Comparison of Different Multi-Strand Tundishes

Anupam Dewan¹ and Siddharth Gupta¹

Abstract - A computational study was carried out to optimize the positions of outlet strands and to compare the operating parameters of two-strand, four-strand and six-strand tundishes. This involved adoption of an Euler-Lagrangian approach to track spherical particles in a steady, three-dimensional flow field obtained by the numerical solutions of Reynolds-averaged Navier-Stokes and energy equations. The standard k-ε model and random walk model were used for modeling the turbulence in flow field and paths of inclusions, respectively. For comparison of different tundishes, two methodologies were adopted, first with equal mass flow rate of liquid steel at the inlet gate for all the tundishes considered (i.e., same capacity) and the second with equal mass flow rate of liquid steel leaving through each outlet strand for all the tundishes. It was found that for different tundishes with the same capacity, a change in the number of outlet strands does not have any significant effect on the operating parameters of the tundishes. For the tundishes with the same flow rate at each strand, the removal efficiency of two strand tundish was found to be more compared to that of four-strand and six-strand tundishes.

Keywords: CFD; Euler-Lagrangian method; Particle tracking; Multi-strand tundish; Turbulence.

Nomenclature

- $u_i$: Velocity
- $T$: Temperature
- $\mu$: Coefficient of viscosity
- $k$: Turbulent kinetic energy
- $c$: Rate of dissipation of turbulent kinetic energy
- $Pr_t$: Turbulent Prandtl number
- $C_p$: Specific heat
- $\phi$: either $k$ or $c$
- $\nu$: Kinematic viscosity

Suffix

- i, j, k: Three cartesian coordinates
- p: Particle
- t: Turbulent

I. Introduction

With the continuous increase in the demand of high quality steel, removal of non-metallic inclusions from the liquid steel, before casting, has become an important operation in a continuous casting process. Tundish is the final unit in a continuous casting process. It is used to maintain a constant head of liquid steel over mould so that the liquid steel enters the mould without any splashing and it also allows ladle exchange without having any interruption in the casting process. Tundish is also used to remove non-metallic inclusions which are a major source of poor quality of steel.

A large number of studies have been reported in the literature dealing with the physical and mathematical modeling of fluid flow conditions together with the inclusion motion behavior inside a tundish for different tundish geometries and flow conditions. Mikki and Thomas [1] simulated the inclusion removal in a single-strand tundish with flow modifiers using three models, viz., inclusion removal model, lumped inclusion removal model and inclusion diffusion model. They found that the effect of thermal buoyancy cannot be ignored in calculating the removal of inclusion particles and that random motion of cluster promotes inclusion separation. Zhang et al. [2] studied three-dimensional fluid flow in a single-strand tundish using three models, viz., floatation to the free surface, collision and coalescence of inclusion, and adhesion to the lining of solid surface. With the help of water models they concluded that collision of inclusion and adhesion to lining are also the major source of inclusion removal and employing flow modifiers favors the inclusion removal.

Morales et al. [3] used water modeling and mathematical simulation techniques to study the effect of turbulence inhibitors in a multi-strand bloom caster tundish and concluded that turbulence inhibitors together with a pair of dams provide better performance as compared to complex furniture employed in a tundish. Jha and Dash [4] performed numerical simulations with different models of turbulence and compared these with experimental results to conclude that the standard k-ε model predicts flow properties closest as compared to that by other turbulence models. Therefore, in the present study the standard k-ε model is used.

Kim [5] constructed a full scale model of a delta shape four-strand tundish and observed that about 99% of inclusions above 150 µm size were separated using the flow modifiers. Rogler [6] developed a physical
produces a large effect on the flow field and the tundish having weirs and turbulence inhibitor in inclusion separation, and streamline experiment, that found that large inclusions have good chance to trap other inclusions.

