1. Introduction

An increase in demand for the sequence life and performance of the steelmaking tundish has driven many changes in the tundish design in the past few decades. These modifications have upgraded the tundish to be utilized as a final stage-refining vessel rather than simply as an intermediate transfer vessel between the steel ladle and casting machine. Numerous developments in tundish design were based on the metallurgical performance of the tundish such as better quality of the steel in terms of steel cleanliness, better homogeneity in the distribution of steel through different strands, etc. One of such tundish, curved shape tundish and its different variants are being used in the steel plants worldwide. The curved shape tundish is believed to be performing better than a conventional delta shape as far as metallurgical performance of the multi-strand tundish is concerned.

Refractory wall wear of the tundish is a serious problem that limits the sequence life of the tundish. It is established that refractory wear may occur due to thermal, chemical, and mechanical attack. Fluid-flow of molten steel, a heavy material, can alone cause erosion of refractory lining of the tundish. Moreover, presence of high temperature and turbulence adds to severity of the erosion phenomenon especially in the high velocity region near inlet stream. By considering the refractory wear due to flow-induced wall shear stress the tundish design can further be improved to increase the sequence life of the tundish by reducing the refractory wall wear rate.

Studies carried out so far have done the analysis of tundish design considering the RTD in the tundish, inclusion flotation, mixing, etc. However, it seems that the role of wall shear stress still remains to be explored in perspective of the tundish design. There is very few published work on the effect of tundish design on the refractory wear due to flow-induced wall shear stress. Such a study of tundish design may have important technological implications.

2. Physical Description

Figure 1 shows symmetrical half of a typical six strand curved shape billet caster tundish. Figures 1(a) and 1(b) show top and symmetrical view of the tundish respectively. The molten steel is poured into the tundish through the shroud submerged in the molten steel in the tundish. The flow of molten steel into the tundish creates enormous turbulence around the pouring point. To minimize turbulence around pouring point a device called pouring chamber is used and is placed below the ladle pouring point as shown in Fig. 1. The curved walls are believed to guide the molten steel flow towards the outlets smoothly.

Different variants of the curved shape tundish were simulated to study the tundish design. The variation in tundish design was made in the inclined wall angle, curvature radius, and tundish width. Table 1 shows the range of design parameters for which the simulations were performed. A bare tundish was also considered to compare it with the
tundish with pouring chamber. All the parameters for the tundish are shown in Table 2.

### Table 1. Range of the parameters studied.

| Parameter               | Existing | Range of study |
|-------------------------|----------|----------------|
| Wall angle, degree      | 10       | 5 – 20         |
| Tundish bottom width at | 1430     | 1430 – 1730    |
| Curvature, mm           | 1074     | 1074 – 1464    |

### Table 2. Operating parameters of the present tundish.

| Parameter               | Value  |
|-------------------------|--------|
| Inlet velocity, m/s     | 1.9    |
| Tundish bottom half length, mm | 2888  |
| Tundish bottom width at side, mm | 300   |
| Outlet diameter, mm     | 172    |
| Bath height, mm         | 840    |
| Shroud diameter, mm     | 66     |
| Submergence depth of the shroud, mm | 130   |

3. Mathematical Model

#### 3.1. Mathematical Formulation and Assumptions

The tundish was assumed to be operating under quasi-steady-state condition isothermally with a flat and slag-free top surface maintained at a constant level. As in the plant, transient thermal phenomena such as variable temperature change in the incoming molten steel stream, ladle or grade change operation are absent for the most of operational time. Hence it would be safe to assume an isothermal steady state operation for the shear stress computation. The standard \( k-e \) model was used to model the turbulence. Wall of the tundish was simulated to be hydro-dynamically smooth. Changes in tundish shape due to erosion were not taken into account. It was assumed that a local equilibrium exists between the dissipation and production of turbulence at the nearest cell center wall. The production of kinetic energy and its dissipation rate at the wall-adjacent nodes, which are the source terms in the kinetic energy equation, are computed on the basis of the local equilibrium hypothesis. Under this assumption, the production of turbulence kinetic energy and its dissipation rate are assumed to be in equilibrium in the wall-adjacent control volume. The following governing equations in tensor form are solved to simulate the flow in the tundish:

**Continuity equation:**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0 \quad \text{(1)}
\]

**Momentum equation:**

\[
\frac{D(\rho U_i)}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho u_i u_j \right] + \rho g_i \quad \text{(2)}
\]

**Turbulence kinetic energy equation:**

\[
\frac{D(\rho k)}{Dt} = D_k + G - \rho e \quad \text{(3)}
\]

