Effect of Shape and Flow Control Devices on the Fluid Flow Characteristics in Three Different Industrial Six Strand Billet Caster Tundish

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Fluid flow phenomenon in a tundish depends upon the shape of tundish. The change in the shapes can bring drastic change in the flow pattern and thus effect the fluid flow characteristics in the tundish. The significant effect of flow control devices on fluid flow phenomenon is also noticed. In the present work, investigation of fluid flow phenomenon was performed for the symmetrical half of a six strand tundish. Fluid flow pattern gets altered by changing the shapes of tundish and pouring chamber. The impact of this change results in a development of various flow patterns. These flow patterns are analysed for capturing the better 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

A six-strand billet caster tundish presents various challenges such as being able to maintain the same casting temperature, homogenous chemistry and similar steel cleanliness in every strand. These challenges make the fluid flow phenomenon in a six-strand tundish more complex. Investigations are currently going on to understand the complexity involved in this type of tundish. The different types of flow patterns were generated by the investigators.^{1–3)}

The understanding of the fluid flow phenomenon is required for designing the effective flow control system and tundish. The flow behaviour inside the six-strand tundish can be understood by analysing the different sets of hypothetical flow patterns. The fluid flow characteristics were derived by performing the RTD analysis for these flow patterns. Ahuja and Sahai have postulated that to achieve desired fluid flow characteristics, 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.⁴⁾

In the present paper, the sets of flow pattern were developed by changing the shape and dimensions of tundish and pouring chamber. These flow patterns were generated by performing the CFD simulations. The flow patterns were analysed and studied to conclude the desired characteristics for the fluid flow in the six-strand tundish. The objective of the current work is to compare and analyse the flow behaviour developed by using different combinations of shape of tundish and flow control devices used in one of the actual plants.

2. Model Development

2.1. Geometrical Description

Simulations were performed for the symmetrical half of three sets of industrial tundishes and flow control devices.

Fig. 1. Schematic top view of Tundish 1, Tundish 2 and Tundish 3 (all dimensions in m).

Fig. 2. (a) Top and sectional view of Pouring Chamber 1 (all dimensions in m). (b) Top and sectional view of symmetrical half of Pouring Chamber 2 (all dimensions in m). (c) Pictorial view of pouring chamber 1. (d) Pictorial view of pouring chamber 2.

These sets of tundishes are named as tundish 1, tundish 2 and tundish 3 in this paper. The flow control devices are known as pouring chamber 1 and pouring chamber 2. The schematic top view with dimensions of all tundishes can be seen from **Fig. 1**. The distance between the outlets is more for tundish 3 as compared to tundish 1 and tundish 2. The top and sectional view of pouring chamber 1 and 2 with dimensions can be seen from **Figs. 2(a)** and **2(b)**. The presence of cylindrical rod shape structure at the inside surface can be visualised from top view in **Fig. 2(b)**. **Figures 2(c)** and **2(d)** shows the pictorial view of the pouring chamber. **Table 1** show the cases investigated by performing the CFD simulation. The operating parameters for tundish 1, tundish 2 and tundish 3 can be seen from **Table 2**.

2.2. Governing Equations

The mathematical model with assumptions for multi-

Table 1. Sets of simulation performed.

S. No.	Cases	Tundish	Pouring Chamber	Strand to Strand distance (m)	Throughput (ton/min)
1	Case 1	Tundish 1	Pouring Chamber 2	1.1	3.7
2	Case 2	Tundish 2	Pouring Chamber 1	1.1	3.9
3	Case 3	Tundish 3	Pouring Chamber 2	1.25	3.8
4	Case 4	Tundish 1	Pouring Chamber 2	1.1	2.2
5	Case 5	Tundish 2	Pouring Chamber 1	1.1	2.4
6	Case 6	Tundish 3	Pouring Chamber 2	1.25	2.3
7	Case 7	Tundish 3	Pouring Chamber 2	1.1	3.8

Table 2. Operating parameters of all the three tundishes.

