Numerical Investigation of Fluid Flow Phenomenon in a Curved Shape Tundish of Billet Caster

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The conventional delta shaped tundish (rectangular with sloping walls) is currently used in many industries for billet caster. The effective volume in this type of tundish is significantly low and results in a lower quality of steel. In the present work, a three-dimensional mathematical model has been used to study the fluid flow characteristics in a six strand billet caster tundish whose one side is curved. The results obtained were compared with a conventional delta shaped tundish and the strong role of curvature in modifying the fluid flow characteristics is noticed. Investigations were performed to study the effect of ladle pouring point in a curved shape tundish. It was found that fluid flow characteristics can be improved by placing the ladle pouring point at the right position. Simulations have been performed for two different shapes of pouring chamber to investigate the role of curvature in the flow control devices. The results obtained confirmed the strong role of curvature to get the improved characteristics for inclusion flotation. The mathematical model has been validated by the experimental results of Singh and Koria for a single strand bare tundish.

KEY WORDS: billet caster tundish; pouring chamber; plug volume; mean residence time; inclusion flotation.

1. Introduction

Continuous casters in modern days are expected to be high productivity machines that produce quality products with least possible defects or inclusions. Tundish is an intermediate vessel in continuous casting placed between the ladle and the mould, designed to supply and distributes molten steel to the various moulds in a multi-strand machine. The population of inclusion and their size distribution exert profound influences on finished steel products. Ahuja and Sahai have postulated that to achieve maximum inclusion separation ratio, there should be a minimum spread of residence time, large ratio of plug to dead volume, relatively large ratio of plug to mixed volume, surface directed flow, and contained region of mixing.1,2)

Researchers in the past have investigated the fluid flow behaviour using physical and mathematical modelling6,7,11,13) in a single strand tundish. They have come up with the various designs of tundish, such as rectangular tundish, tundish with sloping sides, L-shape tundish etc. There have been many studies reported in the literature about the effect of operating parameters as well as various flow modifiers on RTD values in such type of tundishes, which exert considerable influence on the efficiency of inclusion separation.3,4,5) Investigations are currently going on for the efficient design of the multistrand tundish for billet caster. Delta shaped tundish (rectangular with sloping walls) is currently used in many industries. This tundish is bigger in size and has large fraction of dead volume, which is not desired for inclusion flotation. The studies reported in the literature for multistrand tundish have used delta shaped tundish for there investigation.8) In this paper, investigations were performed for billet caster tundish whose one side is curved and results were compared with the existing delta shaped tundish. It was felt that ladle pouring point may have a role in modifying the fluid flow characteristics. Thus, investigation was performed to study the effect of ladle pouring point on the fluid flow characteristics in this type of tundish. The role of curvature in flow control devices was not found in the literature, but it can be possible to improve the fluid flow characteristics by giving the curved shape to the pouring chamber. Thus, it was decided to explore the effect of shapes of pouring chamber on fluid flow characteristics. The pouring chamber developed by Foseco is used for simulation.

2. Model Development

2.1. Geometrical Description

Simulations were performed for the symmetrical half of different shapes of tundishes. Table 1 shows the no. of combination for which the simulation was performed. Figure 1(a) shows the top view of the symmetrical half of curved shape billet caster tundish, while the top view of the delta shaped tundish can be seen from Fig. 1(b). Simulation was also performed for two modified shape of delta shaped tundish to explain the mechanism of curved shape effect on fluid flow characteristics. Figures 1(c) and 1(d) show the top view of this modified tundish. The dimensions of the tundish shown in the Fig. 1(a) are same for all the tundish. Figure 1(a) also shows the three position of ladle pouring points for which the simulations have been performed. The
Table 1. Simulation performed for following cases.

<table>
<thead>
<tr>
<th>Number of Simulation</th>
<th>Shape of Tundish</th>
<th>Shape of Pouring Chamber</th>
<th>Position of Ladle Pouring Point (as shown in Fig 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Curved shape</td>
<td>Contour shape</td>
<td>Position 1</td>
</tr>
<tr>
<td>2</td>
<td>Curved shape</td>
<td>Sharp corner</td>
<td>Position 1</td>
</tr>
<tr>
<td>3</td>
<td>Curved shape</td>
<td>Contour shape</td>
<td>Position 2</td>
</tr>
<tr>
<td>4</td>
<td>Curved shape</td>
<td>Contour shape</td>
<td>Position 3</td>
</tr>
<tr>
<td>5</td>
<td>Delta shape with one angled corner around symmetrical plane</td>
<td>Contour shape</td>
<td>Position 1</td>
</tr>
<tr>
<td>6</td>
<td>Delta shape with straight corner around symmetrical plane</td>
<td>Contour shape</td>
<td>Position 1</td>
</tr>
<tr>
<td>7</td>
<td>Delta shape with straight corners and one side bent in the middle</td>
<td>Contour shape</td>
<td>Position 1</td>
</tr>
</tbody>
</table>