Zhang [9] used the k-ε model of turbulence together with both the stochastic and non-stochastic models to simulate fluid flow in a single-strand tundish. He concluded that the non-stochastic model is not accurate for predicting the inclusion motion and concluded that analyzing the residence time of the particle in molten steel is not so meaningful for studying the behavior of inclusions inside the tundish. Hyrb et al. [10] compared Eulerian and Lagrangian methods to predict particle transport in a turbulent flow. They concluded that Lagrangian formulation provides better insight of particle dynamics provided numbers of particle track were large enough. Therefore, in the present study stochastic model (random walk model) is employed to predict the inclusion motion inside a tundish and 520 numbers of inclusions were used to quantify the fate of inclusions.

Gang et al. [11] showed with their RTD curves, inclusion separation, and streamline experiment, that the tundish having weirs and turbulence inhibitor produces a large effect on the flow field and the inclusion separation. Hou et al. [12] developed a swirling flow tundish (SFT) and concluded that SFT has higher capability of inclusion removal of smaller size as compared to that of a tundish equipped with turbulence inhibitors. Yang et al. [13] used water models, mathematical modeling and industrial trials to design and optimize a two-strand tundish.

Zhang et al. [14] studied the removal efficiency of inclusion in a tundish by using gas bubbles. Their result showed that by bubbling the removal efficiency for large particle does not change much but it has a strong impact on smaller particles. Seshadri et al. [15] built a 1:3 scale physical model of tundish to investigate the effect of gas flow and curtain position inside a tundish. They concluded that bubbling increases the removal efficiency of the tundish and position of gas curtain has a large impact on the removal efficiency of the tundish. Singh et al. [16] designed an optimal set of furniture inside a single-strand tundish using RTD curves and concluded that non-isothermal model is important to develop correct flow field inside a tundish. Raghavendra et al. [17] investigated the behavior of inclusions inside a four-strand asymmetric tundish using the Lagrangian particle tracking approach and concluded that inclusions of higher diameter float easily to the top surface as compared to lower diameter inclusions. Merder et al. [18] investigated the flow inside a six-strand tundish with and without dam. They obtained residence time curves to verify whether tundish condition is suitable for the non-metallic inclusion removal or not.

Meijie et al. [19] used mathematical modeling and experiments to study the effect of gas blowing on the removal of small size inclusions. They concluded that with the help of proper blowing conditions, average inclusion concentration (< 20 µm) decreases by more than 24%. Ding et al. [20] used RTD curves and water model experiments to optimize a single-strand tundish. They concluded that with an optimized tundish inclusion area ratio in casting slabs reduced by 32% as compared to that in the original tundish. Shinde et al. [21] performed mathematical modeling in a single-strand tundish to obtain mixing capacity of the tundish and concluded that the minimum residence time of the tundish decreases with an increase in the tundish bath height. Gupta and Dewan [22] used Euler-Lagrangian approach to optimize a six-strand tundish. They considered the effect of flow modifiers, velocity of liquid steel at inlet gate, properties of inclusions on the performance of a six-strand tundish.

Most studies reported in the literature deal with enhancing the performance of a single type of multi-strand tundish by various methods. The present study deals with an optimization of the positions of outlet strands for two-strand and four-strand tundishes and comparison of two-strand, four-strand and six-strand tundishes. For the optimization and comparison the following parameters were chosen: (a) maximum overall inclusion removal efficiency, (b) outlet strand temperature, (c) minimum temperature loss inside the tundish, (d) minimum deviation in the percentage of inclusion removal and (e) temperature of steel compared between different outlet strands. The inclusion trajectories and velocity fields inside the tundish depend upon inner geometry of the tundish and therefore all the multi-strand tundishes considered in the present study had the same shape and dimensions. For optimization and comparison, two methodologies have been adopted in the present study: (a) mass flow rate through the inlet gate was kept same for all type of multi-strand tundishes considered, i.e., all the tundish had the same capacity and (b) mass flow rate from each outlet strand was kept constant for all types of multi-strand tundishes considered. Computational fluid dynamics (CFD) has emerged an effective and economical tool for the design of steel tundishes and CFD was used in the present study.