S. No.	Parameters	Values					
		Tundish 1	Tundish 2	Tundish 3	Tundish 1	Tundish 2	Tundish 3
1	Throughput (ton/min)	3.7	3.9	3.8	2.2	2.4	2.3
2	Bath height (in mm)	750	850	800	750	850	800
3	Submergence depth of shroud (in mm)	400	400	400	400	400	400
4	Inlet velocity (in m/s)	2.48	2.64	2.56	1.48	1.58	1.53
5	Shroud diameter (in mm)	67	67	67	67	67	67
6	Outlet nozzle diameter (in mm)	22	22	22	17	17	17

Table 3. Expression for RTD characteristics.

S. No	RTD Characteristics	Expressions
1	Theoretical residence time (t_r)	volume of tundish/volumetric flow rate
2	Actual mean residence time (t_m)	$t_m = \frac{\sum C_{av_i} t \Delta t}{\sum C_{av_i} \Delta t}$ i = 1, 2, and 3 (for the three outlets)
3	Average break through time (t_{min})	First appearance of tracer at the outlet (time was averaged for all the three outlets)
4	Fraction of plug volume (V_{PV})	$V_{PV} = t_{min}/t_r$
5	Dispersed plug volume (V_{DPV})	$V_{DPV} = (t_{min} + t_{peak})/t_r$
6	Fraction of dead volume (V_{DV})	$V_{DV} = 1 - t_m/t_r$
7	Fraction of mixed volume (V_{MV})	$V_{MV} = 1 - V_{PV} - V_{DV}$

strand tundish is already published in our previous paper.³⁾

The same model is applied for the present work. The expression for the RTD characteristics can be noted from **Table 3**. The equations solved are mentioned below:

Continuity:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad \text{..... (1)}$$

Momentum equation:

$$\rho \frac{D\bar{U}_i}{Dt} = -\frac{\partial \bar{P}}{\partial x_i} - \frac{\partial}{\partial x_j} (\tau_{ij}^l + \tau_{ij}^t) + g_i (\rho - \rho_0) \quad \text{..... (2)}$$

Where, laminar shear stress, τ_{ij}^l is given by

$$\tau_{ij}^l = -\mu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \quad \text{..... (3)}$$

and Reynolds shear stress, τ_{ij}^t is expressed as

$$\tau_{ij}^t = -\overline{\rho u_i' u_j'} = -\mu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \quad \text{..... (4)}$$

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

Tracer dispersion:

$$\rho \frac{\partial \bar{C}}{\partial t} + \rho \frac{\partial (\bar{U}_i \bar{C})}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\mu_{eff}}{\sigma_c} \frac{\partial \bar{C}}{\partial x_i} \right) \quad \text{..... (5)}$$

Turbulent Kinetic energy:

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

Rate of dissipation:

$$\rho \frac{D\varepsilon}{Dt} = D_\varepsilon + C_1 G \frac{\varepsilon}{k} - C_2 \rho \frac{\varepsilon^2}{k} \quad \text{..... (7)}$$

Where,

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

Here ϕ is k for (6) and ε for (7)

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

Here, $C_1 = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_c = 1$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.3$

2.3. Boundary Conditions

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 mentioned in Table 2 corresponding to throughputs is set at inlet. The turbulent boundary condition is set by defining a turbulent intensity of 2% for the incoming jet. Zero shear stress boundary condition was applied for the free surface of the tundish. Pressure boundary condition of 1 atm was fixed at the outlets of the tundish. A zero gradient or flux boundary condition was applied for the tracer concentration on the walls, free surface and outlets for the tracer dispersion equation.

