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Effect of flow modifiers on the flow behavior of inclusions in steelmaking tundish

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Abstract: The clean steel is major requirement of modern industries. The clean steel provides enhanced mechanical and chemical properties. The melt coming out from furnace and ladle contains high amount if eroded refractory particles. Thus, tundish is a last metallurgical reactor where molten metal can be cleaned through various mechanism. The present paper shows the computational results of flow behavior of inclusion particle inside the tundish geometry. Three-dimensional model of tundish with advanced pouring box (APB) has been used to for the numerical simulation. It has been seen that APB have a significant impact over the inclusion motion behavior in the tundish. Different sizes of inclusion particles have been studied on two types of tundish. It was found that the use of advanced pouring box has enhanced the inclusion removal efficiency of the tundish.

Keywords: Advanced pouring box (APB), Inclusion particle, Tundish, Continuous casting.

1. Introduction

The need of clean steel is requirement of the developing world. A cleaner steel i.e., purer form of steel from all indigenous and exogenous impurities, performs better and has better mechanical properties. In general, impurities in molten steel comes from impure melt in furnace and breaking of refractories lining of ladle and tundish etc. The tundish is last device where impurities can be removed. Hence, the tundish are designed in such a way to minimize the mixing of inclusion particles in melt. The flow modifiers are used to change the flow behaviour of inclusion particles in such a way so it can be trapped at the upper slag level of tundish [1–3].

The investigation of inclusion flow behaviour is a challenging work itself and it is generally studied by the physical model or by a computer simulation of inclusion and melt flow in tundish [4,5]. Moreover, computer simulation is an easier and most versatile method for investigating any metallurgical plant operation. It is also useful for study of steelmaking tundish in continuous casting. Many researchers made significant effort in the area of steelmaking tundish, to enhance the quality and performance of steel. Tundish are designed with one or more nozzles at the bottom wall of the tundish with slide gates or stopper rods for controlling the metal flow rate [6]. Further, variety of flow control devices or tundish furniture, such as weirs, dams, baffles, etc., are used along the length of the tundish. Lighter inclusions particles rise up to the surface of molten steel. Inclusion includes particles of aluminium oxide which has density of about 60% of that of liquid steel. Hence inclusions particle will tend to float on the liquid steel surface according to stokes' law [7].

2. Physical Description

Fig [1] shows the schematic diagram of full scale steelmaking tundish with one input and two output respectively. An advance pouring box (APB) is placed at the Centre of the tundish, the shape of APB is hollow hemisphere with inner diameter of 470 millimetre and wall thickness of 5 millimetre. The tundish volume is taken as 3000 millimetre × 600 millimetre × 800 millimetre with inlet diameter of 76.2 millimetre and length of shroud is 100 millimetre.

3. Mathematical Modeling

3.1. Governing Equations

Continuity:

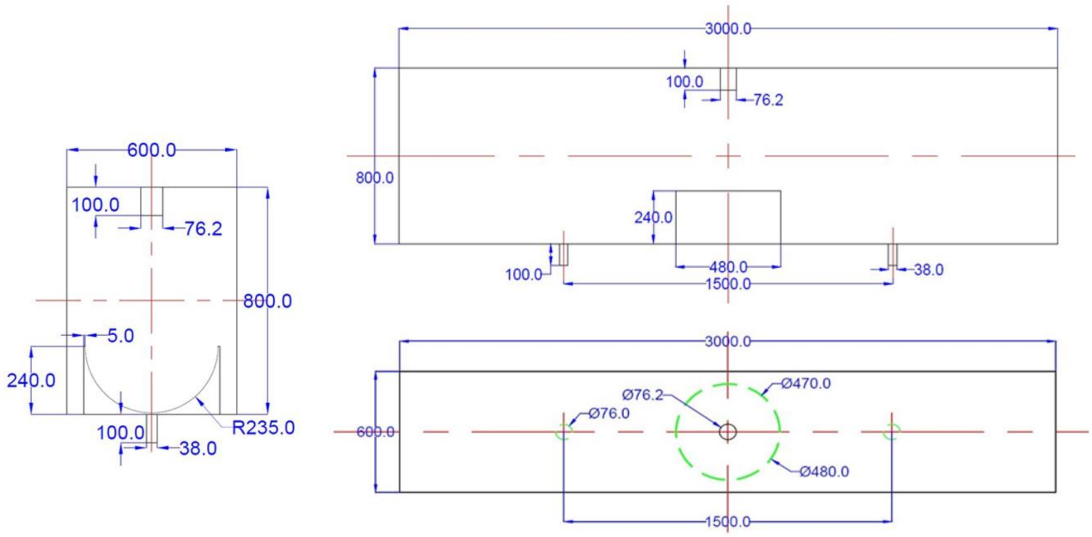

Figure1. Geometry of two strand tundish with APB.