In the present study a steady, 3-D flow field is generated inside all the multi-strand tundishes considered using the standard k-ε model of turbulence. The flow field thus generated was then used to predict the motion of non-metallic inclusions inside the tundish in a Lagrangian frame of reference using the random walk model. Commercial software FLUENT 6.3.26 was used for performing the simulations. The effect of outlet strand positions on the operating parameters of the
tundish were studied in detail and a comparison was performed between tundishes with their best optimized outlet strand position. The geometry of all multi-strand tundishes and methodologies adopted for the optimization and comparison are described in Section II. The governing equations, turbulence model and boundary conditions are presented in Section III. Code validation and computed results are presented in Section IV followed by conclusions.

II. Physical Description of the Problem

The geometry of all the multi-strand tundishes considered in the present study was the same as that used by Merder et al. [18] and Gupta and Dewan [22], which is a six-strand trough-type tundish designed for casting ingot. This tundish was converted to two-strand and four-strand tundishes by closing four and two outlets, respectively. Fig. 1 shows only half of the tundish due to its symmetrical dimensions across the transverse plane passing through the inlet gate of the tundish. The depth of the tundish (steel bath height) \( H \) = 740 mm and other constructional parameters were: \( L_1 = 2785 \text{ mm} \), \( L_2 = 2700 \text{ mm} \), \( L_3 = 500 \text{ mm} \), \( L_4 = 1000 \text{ mm} \), \( W_1 = 1040 \text{ mm} \), \( W_2 = 850 \text{ mm} \), \( W_3 = 640 \text{ mm} \), \( W_4 = 450 \text{ mm} \) [18-22]. Plane A in Fig. 1 refers to a vertical plane passing through all the outlet strands of a tundish. The inlet and outlet diameters of the gate were taken as 66 mm and 14 mm, respectively [18-22].

![Fig. 1. Geometry of the multi-strand tundish.](image)

Figs. 1 and 2 show the positions of outlet strands and their locations with respect to the inlet gate, respectively. The outlet strand farthest from the inlet gate is termed as the F.O. (far outlet) and similar terminology was chosen for the other two outlet strands, i.e., M.O. (middle outlet) and N.O. (near outlet).

![Fig. 2. Positions of outlet strands for all types of multi-strand tundishes considered.](image)

Fig. 3 describes the procedure followed in the present study to optimize the outlet strand positions and for a comparison of different multi-strand tundishes. Since operating parameters depend upon the inner dimensions and shape of a tundish, basic tundish dimensions and shape were chosen from that of a six-strand tundish [18-22]. The six-strand tundish was changed to two-strand and four-strand tundishes by removing four and two outlet strands, respectively. The positions of different strands in a particular tundish were first optimized and subsequently different optimized multi-strand tundishes were compared according to the above-mentioned two criteria. Thus operating parameters were calculated and analyzed for three different strands positions for two-strand and four-strand tundishes shown in Fig. 3. For the six-strand tundish only one case was considered as its all outlet strands were in the operating conditions.

For comparison of different tundishes two methodologies were adopted: (a) same mass flow rate of liquid steel at the inlet gate for all the tundishes considered and (b) same mass flow rate of liquid steel coming out of each strand for all the considered multi-strand tundishes. For example, if the total mass flow rate of a six-strand tundish is 12 units then the mass coming out from each outlet strand is 2 units. For case (a) the mass flow rate at inlet gate for all the multi-strand tundishes were taken as 12 units. For case (b) the mass flow rate at inlet gate for four-strand tundish was taken as 8 units and for two-strand it was taken as 4 units so that the mass flow rate through each outlet strand of all the tundishes remains as 2 units.
The reason for choosing two different methodologies was because for the same mass flow rate at the inlet the outlet mass flow rate of liquid steel is quite high for two-strand tundish and four-strand tundish as compared to that of a six-strand tundish. A large flow rate at the outlet would cause a change in the dimensions or transient parameters for all the process or units after the tundish. For example, the length of the strand will increase as sufficient time is required for the liquid steel to cool and solidify which is dependent on the mass flow rate of liquid steel at the outlet strand gate. The same mass flow rate at each outlet strand causes a decrease in the mass flow rate of liquid steel at the inlet for two-strand and four-strand tundishes as compared to that in a six-strand tundish. This would cause change in dimensions or transient parameters for all the processes or units before the tundish. The dimensions of all the tundishes were taken to be the same and thus the flow rate of liquid steel was maintained by controlling velocities of liquid steel at the inlet gate and outlet strand gates. The values of the properties of liquid steel used were [18-22]: specific density = 7010 kg/m$^3$, specific heat = 821 J/kg·K, thermal conductivity = 30.5 W/m·K and viscosity = 0.007 kg/m·s.