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). 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 density and viscosity of molten steel was kept constant at 7100 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 Koria⁵⁾ for a bare tundish with one inlet and outlet, before proceeding for the industrial size tundish. The matching between experiment and computation was already reported in our previous paper.³⁾

4. Results and Discussion

The 3-D simulations were performed for all the cases mentioned in Table 1. The flow field obtained by solving the momentum and continuity equation was analysed. RTD analysis is performed by injecting the tracer at the inlet and measuring its concentration at the outlet. The tracer is added to visualise the velocity field and phenomenon of short circuiting. The RTD curve is then plotted, which represents the variation of dimensionless concentration of the tracer at the exit with dimensionless time. The dimensionless concentration is the ratio of tracer concentration at the exit with input concentration of tracer *i.e.* Q/V (where Q is the amount of tracer added and V is the volume of tundish). The dimensionless time represent the ratio of time with residence time. The results of RTD were compared for various combinations of tundish and pouring chamber. The results obtained are presented in a sequence:

4.1. Comparison of Performance of Tundishes and Their Pouring Chambers at Higher Throughput (3.7–3.9 ton/min)

The flow patterns were generated for all the three tundishes by using the pouring chambers as mentioned in Table 1. Table 4 show the fluid flow characteristics obtained by performing the RTD analysis. The high ratio of plug to dead volume for tundish 3 and low ratio for tundish 1 can be

noticed at this range of throughput. Thus, the performance of tundish 3 appears to be best and tundish 1 appears to be worst. The reason for presence of high and low dead region can be explained by analysing the fluid flow behaviour in the tundish. Figure 3 shows the flow pattern for vertical plane (ZX) above the outlets for tundish 1, tundish 2 and tundish 3. The formation of circulation loop between outlet 3 and outlet 1 can be visualised for tundish 1 in Fig. 3. The formation of small circulation cell at the top corner above outlet 1 can also be noticed for tundish 1. The vertical downward velocity is high for tundish 2 as compared to tundish 1. The interesting flow pattern is generated for tundish 3 in Fig. 3. The velocity vectors are moving from outlet 3 to outlet 1 and then vertically upward towards the top surface above the outlet 1. The velocity pattern for Symmetrical plane (YZ) of tundish 1, tundish 2 and tundish 3 can be seen from Fig. 4. The velocity of flow vector is high near the shroud for all the tundishes. The low velocity of the flow vectors in circulation loop for tundish 2 as compared to

Fig. 3. Velocity vectors at vertical XZ plane above the outlet for tundish 1, tundish 2 and tundish 3 at higher throughput (3.7–3.9 ton/min).

Table 4. RTD Characteristics for tundish1, tundish 2 and tundish 3.

S. No.	RTD Characteristics	Tundish 1 (case 1)	Tundish 2 (case 2)	Tundish 3 (case 3)	Tundish 1 (case 4)	Tundish 2 (case 5)	Tundish 3 (case 6)	Tundish 3 (case 7)
1	Strand to strand Distance (m)	1.1	1.1	1.25	1.1	1.1	1.25	1.1
1	Throughput (ton/min)	3.7	3.9	3.8	2.2	2.4	2.3	3.8
2	Mean residence time (in s)	311	409	423	513	685	699	418
3	Theoretical residence time (in s)	420	540	536	703	880	885	536
4	V_{PV}	0.05	0.05	0.06	0.05	0.06	0.1	0.05
5	Dispersed plug volume	0.08	0.08	0.08	0.07	0.09	0.15	0.07
6	V_{MV}	0.69	0.71	0.73	0.68	0.72	0.69	0.73
7	V_{DV}	0.26	0.24	0.21	0.27	0.22	0.21	0.22
8	V_{PV}/V_{DV}	0.19	0.21	0.29	0.19	0.27	0.48	0.23

Fig. 4. Velocity vector at symmetrical plane (YZ at $X = 0$) for tundish 1, tundish 2 and tundish 3 at higher throughput (3.7–3.9 ton/min).

tundish 1 can be noticed from Fig. 4. It can be further established from Fig. 4 that pouring chamber 1 is suppressing the velocity at the left side of shroud. The combination of pouring chamber 2 and tundish 3 is making the flow vectors move towards the top surface with optimum velocity. The flow pattern at top plane (XY at $Z = H$) for tundish 1, tundish 2 and tundish 3 can be seen from Fig. 5. The movement in tundish 1 is quite intense as compared to tundish 2 and tundish 3 (as seen from Fig. 5). The velocity in tundish 1 is high as compared to tundish 2 and tundish 3. The collision of two streams coming from opposite side can be seen for tundish 1 in Fig. 5. This collision results in the formation of circulation cell and thus results in a dead zone. The reversal of flow is not desired as it occupies the unnecessary volume and thus enhances the dead volume. The flow vector above outlet 2 and outlet 3 moves with low but optimum velocity in tundish 3.