**Rate of dissipation equation:**

\[
\frac{D(\rho e)}{Dt} = D_e + C_1 G \frac{e}{k} - C_2 \frac{\rho e^2}{k} \quad \text{(4)}
\]

Where

\[ D_e = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_t}{\sigma} \right) \frac{\partial \phi}{\partial x_j} \right] \quad \text{(5)} \]

In this equation, \( \phi \) represents \( k \) for Eq. (3) and \( e \) for Eq. (4).

\[ \mu_t = \rho \frac{C_\mu k^2}{\varepsilon} \quad \text{(6)} \]

\[ G = -\rho u_i u_j \frac{\partial U_i}{\partial x_j} \quad \text{(7)} \]

**Tracer dispersion equation:**

\[
\frac{D(\rho C)}{Dt} = \frac{\partial}{\partial x_i} \left( \mu_{\text{eff}} \frac{\partial C}{\partial x_i} \right) \quad \text{(8)}
\]

Where

\[ \mu_{\text{eff}} = \mu + \mu_t \]

Values of constants used are:

\[ C_1 = 1.44, \quad C_2 = 1.92, \quad \sigma_e = 1.0 \]

\[ \sigma_s = 1.0, \quad \sigma_c = 1.3, \quad C_\mu = 0.09 \]
Wall shear stress:
\[
\frac{\rho u_p C^{1/4}_k \kappa_p^{1/2}}{\tau_w} = \frac{1}{\kappa'} \ln \left( E \frac{\rho y_p C^{1/4}_k \kappa_p^{1/2}}{\mu} \right) \tag{9}
\]

Where
- \( u_p \): mean velocity at the cell center adjacent to the wall,
- \( y_p \): distance from point \( p \) (adjacent to wall) to the wall,
- \( k_p \): turbulent kinetic energy at point \( p \) to the wall,
- \( \kappa' \): von karman constant \((= 0.4187)\),
- \( E \): Empirical constant \((= 9.793)\).

3.2. Boundary Conditions

An overview of the boundaries can be seen from Fig. 1.

Inflow of the molten steel from shroud into the tundish was modeled by defining a velocity inlet condition. For simulating actual operating conditions of the plant, the velocity perpendicular to the free surface was calculated using data of the ladle weight, and the outflow from the tundish. A turbulent intensity of 2% was set at the inlet, which is supposed to model the turbulence in the tundish. To ensure overall mass balance in the tundish an equal outflow condition from all the outlets was set. A no-slip boundary condition was applied at all the walls of the tundish and pouring chamber. The standard wall functions were used based on the proposal of Launder and Spalding. Since symmetrical half of the tundish was modeled, therefore, a symmetry condition was applied at the symmetry by putting horizontal component of the velocity and horizontal gradient of all the gradients zero. At the free surface, zero shear stress boundary condition was applied. For tracer dispersion equation, apart from the above boundary conditions it was considered that all the walls were impervious to the tracer i.e., at all the bounding surfaces a zero flux condition was put. Inlet boundary condition of tracer mass fraction was devised so as a certain amount of tracer is injected for the 1 s initially.

3.3. Solution Methodology

A symmetrical half of the tundish was considered for simulation. The tundish geometry creation and grid generation was done using software ‘Gambit’, while the governing equations were solved in CFD software ‘Fluent’, which uses finite volume technique. To ensure the correct implementation of the wall function approach used in the turbulence modeling, mesh sizes were optimized such that the \( y^+ \) value remains in 30–90 range, where logarithmic law of wall is valid. The second order upwind scheme was adopted for convective term in the governing equations. SIMPLE (Semi-Implicit Method for the Pressure-Linked Equations) algorithm was used to resolve the pressure–velocity coupling in the momentum equation. The grid density was kept comparatively high near the inlet due to high velocity gradients there. The solution was assumed to have converged when the whole field normalized residuals for all the variables \((U, p, k \text{ and } \varepsilon)\) fell below \(10^{-4}\). A value of 7100 kg/m³ and 0.00648 kg/m·s respectively was used for density and dynamic viscosity of molten steel. For solution of tracer dispersion equation, a time step of 0.5 s was used to proceed in time after steady state solution for flow was achieved.