### III. Mathematical Formulation

#### III.1. Governing Equations

For mathematical modeling the following equations were used [23, 24]

**Continuity equation**

$$\frac{\partial u_i}{\partial x_i} = 0$$

**Momentum equation**

$$\frac{\partial}{\partial x_i} \rho u_i u_j = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i$$

Where, \( \mu_{eff} = \mu_0 + \mu_i = \mu_0 + \rho C_\mu \frac{k^2}{\varepsilon} \)

**Energy equation**

$$\frac{\partial}{\partial x_i} \left( \rho u_i h \right) = - \frac{\partial}{\partial x_i} \left( k_{eff} \right) \frac{\partial T}{\partial x_i}$$

Where, \( k_{eff} = k_0 + \frac{C_p \mu_i}{\rho \varepsilon} \)

An accurate representation of fluid turbulence is a challenging task in the simulation of the flow in a steel tundish. We have used the standard \( k-\varepsilon \) model [23], a two equation turbulence model. In the \( k-\varepsilon \) model, two transport equations, one for the turbulent kinetic energy (\( k \)) and other for its dissipation rate (\( \varepsilon \)) are used to calculate the eddy viscosity. It is a widely used turbulence model for industrial applications.

**Turbulent kinetic energy**

$$U_i \frac{\partial k}{\partial x_j} = D_k + P - \varepsilon$$

**Rate of dissipation of turbulence kinetic energy**

$$U_j \frac{\partial \varepsilon}{\partial x_j} = D_\varepsilon + C_1 \rho \frac{P \varepsilon}{k} - C_2 \frac{\varepsilon^2}{k}$$

**Concentration (species) conservation equation**
\[
\frac{\partial}{\partial t} (\rho_c) + \frac{\partial}{\partial x_i} (\rho_c u_i) + \frac{\partial}{\partial x_i} (\rho_c \delta_{ij} \partial x_j) = 0
\]

(6)

The Reynolds stress is given by

\[
u_i u_j = \frac{2}{3} k \delta_{ij} - \nu_i \left( \frac{\partial U_j}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)
\]

Where,

\[
\nu_i = 0.09 \frac{k^2}{e}, \quad \mu_{eff} = \rho \nu_i + \mu
\]

\[
D_\phi = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\phi} \right) \frac{\partial \phi}{\partial x_j} \right]
\]

\[
P = -u_i u_j \frac{\partial U_i}{\partial x_j}
\]

\[
E = h - \frac{p}{\rho} + \frac{u_i^2}{2}
\]

The values of the constants used in the k-ε model are \(C_1 = 1.44\), \(C_2 = 1.92\), \(\sigma_t = 1.0\), \(\sigma_\epsilon = 1.3\) and \(C_\epsilon = 0.09\) [23, 24].

The above-mentioned equations (1) to (5) were solved numerically using the finite volume method to obtain an Eulerian flow field. The boundary conditions described in Section III.2 were applied to obtain an Eulerian flow field. The boundary conditions described in Section III.2 were applied to obtain an Eulerian flow field. The boundary conditions described in Section III.2 were applied to obtain an Eulerian flow field.