The RTD curve for tundish 1, tundish 2 and tundish 3 can be seen from Fig. 6. Figure 6 shows that the time to attain the peak concentration is much below the residence time ($< 20\%$ of residence time) for all the tundishes. Thus, the sharp rise in the peak concentration reflects the presence of short circuiting in all tundishes. The large amount of fluid elements appears to have lower age in tundish 1. This lowers the mean residence time and hence increases the percentage of dead volume.

4.2. Comparison of Performance of Tundishes and Their Pouring Chambers at Lower Throughput (2.2–2.4 ton/min)

The plant is operated at different range of throughputs. It was expected that the results can be altered due to the effect of change in throughputs. Thus, the flow pattern was also obtained for all the tundishes at lowest range of throughput

Fig. 5. Velocity vector at top plane (XY plane at $Z = H$) for tundish 1, tundish 2 and tundish 3 at higher throughput (3.7–3.9 ton/min).

Fig. 6. RTD curve for tundish 1, tundish 2 and tundish 3 at higher throughput (3.7–3.9 ton/min). tundish 3 at higher throughput (3.7–3.9 ton/min).

used in the plant. The fluid flow characteristics obtained by performing the RTD analysis can be seen from Table 4. The ratio of plug to dead volume is compared for all the tundishes. The increase in the performance of tundish 3 and tundish 2 is noticed. The performance of tundish 1 remains to be unaltered. The tundish 3 with pouring chamber 2 is again found to be the best performer tundish among the

three. The performance of tundish 1 is again the worst. The flow pattern for vertical plane (ZX) above the outlets for tundish 1, tundish 2 and tundish 3 can be seen from **Fig. 7**. The magnitude of velocity appears to be slightly lower above outlet 3 in tundish 3. Thus, the optimum velocity is obtained for increased proportion of region in tundish 3. This increase in the region of optimum velocity enhances the plug volume for tundish 3. The observation for symmetrical plane (YZ) and top plane (XY at $Z = H$) for tundish 1, tundish 2 and tundish 3 can be seen from **Figs. 8** and **9**, respectively. The flow patterns in all the planes are almost similar to one obtained at higher throughput. The magnitude of velocity in tundish 2 appears to be improved. Thus, the optimum velocity region seems to be improved in this tundish. The increase in the region of optimum velocity can be clearly noticed for tundish 2 and tundish 3 in **Fig. 9**. **Figure 10** shows the RTD curve for tundishes at this throughput. The significant fall in value of peak concentration is noticed for outlet 1 in tundish 2. However, the nature of the curve for tundish 1 and tundish 2 looks similar to the one observed in **Fig. 6**. The reduction in number of peaks for outlet 3 of tundish 3 in **Fig. 10** as compared to same in **Fig. 6** can also be noticed.

4.3. Prediction of Optimum Range of Velocity Inside the Tundish

The velocity magnitude in the tundish needs to be optimum, as too low velocity can lead to stagnant zone and too high velocity can lead to generation of circulation cells. The high velocity at the meniscus is extremely undesired as it can also lead to fluctuation at the meniscus. The analysis was done to understand the optimum range of velocity in the tundish. **Table 5** shows the percentage region of tundish covered with different range of velocities for all cases. The optimum range of velocities can be derived by correlating the data in **Table 5** with the RTD results in **Table 4**. It was

found that tundish 3 of case 6 is having the maximum region (95%) covered with velocity of 0.001–0.05 m/s, among all the cases. It was also found from **Table 5** that case 6 is having the lowest percentage of region with velocity above 0.05 m/sec. The superior performance with highest plug volume

Fig. 8. Velocity vector at symmetrical plane (YZ at $X = 0$) for tundish 1, tundish 2 and tundish 3 at lower throughput (2.2–2.4 ton/min).