Fig. 1(a). Top view of the curved shape tundish about the symmetry plane with all the position of ladle pouring point (all dimensions are in mm).

Fig. 1(b). Top view of the delta shape tundish about symmetry plane for position-1 of ladle pouring point at position-1 (dimensions are similar to curved shape tundish shown in Fig. 1(a)).

Fig. 1(c). Top view of the delta shape tundish in Case 6 of Table 1 for position-1 of ladle pouring point (dimensions are similar to curved shape tundish shown in Fig. 1(a)).

distance between two ladle pouring points are 200 mm. Table 2 shows all other operating parameters of the tundish. Two different shapes of flow control devices called Pouring chamber were used for the study. Figures 2(a) and 2(b) show the top and sectional view of contour shape pouring chamber, respectively. Top and sectional view of the sharp corner pouring chamber can be seen from Figs. 3(a) and 3(b), respectively.

2.2. Mathematical Formulation and Assumptions

The flow field in the tundish was computed by solving the continuity and momentum conservation equation in
three-dimensional. The standard $k$–$\varepsilon$ model was solved to incorporate the turbulence near the incoming and outgoing stream. The free surface of the liquid in the tundish was assumed to be flat and the slag depth was considered to be insignificant. Natural convection effect was neglected while computing the velocity field. The equation for dispersion of tracer in the tundish was solved to capture the variation of tracer concentration in the tundish and then RTD analysis was performed. Table 3 shows the expression for the RTD characteristics.

### Governing Equations

**Continuity:**

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

**Momentum equation:**

$$\rho \frac{D\overline{U}_i}{Dt} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} (\tau_{ij}^{\text{L}} + \tau_{ij}^{\text{R}}) + \rho \overline{u}_i \quad \text{(2)}$$

Where, laminar shear stress, $\tau_{ij}^{\text{L}}$ is given by

$$\tau_{ij}^{\text{L}} = -\mu_{ij} \left( \frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \quad \text{(3)}$$

and Reynolds shear stress, $\tau_{ij}^{\text{R}}$ is expressed as

$$\tau_{ij}^{\text{R}} = -\rho \overline{u}_i' u_j' = -\mu_{ij} \left( \frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \quad \text{(4)}$$

Here $\overline{U}_i$ is the $i$th component velocity vector, and $i, j$ vary for $x, y, z$ direction.

#### Tracer dispersion

$$\rho \frac{\partial \overline{C}}{\partial t} + \rho (\overline{U}_i \overline{C}) \frac{\partial \overline{C}}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\mu_{\text{eff}}}{\sigma_{\overline{C}}} \frac{\partial \overline{C}}{\partial x_j} \right) \quad \text{(5)}$$

**Turbulent kinetic energy:**

$$\rho \frac{Dk}{Dt} = D_k + G - \rho \varepsilon \quad \text{(6)}$$

**Rate of dissipation:**

$$\rho \frac{De}{Dt} = D_e + C_i G \frac{\varepsilon}{k} \quad \text{(7)}$$

Where,

$$D_{\phi} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_{ij}}{\sigma_{\phi}} \right) \frac{\partial \phi}{\partial x_j} \right] \quad \text{(8)}$$

Here $\phi$ is $k$ for (6) and $\varepsilon$ for (7)

$$\mu_{ij} = \rho C_{\mu} \frac{k^2}{\varepsilon} \quad \text{and} \quad G = \tau_{ij} \frac{\partial \overline{U}_i}{\partial x_j} \quad \text{(9)}$$

Here, $C_i = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_{\overline{C}} = 1$, $\sigma_{k} = 1$, $\sigma_{\varepsilon} = 1.3$.