To model the dispersion of the inclusions in the liquid steel flow field the stochastic tracking model (random walk model) was employed. The random walk model includes the effect of turbulence to predict the motion of individual particles by integrating the trajectory equation using the instantaneous velocity flow field \(u_i\).

\[
u_i = u_i + u_i
\]

(10)

Here, \(u_i\) denotes the mean fluid phase velocity (liquid steel) and \(u_i'\) the fluctuating velocity component which was calculated under the assumption that it obeys a Gaussian probability distribution and is given by

\[
u' = \zeta \sqrt{u'^2}
\]

(11)

Where \(\zeta\) denotes a normally distributed random number and the remainder on the right hand side of Equation (11) was calculated by using the turbulent kinetic energy of each point of the flow and was given by

\[
\sqrt{\bar{u'^2}} = \sqrt{\bar{v'^2}} = \sqrt{\bar{w'^2}} = \sqrt{\frac{2k}{3}}
\]

(12)

To measure the inclusion removal of the tundish, 520 inclusions with diameter 40 µm and density 5000 kg/m³ were introduced uniformly through the inlet gate of all the considered multi-strand tundishes and their fates were recorded. The inclusion removal efficiency is defined as the percentage of number of inclusions which do not escape out through the outlet strands from the tundish and is given by

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

(13)

Where \(N_{in}\) and \(N_{out}\) denote the number of inclusions found at the inlet gate and outlet strand gate of the tundish, respectively. Similar methodology was adopted to calculate the inclusion removal efficiency of each outlet and the overall inclusion removal efficiency of the tundish.

### III.2. Assumptions and Boundary Conditions

The three-dimensional flow was assumed to be steady and incompressible. Any entrainment of gases was neglected. A tundish was assumed to be perfectly flat. Inclusions were assumed to be spherical with diameter 40 µm and density 5000 kg/m³. In the present study micro inclusions were considered and the value of the inclusion density taken was 5000 kg/m³ based on the observations of Mikki and Thomas [1]. All exogenous inclusions and inclusions from other source, such as loose dirt, broken ceramic linings or brickwork were ignored.

A grid independence study was carried out using three grid sizes, i.e., 150000, 270000 and 350000 nodal elements. The average difference between predicted values of inclusion removal between 150000 and 270000 elements was 5% and that...
between 270000 and 350000 elements was 2%. Therefore in the present study, the domain of the tundish was divided in 270000 cells with finer zones at the inlet gate and outlet strands. For computing the velocity and thermal fields, boundary conditions used in the present study were same as those reported by Merder et al. [18]. The velocity at the inlet gate was taken as 0.9 m/s with the turbulence intensity of 5%. The wall functions were employed to obtain the values of $k$ and $\varepsilon$, wall shear stress, and all the velocity components parallel to the boundary at the first computational grid point adjacent to the wall. The top surface of the liquid steel was assumed to be free with the zero shear stress. The outflow boundary condition was assumed for all the outlet strands. For the thermal conditions, the temperature of the liquid steel at the inlet was taken as 1850 K [18-22]. All the heat losses by radiation and convection were converted in the form of heat flux. The heat loss from the top of the tundish was taken as 15000 W/m$^2$ and from other tundish walls it was taken as 2600 W/m$^2$ [18-22]. For the calculations of inclusions, those touching the side and bottom walls were assumed to be reflected whereas those touching the top surface were assumed to be trapped [1]. The SIMPLE algorithm was used for the pressure-velocity coupling and QUICK scheme was used for the discretization of momentum, energy, turbulent kinetic energy and turbulent dissipation rate equations.

**IV. Results and Validation**

**IV.1. Validation**

Before assessing the performance of different multi-strand tundishes, a validation study was carried out against the computational results reported by Merder et al. [18]. By casting two different grades of steel in a single sequence, they generated mixing time characteristics curves for all the outlet strands in a six-strand trough-type tundish. The mixing time characteristics were formed by performing calculations for transient conditions. Firstly steel was cast for certain time interval and then suddenly the whole steel was replaced by a tracer (having same properties as that of steel) whose mass weighted average was plotted against the flow time. Fig. 4 shows a comparison of the present mixing time characteristics with those reported by Merder et al. [18] and it can be seen that a good agreement is obtained between the two. Further, a validation study on the inclusion removal was carried out against the results reported by Mikki and Thomas [1] for a single-strand tundish. They used the standard $k$-$\varepsilon$ model of turbulence together with the random walk model to predict the behavior of inclusions inside a single-strand tundish. A good agreement between the present predictions of inclusion separation and those reported by Mikki and Thomas [1] can be observed in Fig. 5.