Fig. 7. Velocity vectors at vertical XZ plane above the outlet for tundish 1, tundish 2 and tundish 3 at lower throughput (2.2–2.4 ton/min).

Fig. 9. Velocity vector at top plane (XY plane at $Z = H$) for tundish 1, tundish 2 and tundish 3 at lower throughput (2.2–2.4 ton/min).

Table 5. Velocity magnitude in the tundish for different cases.

S. No.	Range of velocity (m/s)	% age region for case 1	% age region for case 2	% age region for case 3	% age region for case 4	% age region for case 5	% age region for case 6	% age region for case 7
1	0–0.001	2	2.3	2	2	5	3	1.8
2	0.001–0.05	65	74.7	81	80	90	95	75.2
3	0.05–6	33	23	17	18	5	2	23

Fig. 10. RTD curve for tundish1, tundish 2 and tundish 3 at lower throughput (2.2–2.4 ton/min).

for case 6 can be noticed from Table 4. The plug volume depends on the path and velocity of the fluid element. Hence, the analysis from Tables 4 and 5 shows that the plug volume can be enhanced by maximising the region of tundish having velocity in the range of 0.001 m/s to 0.05 m/s. The velocity magnitude above 0.05 m/s seems to be detrimental as far as plug volume is concerned. The conclusion can be further strengthened by observing the velocity contours at the meniscus.

Figures 11(a), 11(b) and 11(c) show the velocity magnitude at the meniscus for all the three tundishes at higher throughput. **Figure 11(d)** shows the velocity magnitude at the meniscus for tundish 3 (at lower throughput). The maximum velocity in **Fig. 11(d)** is much lower as compared to other three plots.

It was difficult to derive the lower range of optimum velocity from Tables 4 and 5. However, it can be concluded from Tables 4 and 5 that impact of high magnitude of velocity on dead volume formation is minor. The basis for this conclusion is same value of dead volume for case 3 and case 6, though the velocity magnitude is quite higher in case 3. The comparison of case 1 and case 4 further strengthen our conclusion. The interesting observation about dead volume can be noticed from Table 4. The dead volume was found

to be consistent between 20 to 27% irrespective of tundish geometry or throughput. This shows that even 2% region of low magnitude of velocity is contributing significantly towards dead volume. The conclusion can be further strengthened by observation of data for case 5 and case 6. The tundish in case 5 and case 6 is having much improved curved shape geometry, but the dead volume in both the cases was found to be above 20%. The reason for this can be attributed to the rise in low velocity region as shown in Table 5. Thus, the velocity magnitude below 0.001 m/s is not desired in tundish.