### Boundary Conditions

The boundary conditions for the momentum and the continuity equations can be easily visualised by referring to Fig. 1(a). No-slip condition was set for all the walls of the tundish and the standard wall function was used to incorporate the variation due to turbulence. Symmetry boundary condition was applied at the symmetry plane, which implies a zero gradient condition for all the variables normal to that plane. Inlet velocity of 2 m/s was set for the incoming jet with a turbulent intensity of 2%. Zero shear stress boundary condition was applied for the free surface of the tundish according to references. Pressure boundary condition of 1 atm was fixed at the outlets of the tundish. The tracer concentration was considered to be impervious for the walls of the tundish, hence a zero gradient or flux boundary condition was applied on the walls for the tracer dispersion equation. Zero gradient condition for the tracer was also applied at the free surface and the outlets of the tundish. Mass fraction of tracer at the inlet was set to 0.11 till 1.2 s, after which it was kept to zero. 1.2 s is very small as compared to the mean residence time of the tundish, and thus the influx of the tracer is not expected to affect the local velocity field. This inlet boundary condition of tracer mass fraction was...
decided based on the procedure of tracer injection adopted by Singh and Koria,\(^3,5\) while carrying out the experiment for a slab caster tundish.

2.4. Numerical Procedure

The set of governing equations were discretized using the finite volume technique in a computational domain and solved with the help of above boundary conditions using commercial CFD package (FLUENT). Second order upwind scheme was used for discretization of convective term in the governing equations to provide higher order accuracy. SIMPLE (Semi-Implicit Method for the Pressure-Linked Equations) algorithm was used to resolve the pressure–velocity coupling in the momentum equation. Momentum equation with turbulence was first solved for the steady state to get the velocity field, and then the tracer dispersion equation was solved for unsteady state with momentum and turbulence equations to get the RTD curve. The validation of RTD with the experiments of Singh and Koria is presented in the next section. The density and viscosity of molten steel was kept constant at 7 100 kg/m\(^3\) and 0.006482 kg/m·s respectively, throughout the computational domain.

3. Model Validation

The experimental results for six-strand billet caster tundish were not available in the literature. Thus experimental validation of the computational method was established with the experiment of Singh and Koria\(^4\) for a bare tundish with one inlet and outlet. Table 4 shows the dimensions and operating parameters of tundish, used for validation. It was observed by Singh and Koria that after the injection of the dye, an intense colour patch advanced straight towards the tundish nozzle. This colour patch reached the tundish exit at 30 s and remaining colour dye continued to be dispersed in all other directions. According to them, this phenomenon represents the short circuiting which resulted in two peaks in the RTD curve as shown in Fig. 4.

This phenomenon of short-circuiting was also captured by the computation. Figures 5(a) and 5(b) show the contour of tracer concentration on the bottom plane (that is at \(Y=0.05 H\), where \(H\) is the bath height of the tundish) at 30 s and 55 s, respectively. It can be clearly seen that a region of high concentration of tracer advances towards the exit and reaches there at 55 s. The two peaks in the RTD curve for experiment in Fig. 4 were also captured by the computation, but there is a delay in \(t_{\text{min}}\) and \(t_{\text{peak}}\). The matching between experiments and computations is satisfactory, considering the complexity of turbulent model that was used for computation. However, the idea of discretization schemes and the convergence criteria was made from this comparison.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base length (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>Width (mm)</td>
<td>310</td>
</tr>
<tr>
<td>3</td>
<td>Bath height (mm)</td>
<td>260</td>
</tr>
<tr>
<td>4</td>
<td>Shroud diameter (mm)</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Submergence depth (mm)</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Volumetric flow rate (m(^3)/sec)</td>
<td>1.55 × 10(^4)</td>
</tr>
</tbody>
</table>

Table 4. Operating parameters of slab caster tundish which was used for model validation.\(^4\)

![Fig. 4. Comparison of RTD curve for bare tundish with one outlet (used by Singh and Koria) obtained by experiment and with computation.](image)

![Fig. 5(a). Contour of tracer concentration on horizontal plane \((Y=0.05H)\) at 30 s for slab caster tundish used for validation.](image)

![Fig. 5(b). Contour of tracer concentration on horizontal plane \((Y=0.05H)\) at 55 s for slab caster tundish used for validation.](image)
4. Results and Discussion

The flow field obtained by solving the momentum and continuity equation is analysed and correlated with the RTD characteristics. It was felt that curvature may have a strong role in modifying the fluid flow characteristics. The results of RTD were compared for the two shapes of tundish by studying the ratio of the plug to the dead volume. The analysis of the plug to the dead volume ratio was also done for different pouring points and different shapes of pouring chamber. Simulations results are presented in a sequence.