**IV.2. Optimization of Multi-Strand Tundishes**

A good tundish is the one in which the percentage of inclusion removal from each strand is approximately equal, has a minimum temperature loss between the inlet gate and the outlet strand and has minimum difference in the outlet strand temperatures.

**IV.2.1. For Same Mass Flow Rate at Inlet Gate**

Tables 1 and 2 show the inclusion removal efficiencies, outlet strand temperatures and average outlet strand velocities of liquid steel for all multi-strand tundishes with the same mass flow rate of liquid steel at the inlet gate (case a). The present results of inclusion removal efficiencies are found to be consistent with those reported computationally by Raghavendra et al. [17] for a four-strand tundish.
using the standard $k$-$\varepsilon$ model. The individual efficiency of each outlet in Tables 1 to 2 shows the percentage of inclusions which do not pass through the outlet gate strand and the overall efficiency shows the total percentage of inclusions which do not pass through all the outlet gates. For four-strand and six-strand tundishes, the overall removal efficiency differs from the removal efficiency of each outlet gate strand.

It can be seen that for the two-strand tundish F.O. provides the maximum removal efficiency as compared to that for other outlets in the two-strand tundishes (Table 1). Thus it can be concluded that with an increase in the distance between the inlet gate and outlet strand gate, the inclusion removal efficiency of the tundish increases. Moreover, for all the three cases for the two-strand tundish, the outlet strand temperature and averaged velocity at the outlet are found to be 1844 K and 10.41 m/s, respectively (Table 2). Thus, F.O. strand position provides the best casting conditions for a two-strand tundish as compared to other two positions of the outlet strand.

For the four-strand tundish, with the change in the outlet positions of the tundish the overall inclusion removal efficiency of the tundish is not significantly affected (Table 1). Further, it can be observed that there is no difference between the outlet strand temperature of F.O and M.O (Table 2). Therefore, F.O. and M.O. positions for four-strand tundish produce good casting conditions as compared to those by other two outlet positions.

An increase in the removal efficiency with an increase in the distance between the inlet and outlet gates can be understood by plotting the velocity profiles on a plane passing through the outlet strand of a tundish. Figs. 6 and 7 show the velocity vectors of liquid steel on a plane passing through the outlet strand (plane A) of two-strand tundish with the strand positions at F.O. and N.O.

By using the F.O. as the outlet strand position, a circulation region is produced far away from the outlet strand and thus it does not enhance the percentage of inclusions passing through the outlet strand gate (Fig. 6). We observe from Fig. 7 that by using N.O. for the outlet strand position, a circulation region is produced near to outlet strand of the tundish. In this circulation region more number of inclusions get trapped and finally come out from the outlet strand. This reduces the inclusion removal efficiency of the tundish.

Fig. 6 Velocity vectors drawn on plane A for two-strand tundish having outlet at F.O.

### Table 1

<table>
<thead>
<tr>
<th>Tundish Outlet Positions</th>
<th>F.O. $\eta$ (%)</th>
<th>M.O. $\eta$ (%)</th>
<th>N.O. $\eta$ (%)</th>
<th>Overall $\eta$ (%)</th>
</tr>
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<tbody>
<tr>
<td>Two-Strand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F.O.</td>
<td>81.59</td>
<td>...</td>
<td>...</td>
<td>81.59</td>
</tr>
<tr>
<td>M.O.</td>
<td>...</td>
<td>79.42</td>
<td>...</td>
<td>79.42</td>
</tr>
<tr>
<td>N.O.</td>
<td>...</td>
<td>...</td>
<td>74.59</td>
<td>74.59</td>
</tr>
<tr>
<td>Four-Strand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F.O. &amp; M.O.</td>
<td>88.13</td>
<td>89.57</td>
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<tr>
<td>M.O. &amp; N.O.</td>
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<td>91.05</td>
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<tr>
<td>F.O. &amp; N.O.</td>
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<td>87.94</td>
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<tr>
<td>Six-Strand</td>
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<tr>
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<td>94.38</td>
<td>94.02</td>
<td>91.83</td>
<td>80.23</td>
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### Table 2