$$\frac{\partial \mathbf{u}_i}{\partial \mathbf{x}_i} = 0 \quad (1)$$

Momentum:

$$\frac{\partial}{\partial x}\rho u_i u_j = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) \quad (2)$$

Where,

$$\mu_{eff} = \mu_0 + \mu_t = \mu_0 + \rho C_\mu \frac{k^2}{\epsilon} \quad (3)$$

Energy Equation:

$$\frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}(k_{eff})\frac{\partial T}{\partial x_i} \quad (4)$$

Concentration,

$$\frac{\partial(\rho C)}{\partial t} + \frac{\partial(\rho u_i C)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{\mu_{eff}}{\sigma_c}\frac{\partial C}{\partial x_i}\right) \quad (5)$$

Theoretical Mean Residence Time,

$$\tau = \frac{\text{Volume of the tundish}}{\text{Volumetric flow rate}} \quad (6)$$

Actual Residence Time,

$$t_r = \frac{\sum C_{avi} t_i}{\sum C_{avi}} \quad (7)$$

In equation (8), the integration is carried over a time span 2τ with an equal interval of time step

$$\text{Fraction of dead volume of the tundish} = 1 - \frac{t_r}{\tau} \quad (8)$$

Break through time, tp = First appearance of tracer at the exits. (9)

$$\textit{Equation of plug volume} = \frac{V_p}{V} = \frac{t_p}{\tau} \quad (10)$$

$$\textit{Fraction of mixed volume} = \frac{V_m}{V} = 1 - \left(\frac{V_p}{V} + \frac{V_d}{V}\right) \quad (11)$$

4. Numerical Details

Because of symmetry at Centre plane computation was carried out for half of the tundish geometry. At inlet mean vertical velocity is assumed to be uniform through its cross section and other two perpendicular velocities are assumed to be zero. All velocities are set to zero at every wall. No slip-condition are assumed at the wall. The inlet velocity is set at 1.4 m/s. K- epsilon model is considered because previously fluid flow is turbulent in nature. Solution method is set to simple with discretization of second order upwind. For inclusion trapping, the upper wall is assumed to trap condition. And the bottom and side wall are set to reflect. The inclusion particle that not trap and leaves the tundish volume are considered as escaped. The percentage of inclusion removal has been calculated from outlets.

CFD software was used for solving the set of equations and generating the results. From the molten steel flow, the lighter inclusion particle rise up to the surface of tundish slag with terminal velocity, V_t given by stokes' relation [8–10].

$$V_t = \frac{2R^2 p(\rho_S - \rho_S)g}{9\mu_S}$$

Where Rp is the particle radius, ρ_s and μ_s are density and viscosity of molten steel, respectively, ρ_p is the particle density, and g is acceleration due to gravity.

5. Results

Numerical simulations have been carried out for inclusion removal in steelmaking tundish. Two cases have been considered first with flow of steel in bare tundish and in second with flow modifier (APB). Results are tabulated for both cases i.e. with bare tundish and in second case tundish along with (APB).

5.1 Bare Tundish (Case-I)

Table 1. Percentage of trapped particle and escaped particle associated with different particle diameter in bare tundish.

Inclusion diameter (μm)	Injected particles	Trapped particles	Escaped particles	% of Trapped particle	% of Escaped particle
10	1080	513	567	47.50	52.50
20	1080	561	519	51.94	48.05
40	1080	593	487	54.90	45.09
80	1080	717	363	66.38	33.61
120	1080	752	328	69.62	30.37
160	1080	817	263	75.64	24.35
200	1080	881	199	81.57	18.42

Table 2 shows greater percentage of trapped particle as compared to table 1. So it is concluded the tundish with APB is more efficient in inclusion removal.

5.2 Tundish with APB (Case-II)

The fig. 2 shows the vector profile of liquid steel inside the tundish volume. It is noted that here the flow is upward in both direction and reaches to the top surface, where the lighter inclusion particle trap into the tundish slag.

