Numerical model of liquid metal flow in steel making tundish with flow modifiers

Manas Vasantrao More¹, Sandip Kumar Saha², Vishal Marje³, G. Balachandran³

¹Research & Development, Kalyani Center for Technology and Innovation (KCTI), India
²Department of Mechanical Engineering, Indian Institute of Technology Bombay, India
³Kalyani Carpenter Special Steel Pvt Ltd. (KCSSPL), India
E-mail: manas.more@bharatforge.com

Abstract. The optimum condition for clean steel production in the tundish of a continuous casting process reactor can be obtained using numerical modelling. Five different arrangements of flow modifier in the form of impact pad systems deployed in an eight ton, delta shaped, and two strand bloom caster tundish are analysed and optimum design of the impact pad to improve the inclusion removal efficiency is evolved. Reynolds Averaged Navier-Stokes (RANS) equations with standard k-ε model of turbulence and energy equation are used to study fluid flow and inclusion flotation in the tundish. The inclusion separation efficiency is evaluated by solving the inclusion transport equation. Height variations along with additional notch amongst different impact pads yield best micro inclusion separation efficiency.

1. Introduction

The continuous casting system is comprised of a ladle, a tundish, a mould and flow connectors (submerged entry nozzle). Tundish was originally developed as an intermediate vessel placed between the ladle and the mould, to evenly distribute molten steel to different moulds, at constant rate. In addition, the tundish is used to maintain the heat of the molten metal and increase the removal of detrimental non-metallic inclusions [1-2]. Fluid flow equations along with the energy equation were used to predict the temperature distributions under non-isothermal conditions [3-5]. Numerical modelling was used to predict parameters such as residence time distributions (RTD) [5] and distribution of top surface slag layer [6]. Solhed et al [6-7] included additional differential equations to describe inclusion trajectories and inclusion number density distribution. Standard k-ε model of Launder and Spalding [8] was used to calculate an eddy viscosity. Jha et al. [9] studied the effect of different turbulence models on the residence time distribution predictions along with LES model (large eddy simulation) in tundish modelling. Few studies used the low Reynolds number model of Launder and Jones [10-11] to study residence time distributions in a six-strand tundish and found better agreement with the experimental results. The present study concentrates on the performance of the tundish on account of inclusion separation efficiency. Five different design of flow modifier (i.e. impact pad) systems are studied to find out the novel design for a given tundish system.
2. Mathematical modelling

Fig. 1 shows the schematic diagram of the numerical domain of a tundish whose bare capacity was 8 tons, assuming a transverse symmetry plane. The shroud diameter and its immersion height considered were 67 and 400 mm, respectively. The system considers a submerged entry nozzle (SEN) diameter which is 45 mm and with a stopper rod diameter of 120 mm. A dam is present in between the inlet shroud and outlet. The five cases have impact pads having variations in the shape and size.

![Schematic model and boundary conditions of a two strand tundish with different flow modifiers](image)

**Figure 1.** Schematic model and boundary conditions of a two strand tundish with different flow modifiers

2.1. Governing equations

The governing equations considered are the continuity, momentum and energy equations, to evaluate flow behaviour and inclusion trajectories.

- **Continuity equation:**
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
  \]

- **Momentum equation:**
  \[
  \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla P + \nabla \cdot [(\mu_t + \mu_r) \nabla \mathbf{u}] + F_{BY} \tag{2}
  \]

- **Energy equation:**
  \[
  \frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho \mathbf{u} T) = \nabla \cdot \left[ \left( \frac{k_t}{C_p} + \frac{\mu_t}{Pr_t} \right) \nabla T \right] \tag{3}
  \]

In equation 2, \( F_{BY} \) represents thermally induced buoyancy force term. The acceleration due to gravity \((g)\) acts along the negative direction of \(x\)-axis (Fig. 1). Reynolds Averaged Navier-Stokes (RANS) equation and the averaged continuity equation are solved for mean quantities of velocity and pressure. The standard \(k-\epsilon\) model of Launder and Spalding [8] is used as the closure equation, which is given as,
Kinetic energy:
\[ \frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho u k) = \nabla \cdot (G_k) + G - \rho \varepsilon \] (4)

Dissipation rate:
\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho u \varepsilon) = \nabla \cdot (G_\varepsilon) + \frac{\varepsilon}{k} (C_1 G - C_2 \rho \varepsilon) \] (5)

Where \( \mu_t = C_\mu \frac{\varepsilon^2}{C_\mu \frac{k^2}{\varepsilon}} \), \( \Gamma_k = \frac{\mu_{\text{eff}}}{\sigma_k} \) and \( \Gamma_\varepsilon = \frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \) are turbulent viscosity, diffusion coefficients for turbulent kinetic energy and its dissipation rate, respectively. \( \mu_{\text{eff}} \) is the effective viscosity given by \((\mu_t + \mu_r)\). The turbulent viscosity \((\mu_t)\) & generation term \(G\) in equation 4 is given,
\[ \mu_t = C_\mu \frac{k^2}{\varepsilon} \] (6)
\[ G = \mu_t \frac{\partial u_j}{\partial x_i} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \] (7)

The recommended values of the constants for the standard k-\(\varepsilon\) model are \(C_1 = 1.44, C_2 = 1.92, C_\mu = 0.09, \sigma_k = 1\) and \(\sigma_\varepsilon = 1.3\) as proposed by Launder and Spalding [8].