<table>
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<th>Tundish Outlet Positions</th>
<th>F.O. (K)</th>
<th>M.O. (K)</th>
<th>N.O. (K)</th>
<th>Maximum difference from inlet</th>
<th>Averaged outlet-strand velocity (m/s)</th>
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<td></td>
<td></td>
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<tr>
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<td>1844</td>
<td>...</td>
<td>...</td>
<td>6</td>
<td>10.41</td>
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<tr>
<td>M.O.</td>
<td>...</td>
<td>1844</td>
<td>...</td>
<td>6</td>
<td></td>
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<tr>
<td>N.O.</td>
<td>...</td>
<td>...</td>
<td>1844</td>
<td>6</td>
<td></td>
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<tr>
<td>Four-Strand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M.O. &amp; N.O.</td>
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<td>1844</td>
<td>...</td>
<td>6</td>
<td>5.21</td>
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<td>...</td>
<td>1843</td>
<td>1845</td>
<td>7</td>
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<tr>
<td>Six-Strand</td>
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</tr>
<tr>
<td>F.O. M.O. &amp; N.O.</td>
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<td>1844</td>
<td>1846</td>
<td>6</td>
<td>3.4</td>
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For Same Mass Flow Rate at Outlet Strand Gate (Different Capacities)

Tables 3 and 4 show the inclusion removal efficiencies, outlet strand temperatures and inlet gate velocities of the liquid steel for all considered multi-strand tundishes with the same mass flow rate of liquid steel through each of their outlet strands (case b). The mass flow rate at the outlet strand gate of the six-strand tundish was chosen as the reference flow rate for calculating the mass flow rate at the inlet of different multi-strand tundishes. The principle of conservation of mass was employed to calculate the mass flow rate of liquid steel at the inlet which was then converted in terms of velocity.

It can be seen from Tables 3-4 that multi-strand tundishes having different mass flow rate at the inlet gate also follow the same pattern of inclusion removal efficiency as that of the tundishes with the same mass flow rate at the inlet (Tables 1-2). Thus we can conclude that optimum positions of the outlets are independent of the velocity of the liquid steel at the inlet gate. However, by this methodology the inclusion removal efficiency of two-strand tundish is found to be more than that of the four-strand and six-strand tundishes. The temperature drop inside the tundish was maximum in the two-strand tundish and minimum in the six-strand tundish (Table 4).

An increase in the removal efficiency of the tundish with a decrease in the inlet flow velocity can be understood with the help of governing equation (7) for the behaviour of inclusions. With a decrease in the inlet flow velocity the influence of the drag force on particle forces decreases. The direction of drag forces are along the direction of flow and direction of density difference term is always towards the top wall. Thus, with a decrease in magnitude of drag force the effect of gravitational force increases thus resulting in an increase in the removal efficiency of the tundish.

An increase in the loss of temperature inside the tundish can be understood by comparing the mixing time curve or the step type residence time curve for both two-strand tundishes (Fig. 8) with the same mass flow rate at the inlet (case a) and the same mass flow rate at each outlet strand (case b). Fig. 8 shows that the residence time of liquid steel inside a tundish for the case (b) is more than three times greater than that of the tundish for case (a). Thus the time spent by liquid steel inside tundish for different capacities (case b) is large which results in a large temperature loss inside the tundish. Moreover, as the time spent by the liquid steel inside the tundish increases, time available for inclusions to travel towards top wall increases due to which more number of inclusions get trapped on the top wall and this increases the inclusion removal efficiency of the tundish.