4.1. Comparison of Different Shapes of Tundish

Simulations were performed for two different shapes of tundish shown in Figs. 1(a) and 1(b). The effect of curvature can make the flow slow and smooth and can reduce the turbulence near the inlet stream. The motivation behind this work was to get the desirable fluid flow characteristics with lesser volume of tundish. The volume of tundish in Fig. 1(b) is more as compared to curved shape tundish in Fig. 1(a) because of larger width of delta shaped tundish. It was found from the RTD analysis that even though the volume of delta shaped tundish is more, but its mean residence time is less as compared to the curved shape tundish. This results in the large fraction of the dead volume for delta shaped tundish. Table 5 shows the comparison of the plug, dead and mixed volumes for two types of tundishes. Figures 6(a) and 6(b) show the RTD curve for two tundishes, which is plotted between dimensionless concentration and dimensionless time. The dimensionless concentration was obtained by dividing the concentration \( C_i \) by \( Q/V \), where \( Q \) is the amount of tracer added and \( V \) is the volume of the tundish. It can be seen from Fig. 6(a) that there is only one peak in the RTD curves for all the outlets of curved shape tundish. The RTD curve for delta shaped tundish in Fig. 6(b) has more than one peak from all the outlets. This reflects the presence of short-circuiting from all the outlets in delta shape tundish. Thus, the extent of short-circuiting is less in curved shape tundish as compared to delta shape tundish.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>RTD characteristics</th>
<th>Delta shape tundish with contour Pouring chamber</th>
<th>Curved shape tundish with contour Pouring chamber</th>
<th>Curved shape tundish with sharp corner Pouring chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean residence time (sec)</td>
<td>476</td>
<td>529</td>
<td>481</td>
</tr>
<tr>
<td>2</td>
<td>( V_{PL} )</td>
<td>0.02</td>
<td>0.29</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>( V_{DC} )</td>
<td>0.57</td>
<td>0.52</td>
<td>0.69</td>
</tr>
<tr>
<td>4</td>
<td>( V_{OV} )</td>
<td>0.41</td>
<td>0.19</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 5. Comparison of RTD characteristics for three different type of cases.

Fig. 6(a). RTD curve for a curved shape tundish for position-1 of ladle pouring point.

Fig. 6(b). RTD curve for a delta shape tundish for position-1 of ladle pouring point.
to delta shaped tundish. This is because of the large width of the delta shaped tundish, consistent with the findings of Singh and Koria that wider tundish results in a short-circuiting.3)

It can be seen from Table 5 that the ratio of plug to mixed volume is much higher for the curved shape tundish. The reason for this can be explained by referring to Figs. 7(a) and 7(b) which show the velocity vector plot for the two tundishes at vertical cross-section plane containing the outlets. It can be seen from Fig. 7(a) for curved shape tundish that velocity vectors are straight and flow gradually moves from outlet 1 to outlet 3. The flow field in Fig. 7(b) for delta shaped tundish is divided into two strong recirculation cells. Due to strong recirculation cells, the ratio of mixed volume is more for the delta shaped tundish. Table 5 also shows the large fraction of dead volume for delta shaped tundish as compared to the curved shape tundish, due to the stagnant zone formed in the former. The velocity field for the horizontal plane just below the top surface (at $Y = 0.95H$, where $H$ is the bath height) in Figs. 8(a) and 8(b) explain it more clearly. The flow filed in Fig. 8(a) for curved shape tundish is smoother and gradual as compared to the delta shaped tundish. Thus, the volume is used more efficiently in such type of tundish. The flow field in Fig. 8(b) shows the formation of small circulation cells at the centre of the plane which increases the dead volume. These circulation cells were formed by the collision of the two streams coming from opposite direction.