2.2. Tundish performance analysis

2.2.1. Residence time distribution (RTD). Residence time distribution (RTD) accounts the fraction of dead volume \((V_d)\), dispersed plug volume \((V_p)\) and mixed volume \((V_m)\) over a total tundish volume \((V)\). For efficient performance of any reactor, the dead volume fraction should be the least. In this study, the modified mixed model of Sahai and Emi [13] is adopted. In this technique, a tracer or pulse is added to the system and the response to this pulse is recorded, which gives a typical curve, known as \(C\) curve for a pulse. \(C\) curve is represented in the non-dimensional form, in which, the concentration is normalised on the basis of a uniform, well mixed concentration value, while corresponding residence times are normalised with respect to the nominal holding, or theoretical residence time as non-dimensional concentration \(C\) and non-dimensional time \(\Theta\), where \(V=\) volume of tundish liquid and \(\nu=\) volumetric flow rate of liquid.
\[ \Theta = \frac{t}{\bar{t}} = \left( \frac{V_d}{V} \right) \] (8)
\[ V_d = 1 - \theta_a \] (9)
\[ V_p = 1 - V_d - V_{dp} \] (11)
\[ V_m = 1 - V_a - V_{dp} \] (11)
\[ V = V_m + V_p + V_d \] (12)

From the \(C\) curve, dimensionless mean of RTD \(\bar{\Theta}\) & dimensionless variance is calculated as,
\[ \bar{\Theta} = \frac{\int_0^\infty \Theta C d\Theta}{\int_0^\infty C d\Theta} \] (13)
\[ \sigma^2 = \frac{\int_0^\infty (\Theta - \bar{\Theta})^2 C d\Theta}{\int_0^\infty \Theta C d\Theta} \] (14)

2.2.2. Inclusion separation model. Inclusion trajectories are calculated using Lagrangian particle tracking method [12], which solves a transport equation for each inclusion as it travels through the previously-calculated constant molten-steel flow field. The forces acting on a particle of mass \((m_p)\) are the drag force, the buoyancy force and the force due to added mass.
\[ \frac{d\vec{u}_p}{dt} = F_D(u - u_p) + \left( \frac{\rho_c - \rho}{\rho_c} \right) g \] (15)
\[ F_D = \frac{18 \mu_1 C_D Re}{24 \rho_c d_i^2} \] (16)

In equation 16, Reynolds number can be obtained as,
\[ Re = \frac{\rho d_c |u - u_p|}{\mu_t} \] (17)
\[ u'_p = \zeta_i \sqrt{U_p^2} = \zeta_i \sqrt{\frac{2k}{3}} \] (18)
The effect of the chaotic behaviour of non-metallic inclusions in the melt motion model is described by Discrete Random Walk model (DRW) called stochastic model. In this model, a random velocity vector \( (u'_p) \) is added to the calculated time-averaged vector \( (\bar{u}_p) \) to obtain the inclusion velocity \( (u_p) \) at each time step as it travels through the fluid. Each random component of the inclusion velocity is proportional to the local turbulent kinetic energy level \( (k) \).

The ratio of number of trapped inclusions to the total number of inclusions leaving the inlet shroud gives the separation efficiency in percentage, which can be calculated as,

\[
\eta = \frac{N_{in} - N_{out}}{N_{in}} \times 100
\]  

2.2.3. Initial and boundary conditions. Liquid steel is considered as a working medium inside the tundish. The inlet velocity and temperature of steel are considered as 0.423 m/s and 1823 K, respectively for the steady and the transient case. Pressure outlet condition is used for the outlet. The detailed boundary conditions are as shown in (Fig. 1). Radiative heat flux \( (q^r) \) is calculated by Stephan-Boltzmann equation considering tundish wall temperature of 1123 K.

At \( t = 0 \)

\[
F_i = 0
\]  

At inlet:

\[
u_{in} = 0.423\ m/s, T_{in,l} = 1823\ K, T_{in,g} = 318\ K
\]  

At outlet:

\[\nabla P = 0\]

At slag wall:

\[\text{Free surface: } \frac{\partial u_{x,t}}{\partial y} = 0 \text{ and } \frac{\partial u_{x,t}}{\partial z} = 0, q^r = 26\ kW/m^2\]

At side walls:

\[\text{No slip condition: } u_i = 0, q^r = 26\ kW/m^2\]

At symmetry plane:

\[
\frac{\partial u}{\partial y} = 0 \text{ and } \frac{\partial T}{\partial y} = 0
\]

For steady state, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used for pressure–velocity coupling [12]. Commercial software ANSYS FLUENT 14 is used to solve the governing equations along with initial and boundary conditions. The coefficients in momentum and \( k-c \) equations are calculated using the second order upwind scheme. The turbulence intensity & convergence criteria are taken as 5\% & \( 1 \times 10^{-7} \).