3.4. Validation of Model

A basic validation of the mathematical model was done with the experimental data of bare tundish having one inlet and one outlet. The experimental data of RTD was chosen for the tundish having W/L of 0.167 that is close to the tundish used in the present study. It can be observed that the RTD curve shows only a peak that indicates absent of short-circuiting in a narrow tundish. It would be shown through the RTD curve later that short-circuiting was also found to be absent in the six strand curved type tundish used in the present study. A detail study of this can be found elsewhere. Rest of the parameters used in the validation were same as in the Ref. 4). The RTD data of present mathematical model is compared with the experimental data in Fig. 2. Dimensionless time and concentration are defined same as in Ref. 4). The overall characteristics of the RTD curve matches with the experimental data quite satisfactorily. The validation gave the idea of turbulence modeling, grid density and convergence criteria.

4. Results and Discussion

The simulations were carried out with and without pouring chamber to understand the role of pouring chamber in the wall shear stress. It was found that pouring chamber has a dominant role in reducing the wall shear stress by modifying the fluid flow in the tundish. Once the role of pouring chamber was understood for the basic geometry, the rest of the simulations for other modified geometries were carried out with pouring chamber as per actual practice. Effect of tundish geometry on wall shear stress was studied by changing the geometrical parameters like curvature radius, tundish width by changing shroud to near wall distance, and wall inclination angle.

4.1. Wall Shear Stress Profile in the Curved Tundish

Flow-induced wall shear stress has been computed in the tundish mainly observing the maximum wall shear stress area because this is the area that limits the life of the tundish. Figure 3 shows the predicted location of peak wall shear stress and actual location of erosion in the tundish after a sequence at the plant. It can be seen that peak shear stress aggravates the erosion of the refractory wall of the tundish near shroud. To better understand the wall shear...
stress distribution on the tundish wall a bare and a pouring chamber tundish has been analyzed. The shear stress profile for the tundish with and without pouring chamber is compared in the Fig. 4. The profile shows the shear stress variation along the curved wall near shroud vertically at symmetry plane as indicated by a bold line in the Fig. 3. A reduction in the peak shear stress on the wall was observed with pouring chamber, while the area of peak shear stress on the wall remains same. The first small peak in case of bare tundish is because of circulatory motion at the bottom corner of the tundish while in case of tundish with pouring chamber is because of circulatory motion in the corner forming with pouring chamber and tundish wall. The reason behind the reduction in shear stress due to use of pouring chamber can be understood through analysis of flow field as shown in the Fig. 5. Figures 5(a) and 5(b) show the velocity vectors for bare tundish and pouring chamber tundish respectively at the symmetry plane. For the sake of clarity, all the vectors are shown to be of equal size. As can be seen, pouring chamber helps to direct the fluid from shroud towards bulk of the fluid away from the curved wall near shroud. As point of bifurcation of the molten steel, as indicated in Fig. 5, flow along the curved wall near shroud is shifted downward towards bottom of the tundish, the amount of fluid movement towards the zone near curved wall reduces, which causes reduction in peak shear stress on the wall.

4.2. Role of Wall Curvature
Curved wall of the tundish plays an important role for achieving the desired fluid flow in the tundish thus is one of the most useful parameter in the curved shape tundish design. Four curvatures 1075, 16150, 1300, and 1464 mm were used with rest of the dimensions of the tundish unchanged. The shroud to near wall distance and tundish width was kept constant at 350 and 1530 mm respectively.
As shown in Fig. 6, peak wall shear stress decreases as curvature radius increases. The rate of decrease of peak shear stress in the initial range of curvature was found to be more as compared to later range of curvature change. Figure 7 compares the free surface flow for all the four curvature studied. As shown by curved arrow in the Fig. 7, the point of bifurcation of the molten steel flow shifts towards symmetry plane as curvature radius is increased. In other words, role of the curve wall becomes more effective as a bigger curvature radius guides the flow towards outlet along the curved wall sooner than the smaller curvature radius does as the molten metal comes through shroud, thus helps in releasing the local pressure that causes lower wall shear stress.

4.3. Effect of Wall Inclination Angle

A typical industrial tundish has its walls are generally inclined outside i.e. wider at top than the bottom. Such a design is useful in clearing the skulls. The inclination angle of the wall has important implications as far as fluid flow is concerned. As a result of altered fluid flow the wall shear stress and other characteristics changes accordingly. The predicted results with different inclined walls reveal an interesting effect on wall shear stress. Simulations have been performed for 5°, 10°, 15°, and 20° wall inclination angles to see the effect on the wall shear stress. Figure 8 shows the change in peak wall shear stress, as wall inclination angle is changed from 5° to 20°. The rate of change of wall shear stress from 10° to 15° is found to be maximum. The finding may have important technological implication. The reason for the above said behavior can be understood by seeing fluid flow pattern in the tundish. The circulatory pattern around the shroud was observed to be main cause of the peak wall shear at the wall near shroud. Hence analyzing the flow pattern at symmetry plane can be helpful. Figure 9 shows the velocity vectors at the symmetry plane for all the wall inclination angles studied. As mentioned earlier, a circulatory fluid flow forms around the inlet shroud. If velocity vectors are seen at symmetry plane the two circulatory regions can be termed as two eyes around the inlet shroud. As wall angle increases the size of the eyes also increases as greater space is available for fluid movement. This consequently, reduces the momentum of the flow, hence the shear stress.