4.4. Effect of Shapes of Tundish

The shapes of tundish are an important factor affecting the fluid flow phenomenon inside the tundish. The simulation performed in this work shows the better performance for tundish 3 and worst for tundish 1. Tundish 1 and tundish 3 are using the same pouring chamber. Thus, the role of curved shape of tundish 3 in enhancing the flow characteristics can easily be derived. The effect of shapes can be further diagnosed by comparing the tundish 2 and tundish 3. The performance of tundish 3 is better than tundish 2. The tundish 2 is using pouring chamber 1 as compared to pouring chamber 2 used by tundish 3. The major difference in the shapes of tundish 2 and tundish 3 is strand to strand distance. The reason for better fluid flow characteristics for tundish 3 as compared to tundish 2 can be either shapes of pouring chamber or difference in the distance between two outlets. Thus, it was felt that further analysis about better performance of tundish 3 needs to be performed. Hence, the simulation was performed for case 7 in Table 1 to see the effect of strand to strand distance on flow velocities in the tundish. The pouring chamber 2 is used for this case. The performance of case 7 is compared with case 3 to derive the conclusion about strand to strand distance. The flow field obtained shows insignificant difference in the pattern. However, the difference in the magnitude of the velocity near the outlet is noticed for all the outlets. **Figure 12** shows the comparison of the plot of velocity magnitude with dimensionless distance between tundish bottom and top surface of tundish (vertical distance) above the outlet. This comparison is drawn for velocity field above all the outlets of the tundish. The significant difference in the velocity magnitude appears to be near the outlet (at tundish bottom). The difference in the velocity magnitude seems to be insignificant in the rest of the domain. The important observation about the difference in the velocity magnitude (near the outlet) of different strands can be noticed from **Fig. 12**. This observation suggests that the lower velocity may cause insufficient supply of molten steel to the mould resulting in reducing casting speed. **Figure 13** shows the RTD curve for case 7. The RTD characteristic in Table 4 for case 7 shows minor

Fig. 11. (a) Velocity magnitude at the meniscus for tundish 1 at higher throughput (m/s). (b) Velocity magnitude at the meniscus for tundish 2 at higher throughput (m/s). (c) Velocity magnitude at the meniscus for tundish 3 at higher throughput (m/s). (d) Velocity magnitude at the meniscus for tundish 3 at lower throughput (m/s).

Fig. 12. Plot of velocity magnitude with dimensionless distance (vertical) from tundish bottom to top surface of the tundish above the outlets.

Fig. 13. RTD curve for tundish 3 (strand to strand distance = 1.1 m) at throughput of 3.8 ton/min.

variation as compared to case 3. Thus, the contribution of strand to strand distance on the fluid flow phenomenon inside the tundish seems to be minor. Hence, the shape of pouring chamber 2 is producing better fluid flow characteristics.

4.5. Effect of Shapes of Pouring Chamber

The shapes and dimensions of pouring chambers are described in Figs. 2(a) and 2(b). The height of the pouring chamber 1 is more as compared to pouring chamber 2. The opening area of pouring chamber 2 is large as compared to pouring chamber 1. The pouring chamber 2 is also having a large contact surface due to presence of cylindrical rod shaped structure. According to simulation performed in the current work, the pouring chamber 1 appears to be produc-

Table 6. Mean residence time of all the outlets for three tundishes at higher throughput.

S. No.	Parameters	Tundish 1			Tundish 2			Tundish 3		
		Outlet 1	Outlet 2	Outlet3	Outlet1	Outlet 2	Outlet3	Outlet 1	Outlet 2	Outlet 3
1	Throughput (ton/min)	3.7	3.7	3.7	3.9	3.9	3.9	3.8	3.8	3.8
2	Minimum residence time (Sec)	10	20	30	10	20	50	20	20	60
3	Mean Residence Time (Sec)	328	308	299	379	388	463	387	416	476
4	Theoretical Residence time (Sec)	420	420	420	540	540	540	536	536	536
5	Effective volume (in %)	78	73	71	70	72	86	72	77.5	89

Table 7. Mean residence time of all the outlets for three tundishes at lower throughput.

S. No.	Parameters	Tundish 1			Tundish 2			Tundish 3		
		Outlet 1	Outlet 2	Outlet3	Outlet1	Outlet 2	Outlet3	Outlet 1	Outlet 2	Outlet 3
1	Throughput (ton/min)	2.2	2.2	2.2	2.4	2.4	2.4	2.3	2.3	2.3
2	Minimum Residence Time (sec)	20	30	60	30	40	90	40	40	175
3	Mean Residence Time (Sec)	533	509	505	676	638	733	610	661	844
4	Theoretical Residence time (Sec)	703	703	703	880	880	880	885	885	885
5	Effective volume (%)	76	72	72	77	73	83	69	75	95

ing more suppression. Though the suppression is more for pouring chamber 1, but the performance of pouring chamber 2 appears to be better according to RTD analysis. Thus, the strong role of height and opening area of pouring chamber on fluid flow phenomenon is noticed.