Table 1. Thermo physical properties of liquid steel and air used in the numerical analyses

| Properties       | Liquid steel | Air       |
|------------------|--------------|-----------|
| \( \rho \) (kg/m\(^2\)) | 7010         | 1.225     |
| \( C_p \) (J/kg-K) | 821          | 1006.43   |
| \( k \) (W/m.K)   | 30.5         | 0.0242    |
| \( \mu \) (kg/m.s) | 0.00648      | 0.000178  |

3. Results and discussions

3.1. Residence time distribution (RTD)

Fluid flow in tundish is typically characterized by residence time distribution (RTD) curves. The RTD is frequently plotted as dimensionless concentration versus dimensionless time. This information is
graphed as a function of time with respect to tracer concentration that provides the RTD curve, which is also commonly known as a C curve. The plug flow fraction is defined by the advent of the first injected tracer volume at the tundish outlet nozzle. The mixed also called dispersed volume is indicated by the tail of the C curve, viz. from the apex to the time defined as 2Θ. Dead flow in RTD curves is generally defined as the portion of the injected tracer persisting beyond 2Θ. It can be noted from the (Fig. 2) & (Table 2) that, in terms of least dead volume fraction, Case 3 is the most efficient model amongst all design. The highest dispersed plug flow volume fraction is obtained for case 5.

![Figure 2. C Curve for (a) case 1, (b) case 2, (c) case 3, (d) case 4 & (e) case 5](image)

### 3.2. Dead volume, dispersed plug flow volume, mixed volume and Inclusion separation efficiency

To study the performance of various flow modifiers based on the RTD curves based on modified mixed model of Sahai and Emi [13] are tabulated in Table 2. The highest dispersed plug flow volume fraction is obtained for case 5.

| Design  | Dead volume fraction | Dispersed plug flow volume fraction | Mixed volume fraction |
|---------|----------------------|-------------------------------------|-----------------------|
| Case 1  | 0.564                | 0.096                               | 0.34                  |
| Case 2  | 0.532                | 0.091                               | 0.378                 |
| Case 3  | 0.485                | 0.097                               | 0.416                 |
| Case 4  | 0.564                | 0.096                               | 0.34                  |

Inclusion separation efficiency for different cases is performed using discrete phase model (DPM). The size of the inclusions varies from 1 to 100 μm. High Alumina (Al₂O₃) containing 94-96% aluminium oxide with density of 3960 kg/m³ is chosen as an inclusion material. For tracking inclusion trajectories, trap boundary condition is used for the slag wall. Stochastic tracking (random walk) model is used to predict the dispersion of inclusion. Table 3 shows the effect of flow modifiers on inclusion removal efficiency of the tundish.

The various sizes of inclusion diameter are analysed by which it can be noted that the highest separation efficiency is achieved for case 5. The important part is the effectiveness of this design in separating micro inclusions (<50 μm), which ultimately determines the steel quality. These effects can reduce the inclusion separation efficiency by 10% from those obtained in real situations.
| Inclusion diameter (µm) | Inclusion separation efficiency (%) |
|------------------------|-------------------------------------|
|                        | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| 1                      | 36.04  | 40.82  | 46.52  | 47.32  | 62.51  |
| 10                     | 36.14  | 41.67  | 47.55  | 48.79  | 63.29  |
| 20                     | 41.67  | 44.71  | 49.77  | 50.52  | 67.74  |
| 30                     | 53.47  | 49.04  | 55.81  | 56     | 66.52  |
| 40                     | 66.04  | 58.94  | 62.14  | 63.97  | 69.24  |
| 50                     | 72.32  | 68.86  | 70.91  | 71.13  | 73.33  |
| 60                     | 77.22  | 74.81  | 77.71  | 75.77  | 77.43  |
| 70                     | 80.79  | 80.48  | 81.97  | 79.67  | 81.81  |
| 80                     | 83.03  | 84.31  | 83.67  | 83.43  | 86.17  |
| 90                     | 87.18  | 88.74  | 87.66  | 87.08  | 90.29  |
| 100                    | 89.16  | 92.24  | 90.68  | 90     | 92.9   |

4. Conclusion
A detailed numerical analysis of tundish with different flow modifier is performed to study the effect of different flow modifiers on the fluid flow characteristics under non-isothermal conditions. Different heights of flow modifiers and wide range of inclusion sizes are considered to assess their effects on the inclusion removal efficiency inside the tundish. The use of dam, round and short impact pads is not recommended, as it results in very low values of micro inclusion separation efficiency. Height variations in short box type impact pad from height of 0.1 to 0.2 m yields better results in removal of inclusion. It is found that the long modified box type turbulence inhibitor/impact pad arrangement (case 5) gives the best solution considering all the performance aspects, namely RTD, inclusion separation and temperature variation inside a tundish. The findings obtained in the present study could be used to formulate the guidelines for designing efficient tundish in steel industries.

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