In addition to reduced shear stress, the fluid flow pattern...
also improves while pouring chamber is used. With smaller angles (5°–10°), the plunging liquid jet stream from inlet shroud does not go straight to the bottom but is bend towards the nearer wall. This is because of unsymmetrical velocity magnitude on either side of inlet stream. Higher velocities near the nearer wall lead to pressure drop that is compensated by bending of inlet stream. It is important to mention here that the pouring chamber function will be more effective if inlet stream comes at the center of pouring chamber. While with the greater angles (>10°), the inlet stream is more smoothly received in the tundish going straight.

4.4. Effect of Tundish Width

Width of the tundish can be changed by many ways like: A) changing the normal distance between outlets and inlet, B) changing distance between outlet and the wall near outlets, C) changing the distance between inlet and the wall near shroud. Every option was analyzed before making change in original tundish width. Option A and B will make narrow region (where outlet 2 and 3 are located) of the tundish wider which may adversely affect metallurgical performance of the tundish. Also, distances in option A and B have to be kept constant to avoid greater increases in volume of the tundish as increase in tundish volume would be maximum per unit change in width. It will increase the heat loss due to increased free surface area as the distances run across full length of the tundish. This leaves the option C to make change in the tundish width without changing much the original metallurgical characteristics of the tundish. Thus, the bottom width of the tundish was changed by changing the distance between shroud to near wall in the original tundish. The distance between shroud and near wall was changed in the range 250 to 550 mm. As shown in Fig. 10, the peak wall shear stress decreases as the tundish width in above said manner is increased. As the near wall gets farther from shroud, the circulatory current effect on the wall reduces as shown in Fig. 11. This indicates that it is strong circulatory motion that causes the erosion in the region. While making such a change metallurgical performance of the tundish must not be sacrifice. To see the effect of change in tundish width a RTD analysis was carried out with tundish width of 1 430 and 1 630 mm. Figure 12 shows the RTD curves for both the widths. As can be seen there is very little change in metallurgical performance of the tundish with the kind of change incorporated in the tundish to increase the width. This is because narrow region of the tundish, which is believed to be deciding factor in the metallurgical performance of the tundish, was kept unchanged. Table 3 shows the RTD characteristics parameters evaluated based on multiple strand tundish theory. RTD analysis showed no detrimental effect on metallurgical performance of the tundish rather some improvement was observed in the dead volume.

5. Conclusions

Flow-induced wall shear stress has been predicted for various design of curved shape billet caster tundish through 3-D mathematical modeling. The location of peak wall shear stress matched with the observed erosion area in the
actual plant tundish after a sequence. The role of pouring chamber in wall shear stress has been established. The effect of various design parameters was studied. The following observations have been made:

(1) The presence of pouring chamber helps in reducing the flow-induced shear stress on the refractory wall of the tundish.

(2) Circulatory flow around shroud was found to be main cause of the erosion due to molten steel flow.

(3) An increase in the wall inclination angle decreases the wall shear stress, while the rate of change in shear stress was maximum in the range 10–15 degree.

(4) A bigger curvature radius was found to be helpful in reducing the shear stress as it helps to guide the molten steel from circulatory region towards outlets earlier.

(5) By increasing tundish width by increasing shroud to near wall distance was found to be helpful in reducing the shear stress on the wall.

Nomenclature

- $C$: Mass fraction of injected tracer
- $g$: Acceleration due to gravity
- $k$: Turbulent kinetic energy
- $L$: Length of the tundish
- $p$: Pressure
- $RTD$: Residence time distribution
- $t$: Time
- $U$: Mean velocity
- $W$: Width of the tundish
- $x$: Coordinate for measure of distance
- $\rho$: Density of the fluid
- $\mu$: Co-efficient of viscosity
- $\bar{u}\bar{u}_i$: Average turbulent stress
- $\epsilon$: Rate of dissipation of turbulent kinetic energy
- $\sigma$: Coefficients
- $\phi$: Either $k$ or $\epsilon$

Subscripts

$i,j$: $i$th or $j$th component in three Cartesian coordinate
directions \( x \), \( y \) and \( z \)

t: Turbulence
eff: Effective

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