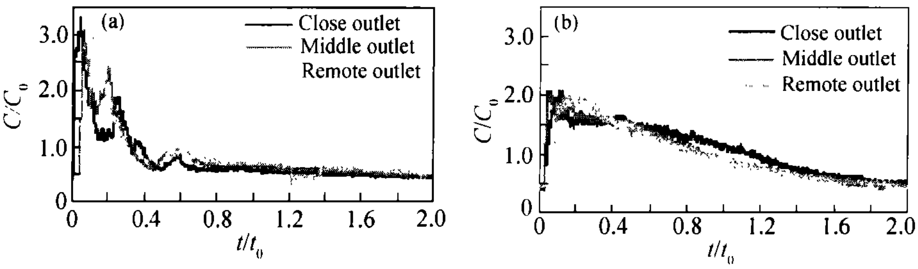


Figure 3 Measured RTD curves for hot water model experiments: (a) case 1; (b) case 2.

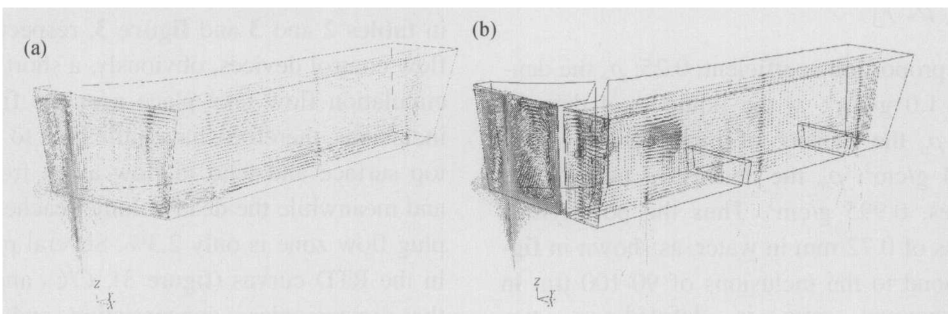


Figure 4 Calculated velocity vector distributions: (a) case 1; (b) case 2.

Figure 5 shows the calculated ink dispersion in the tundish. The shallow color in the figure stands for the liquid steel flow direction. The figure clearly indicates that by using weir and dams, a more upward flow pattern is generated than that without flow control devices, this favors inclusion removal. It also shows that without flow control devices, the jet directly reaches the closest outlet, which is bad for uniform temperature, bad for inclusion removal, and this phenomena is eliminated by using weir and dams. This result agrees well with the water model.

3.2 Effect of non-isothermal condition on temperature and flow pattern

For the hot water experiments, the dimensionless temperature T/T_0 *versus* dimensionless time t/t_0 is shown in **figure 6**. Opposite to the room temperature water model experiments, in the current hot water model, the fluid firstly reaches the remote outlet, and then back to the close outlet due to the density difference induced by temperature difference. When without flow control (case 1), the fluid directly reaches the close outlet and enter the mold without full heat exchange with other liquid in the tundish, thus there is a strong temperature fluctuation at the close outlet area as shown in figure 6. Compared with case 1, the temperature fluctuations of the liquid in the tundish with flow control devices decrease obviously in case 2.

It is well known that the natural convection induces an upward flow, and it is very important especially when the tundish has a big volume and a long flow distance. The liquid flows upward due to this natural convection effect in the hot water model while the fluid flows downward and directly reaches the bottom of the tundish in the cold water model as shown in **figure** 7. This upward flow pattern is surely in favor of inclusion removal because inclusions are able to reach the top surface more quickly. The good agreement between figures 5 and 7 for case 1 at room temperature indicates the accuracy of the mathematical simulation.

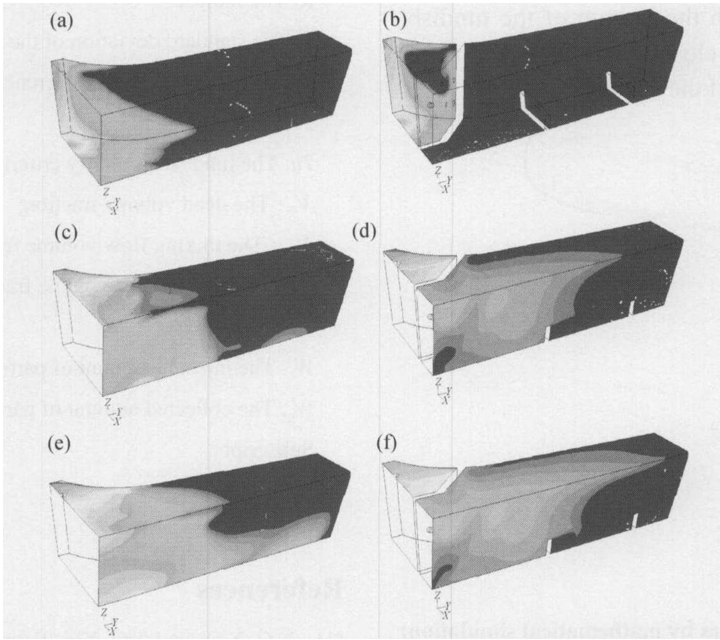


Figure 5 Calculated ink dispersions at room temperature (the shallow colour stands for the liquid steel flow direction): (a) case 1, 7 s; (b) case 2, 7 s; (c) case 1, 30 s; (d) case 2, 30 s; (e) case 1, 45 s; (f) case 2, 45 s.