The reason for slow flow in the curved shape tundish is the large contact surface area for the fluid inside this tundish. This phenomenon of curved shape is explained by performing some more simulations for modified shape of delta shaped tundish. This modified shape results in the increase of the contact area of fluid with tundish wall. All other parameters are fixed on the same value, as for earlier simulation. Figures 8(c) and 8(d) show the flow field on the plane just below the top surface for these two tundish. It can be seen from these figures that the flow expands and circulate above outlet 1 as the volume of tundish above outlets 2 and 3 is reduced. Thus, the flow is captured and made circulatory above outlet 1 by compressing the volume above outlets 2 and 3. It can be further seen from Fig. 8(a) that curved shape is making the flow more circulatory above outlet 1. This phenomenon of circulatory flow increases the path of the fluid and thus results in a momentum loss. This results in increase of the plug flow.
4.2. Effect of Ladle Pouring Point

It has been seen from the above that curved shape tundish has better fluid flow characteristics for inclusion flotation as compared to the delta shaped tundish. Figure 6(a) and Figs. 9(a), 9(b) show the RTD curve for position-1, 2 and 3 of ladle pouring point, respectively. It can be seen that as the ladle pouring point is shifted towards the outlet (i.e. the distance between the inlet and the outlet reduces), the number of peaks in the RTD curve increases. Figures 10(a) and 10(b) show the variation of residence time and the ratio of the plug to dead volume with respect to the perpendicular distance between inlet and the outlet. The residence time and plug volume are more for position-1 and decreases sharply between position-1 and 2, while it decreases slowly between position-2 and 3. Since the variation between the position-2 and 3 was slow, hence it was decided to carry out simulation for some more positions between position-2 and 3. It was found that both the ratio of plug to dead volume and residence time becomes constant while reaching near position-3. This can be explained more clearly by analyzing the flow behaviour at different planes for all the three positions of ladle pouring point. Velocity field for different positions are discussed below:

4.2.1. Position-1

Position-1 of ladle pouring point shown in Fig. 1(a) is at the left corner of the pouring chamber, which is near the curved wall of the tundish. Figure 11(a) shows velocity field at symmetrical plane (at \( X = L \), where \( L \) is the length of symmetrical half of tundish) for position-1. The incoming jet stream in Fig. 11(a) strikes the pad of the pouring chamber, rises up and expands towards the right side of the tundish (i.e. opposite to the curved wall). It looses the momentum, while rising and expanding. The flow field separates into two streams after reaching the top surface, due to the effect of wall shear stress and decrease in the inertial force. Figure 11(b) shows the flow field at the top surface (i.e. at \( Y = H \)). It can be seen that the flow vectors in this flow field originates from a point (called origin point in this paper) which is farther from curved wall. Thus, the flow vector which expands opposite to the curved wall strikes the wall faster and turns towards outlet 2, as compared to the vectors moving towards the curved wall. This in turn compresses the flow vector which expands in the direction of curved wall and reverses its direction. The magnitude of the velocity vector becomes almost negligible between outlet 2 and outlet 3. This is the reason for the large difference in \( t_{\text{min}} \) for the outlet 2 and outlet 3 as shown in RTD curve.
Fig. 10(a). Variation of mean residence time with perpendicular distance between inlet and outlet for curved shape tundish.

Fig. 10(b). Variation of ratio of plug to dead volume with perpendicular distance between inlet and outlet for curved shape tundish.

Fig. 11(a). Velocity field at the symmetrical plane (X=L) for the position-1 of ladle pouring point in a curved shape tundish with $V_{max}=0.2 \text{ m/s}$.

Fig. 11(b). Velocity field at the horizontal top surface (Y=H) for the position-1 of ladle pouring point in a curved shape tundish with $V_{max}=0.05 \text{ m/s}$.

Fig. 12(a). Velocity field at the symmetrical plane (X=L) for the position-2 of ladle pouring point in a curved shape tundish with $V_{max}=0.5 \text{ m/s}$.

Fig. 12(b). Velocity field at the top surface (Y=H) for the position-2 of ladle pouring point in a curved shape tundish with $V_{max}=0.15 \text{ m/s}$.
in Fig. 6(a) for this Position. This result in a large plug volume compared to other Positions.

4.2.2. Position-2

Ladle pouring point is at the middle of the pouring chamber for this Position. Flow field for the symmetrical plane is shown in Fig. 12(a). Unlike position-1, the jet stream in this case after striking the pad rises and expands in both the directions. The circulation cells formed on both sides of the shroud can be seen from Fig. 12(a). The circulation cell formed on left side of the shroud is smaller than the cell formed on the right side. This is due to the smaller space between shroud and curved wall as compared to the space on the other side. These circulation cells enhance the velocity of the flow stream passing over it. Figure 12(b) shows that flow vectors at the top surface (i.e. at \( Y = H \)) which expands in both the directions. The origin point of the flow vectors in this case coincides with the position of ladle pouring point and is nearer to the curved wall. Thus, the flow vectors in the direction of curved wall strikes the wall faster than the vectors moving opposite to the curved wall. These flow vectors follow the path of curvature before moving towards the space above outlet 2. This gives extra time to the flow vectors expanding in opposite direction of curved wall, to strike the wall and turn towards the outlet 2 before being compressed by the vectors from the other side.