4.6. Comparison of Mean Residence Time of Different Strand

The major concern in the multi-strand tundish is to achieve the superior quality from all the strands. Thus, minimum as well as mean residence time for all the strands is to be maximised for getting the better performance of tundish. **Table 6** shows the comparison of minimum and mean residence time for the three tundishes at all the outlets (at higher throughput). The performance of outlet 3 appears to better w.r.t mean residence time for all the tundishes except tundish 1. Tundish 1 shows the better performance of outlet 1. This might be due to the reversal of flow. However, the minimum residence time was found to be higher for outlet 3 in all the tundishes. **Table 7** shows the comparison of minimum and mean residence time for the three tundishes at all the outlets (at lower throughput). Here, also the tundish 3 shows the superior performance of outlet 3 and outlet 2 w.r.t mean residence time. The reduction in throughput increases the minimum residence time of all the strands. The maximum variation of minimum residence time between strands was observed for tundish 3 at both the throughputs. The more suppression of flow near the outlet or by reversing the flow can produce better results for outlet 1 but over all performance can be hampered.

The inclusion flotation inside the tundish can be enhanced by increasing the plug volume and reducing the dead volume. The plug volume can be increased by increasing the path and reducing the velocity of the fluid element. However, the velocity magnitude should be maintained at an optimum level as low velocity can lead to formation of stagnant region. The vertical as well as horizontal rotation of flow vector in the region near the outlet 1 can improve the flow

characteristics in tundish. This rotation of flow vectors will increase the path for fluid element and will enhance the mixing in the region near the outlet 1. Hence, the flow will become more uniform in the tundish. This phenomenon of capturing the incoming stream in the vicinity of outlet 1 will enhance the plug volume and leads to reduction in dead volume.

5. Conclusion

The fluid flow characteristics for better inclusion flotation was studied for three industrial six strand tundish in present work. The following conclusions were drawn from the study.

- According to the prediction of CFD simulation, the curved shape in tundish will have a dominant role in modifying fluid flow characteristics in spite of whatsoever pouring chamber is used. The effect of curvature can not be compensated by changing the design of pouring chamber.
- The variation in the strand to strand distance can alter the magnitude of the velocity near the outlet at the tundish bottom. However, the effect on fluid flow phenomenon in the rest of the domain appears to be insignificant.
- The suppression of fluid flow in the tundish can be enhanced by reducing the opening area and increasing the height of pouring chamber.
- The more suppression may not produce the superior fluid flow characteristics in the tundish. Thus, the height and opening area of pouring chamber needs to be optimized w.r.t. fluid flow characteristics.
- The flow patterns inside the tundish are not altered by changing the throughput.
- The range of velocity magnitude from 0.001 m/s to 0.05 m/s appears to be the best limit in the tundish. Thus, the sole effect of throughput appears to be altering the region of optimum velocity. The alteration in the region

of optimum velocity due to change in throughput can effect the performance of tundish.

- The superior performance of steel going out from outlet 1 can be achieved by increasing the suppression through pouring chamber or reversing the flow, but overall performance will be hampered.

Nomenclature

$\bar{C}$: Mass fraction of the injected tracer
 C_{av} : Average concentration of tracer from i_{th} 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_m : Actual mean residence time
 t_{min} : Average breakthrough time
 t_r : Theoretical mean residence time
 t_{peak} : Time taken to attain peak concentration of tracer at the outlet
 $\bar{U}$: Velocity
 u' : Velocity fluctuation
 V: Volume

Greek Symbols

ρ : Density of steel
 μ : Molecular viscosity of steel
 μ_t : Turbulent viscosity of steel
 μ_{eff} : Effective viscosity of steel
 σ_c : Turbulent Schmidt number
 ε : Rate of dissipation of turbulent kinetic energy
 τ^l : Laminar shear stress
 τ^t : 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
 DPV: Dispersed volume

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