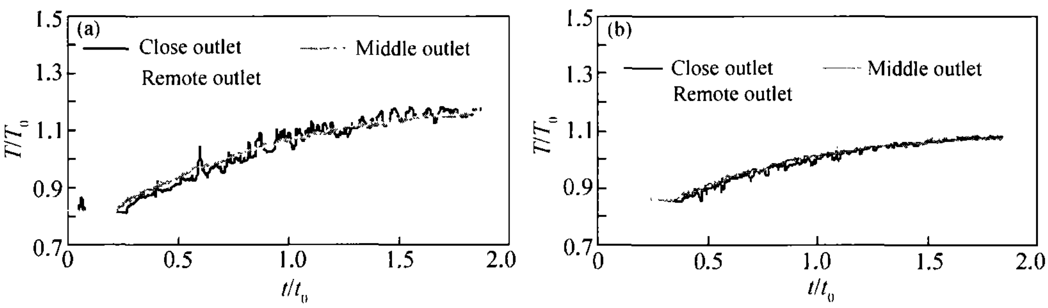


Figure 6 Measured temperature curves for hot water model experiments: (a) case 1; (b) case 2.

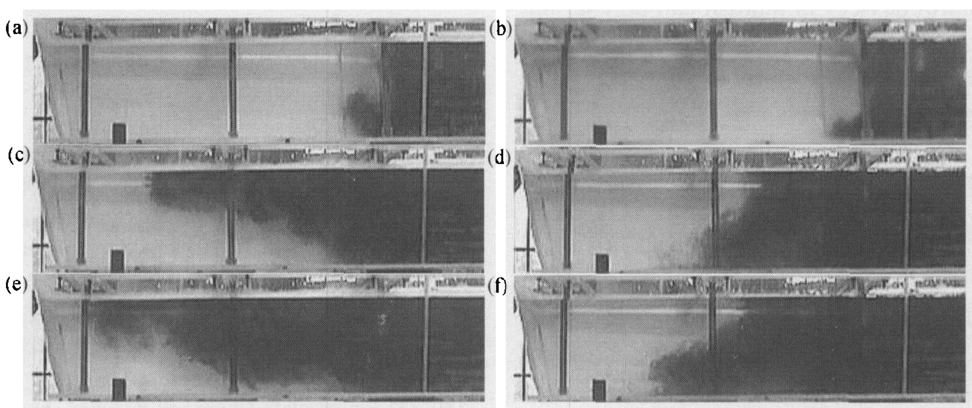


Figure 7 Flow pattern comparison between the cold water model and hot water model for case 1: (a) 7 s, hot water; (b) 7 s, cold water; (c) 30 s, hot water; (d) 30 s, cold water; (e) 45 s, hot water; (f) 45 s, cold water.

3.3 Inclusion removal and motion trajectory

The flow control devices have an influence on inclusion removal in the tundish. The experiment result indicates that the removal of particles to the top surface is well improved by the flow control devices. The particles can be removed by 98.4% with flow control devices, around 3.5% higher than that without flow control devices.

The calculated trajectories of some inclusions are shown in **figure 8**. With flow control, because of the generated upward flow pattern, more and more particles move to the top surface, and there are only few inclusions reach the middle outlet and the remote outlet. Without flow control, because of the short flow, the particles quickly reach the bottom of the tundish, and move directly to the close outlet, and also many reach the middle outlet and the remote outlet.

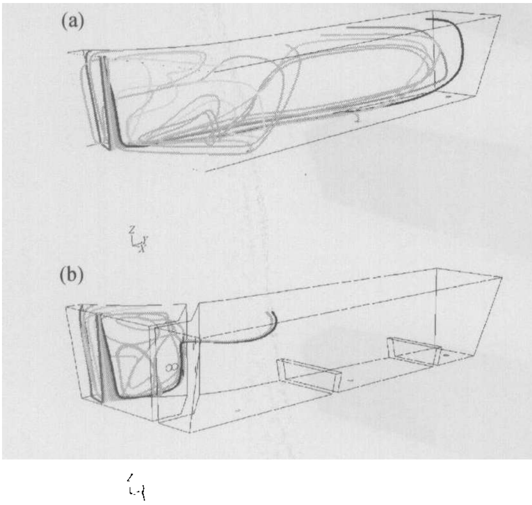


Figure 8 Particle trajectories by mathematical simulation: (a) case 1; (b) case 2.

4 Conclusions

(1) Physical and mathematical simulations for a 6-strand bloom tundish was carried out. The water model agrees well with the mathematical simulation.

(2) Natural convection has an important effect on fluid flow in a continuous casting tundish, which should be considered during physical and mathematical simulations on fluid flow and inclusion removal in the tundish.

(3) Flow control devices in tundish can play an important role in modifying the fluid flow pattern, improving the temperature uniformity and increasing the inclusion removal.

Nomenclature

λ: The proportion coefficient;

β_p: The coefficient of volume expansion for steel;

β_m: The coefficient of volume expansion for water;

τ_1, τ_2, τ_3: The short residence time of the close outlet, middle outlet and remote outlet;

$\bar{\tau}_1$, $\bar{\tau}_2$, $\bar{\tau}_3$: The average residence time of the close outlet, middle outlet and remote outlet;

$\bar{\tau}$: The average residence time;

η : The removal ratio;

ρ_w : The density of hot water;

ρ_{st} : The liquid steel density;

ρ_p : The density of inclusions in steel;

Fr : Froude number;

L : The length;

Q : The flow rate;

R: The radius;

S: The standard deviation of the average residence time;

ΔT_m: The temperature difference;

T: The temperature;

Tu: The tundish similarity criterion number

V_d : The dead volume fraction;

V_m : The mixing flow volume fraction;

V_P : The piston flow volume fraction;

U: The velocity;

W_e: The injected amount of particles to domain;

W_g: The collected amount of particles at the outlets;

Subscript

m: model;

p: prototype.

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