Thus, the flow vector in this case moves straight with higher magnitude of velocity as compared to the position-1 where the flow returns backward. This is the reason for decrease in the ratio of plug to dead volume as compared to position-1.

4.2.3. Position-3

This position of ladle pouring point is at the right corner of the pouring chamber and closest to the outlet, exactly opposite to the position-1 (w.r.t Pouring chamber). It can be seen from Fig. 13(a) that liquid steel after striking the pad, rises up and expands in a gap between the pouring chamber and the curved wall. The circulation cell formed between the left side of the pouring chamber and the curved wall can be seen from Fig. 13(a). This circulation cell enhances the momentum of flow stream passing over it. The origin point for this position is nearer to the corner of the curved wall as shown in Fig. 13(b). Thus, the flow stream expands only in one direction. The magnitude of velocity vectors are more for this position as compared to the other two positions. The velocity vectors above outlets 2 and 3 have higher magnitude as compared to other positions. Thus, the straight flow and high magnitude of the velocity throughout the domain results in a short-circuiting and low ratio of plug to dead volume.
4.3. Comparison of Different Shapes of Pouring Chamber

Simulations were also performed to study the effect of the shapes of the pouring chamber on the fluid flow characteristics in a curved shape tundish. Figures 2 and 3 shows the two different shapes of pouring chamber chosen for simulation. Operating parameters were fixed at values similar to the previous cases and ladle pouring point is placed at position-1 for present simulation. The comparison of RTD curve for contour and sharp corner pouring chamber can be seen from Fig. 14(a). It can be easily concluded by comparing these RTD curves that short-circuiting increases for the sharp corner pouring chamber. The considerable fall in the value of $t_{\text{max}}$ for all the outlets can be noted from Fig. 14(a). The straight flow can be seen from velocity field in Fig. 14(c). Figure 14(b) shows the velocity field in symmetrical plane. This results in a low ratio of plug to dead volume for sharp corner pouring chamber, as shown in Table 5. Thus, the role of contour shape pouring chamber in making the circulatory flow above outlet 1 is established.

5. Conclusion

Mathematical model was developed to study the fluid flow characteristics for better inclusion flotation in present work. The following conclusions were drawn from the study:

1) It was found that the curvature has a strong role in modifying the fluid flow characteristics.
2) Simulation performed shows that curved shape tundish has an advantage over delta shaped tundish. It can give better fluid flow characteristics with less volume.
3) The study performed for the ladle pouring point shows that flow can be made circulatory above outlet 1 by changing the position of ladle pouring point. Thus, plug volume can be increased.
4) The effect of shapes of the pouring chamber on fluid flow characteristics was studied for curved shape tundish. The considerable increase in the plug volume and the mean residence time for contour shape pouring chamber is noted.
5) It can be concluded that curved shape tundish with smaller volume can replace delta shaped tundish of larger volume.

**Nomenclature**

- $C$: Mass fraction of the injected tracer
- $C_{\text{av}}$: Average concentration of tracer from ith outlet
- $H$: Bath height of the tundish
- $L$: Length of half tundish
- $k$: Turbulent kinetic energy
- $P$: Pressure
- RTD: Residence time distribution
- $t$: Time
- $t_{\text{av}}$: Actual mean residence time
- $t_{\text{max}}$: Maximum breakthrough time
- $t_{\text{m}}$: Theoretical mean residence time
- $U$: Velocity
- $u'$: Velocity fluctuation
- $V$: Volume

**Greek symbols**

- $\rho$: Density of steel
- $\mu$: Molecular viscosity of steel
- $\mu_{\text{t}}$: Turbulent viscosity of steel
- $\mu_{\text{eff}}$: Effective viscosity of steel
- $\nu_{\text{t}}$: Turbulent Schmidt number
- $\varepsilon$: Rate of dissipation of turbulent kinetic energy
- $\tau$: Laminar shear stress
- $\tau^*$: Turbulent shear stress

**Suffix**

- $i, j, k$: Three Cartesian co-ordinate directions $x, y$ and $z$
- DV: Dead volume
- MV: Mixed volume
- PV: Plug volume

**REFERENCES**