The fig 3: Shows the curve for tundish with APB design. It is clear from the figure that percentage of trapped inclusion particle is increasing with increase in the size of inclusion particle i.e. larger inclusion particle is more in number as compared to smaller inclusion particle.

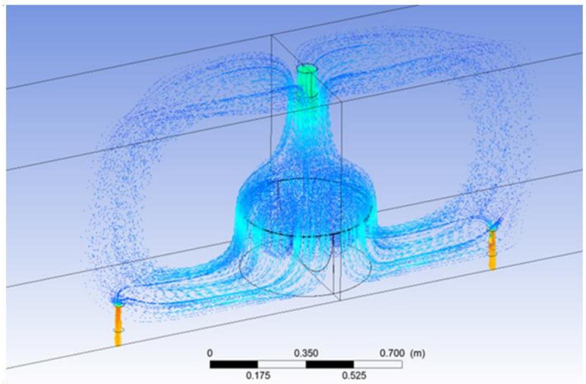

Figure 2. Vector profile of steel coming from the inlet nozzle.

Table 2. Percentage of trapped particle and escaped particle associated with different particle diameter in tundish with APB.

Inclusion diameter (μm)	Injected particles	Trapped particles	Escaped particles	% of trapped particle	% of escaped particle
10	1080	909	171	84.16	15.83
20	1080	917	163	84.90	15.09
40	1080	900	180	83.33	16.66
80	1080	924	156	85.55	14.44
120	1080	920	160	85.18	14.81
160	1080	925	155	85.64	14.35
200	1080	932	148	86.29	13.70

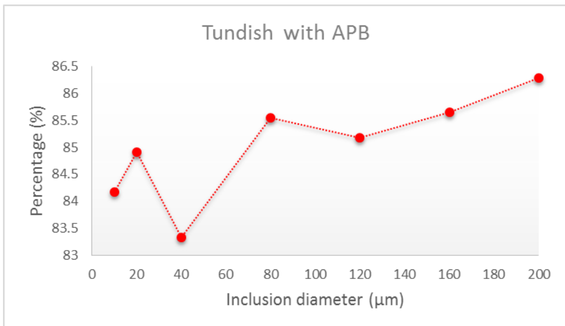

Figure 3. Curve between inclusion diameter and percentage of inclusion particle trapped in tundish with APB.

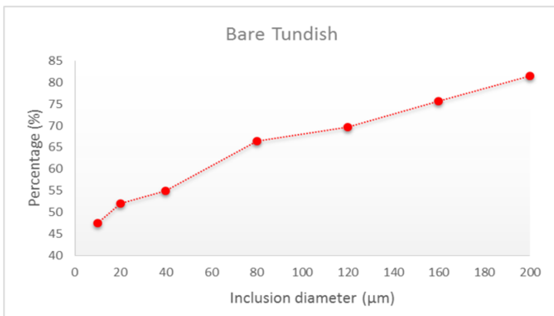

Figure 4. Curve between inclusion diameter and percentage of inclusion particle trapped in bare tundish.

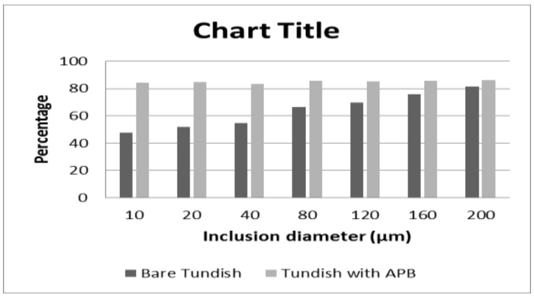

Figure 5. Chart for bare tundish and Tundish with APB (For percentage of trapped particle Vs inclusion diameter).

6. Conclusion

Numerical simulation has been carried out to investigate the flow behavior of liquid steel inside the tundish and the effect of flow control devices (ABP) on inclusion flotation. Removal of inclusions is important for the production of clean steel. It has been observed that the use of flow control device (APB) plays an important role on fluid flow behavior and inclusion floatation inside tundish. From the vectors diagram, it has been clearly observed that large amount of fluid flows towards upper surface of the tundish. The percentage of entrapment of larger size inclusion was more as compared to the smaller size inclusion particles. It was found that the use of APB in the tundish increases the mean residence time and help in removing the inclusion particle. Further, it was observed that the flow modifier helps to increase the trapped percentage of inclusion particle.

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