### Table 3

<table>
<thead>
<tr>
<th>Tundish</th>
<th>Outlet Positions</th>
<th>F.O. η</th>
<th>M.O. η</th>
<th>N.O. η</th>
<th>Overall η</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Strand</td>
<td>F.O.</td>
<td>85.50%</td>
<td>…</td>
<td>…</td>
<td>85.50%</td>
</tr>
<tr>
<td></td>
<td>M.O.</td>
<td>…</td>
<td>85.42%</td>
<td>…</td>
<td>85.42%</td>
</tr>
<tr>
<td></td>
<td>N.O.</td>
<td>…</td>
<td>…</td>
<td>76.65%</td>
<td>76.65%</td>
</tr>
<tr>
<td>Four-Strand</td>
<td>F.O &amp; M.O</td>
<td>91.30%</td>
<td>90.48%</td>
<td>…</td>
<td>81.78%</td>
</tr>
<tr>
<td></td>
<td>M.O &amp; N.O</td>
<td>…</td>
<td>92.01%</td>
<td>87.09%</td>
<td>79.11%</td>
</tr>
<tr>
<td></td>
<td>F.O &amp; N.O</td>
<td>91.21%</td>
<td>…</td>
<td>87.65%</td>
<td>78.86%</td>
</tr>
<tr>
<td>Six-Strand</td>
<td>F.O, M.O &amp; N.O</td>
<td>94.38%</td>
<td>94.02%</td>
<td>91.83%</td>
<td>80.23%</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Tundish</th>
<th>Velocity at inlet (m/s)</th>
<th>Outlet Positions</th>
<th>F.O. (K)</th>
<th>M.O. (K)</th>
<th>N.O. (K)</th>
<th>Maximum difference from inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Strand</td>
<td>0.305</td>
<td>F.O.</td>
<td>1833</td>
<td>…</td>
<td>…</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.O.</td>
<td>…</td>
<td>1833</td>
<td>…</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N.O.</td>
<td>…</td>
<td>…</td>
<td>1833</td>
<td>17</td>
</tr>
<tr>
<td>Four-Strand</td>
<td>0.612</td>
<td>F.O &amp; M.O</td>
<td>1841</td>
<td>1841</td>
<td>…</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.O &amp; N.O</td>
<td>1840</td>
<td>1843</td>
<td>1843</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F.O &amp; N.O</td>
<td>1840</td>
<td>1843</td>
<td>1843</td>
<td>10</td>
</tr>
<tr>
<td>Six-Strand</td>
<td>0.9</td>
<td>F.O, M.O &amp; N.O</td>
<td>1844</td>
<td>1844</td>
<td>1846</td>
<td>6</td>
</tr>
</tbody>
</table>
IV.3. Comparison of Multi-Strand Tundishes with Two Adopted Methodologies

By comparing the above mentioned multi-strand tundishes against the maximum overall inclusion efficiency, outlet strand temperatures, minimum band width of inclusion removal, and temperature of each strand, we can conclude that for the same capacity tundishes, a change in the number of outlet strands does not have any significant effect on the operating parameters of the tundish provided an optimum position of the outlet strand is used. For tundishes having the same mass flow rate at each outlet strands (different capacity) two-strand tundish is found to be somewhat superior in the removal of non-metallic inclusions but temperature loss in two-strand tundish is quite high as compared to that in a six-strand tundish.

V. Conclusions

An Euler-Lagrangian mathematical modeling was used to find optimum positions of outlets and to compare different multi-strand tundishes. This was done on the basis of the maximum overall inclusion removal efficiency, outlet strand temperature, maximum temperature loss inside the tundish and maximum difference of inclusion removal together with temperature difference between different outlet strands. The following conclusions may be drawn from the present study:

- For the two-strand tundish the inclusion removal efficiency increases with an increase in the distance between the inlet gate and outlet gate and the optimum outlet strand positions are independent of the velocity of liquid steel at the inlet.
- With an increase in the distance between the outlet strands the variation in the inclusion removal efficiency and temperature of the outlet strand increases.
- For the same mass flow rate of liquid steel at the inlet, different multi-strand tundishes (two-strand, four-strand, and six-strand) with the same dimensions, shape and boundary conditions have the same inclusion removal efficiency.
- For different mass flow rates of tundishes the two-strand tundish was found to be somewhat superior in the removal of inclusions from the liquid steel as compared to four-strand and six-strand tundishes.
- With a decrease in the inlet velocity of the liquid steel, the inclusion removal efficiency of the tundish increases and simultaneously the temperature loss in the tundish increases. Velocity of the liquid steel at the inlet is an important parameter for designing the operating conditions of the tundish.

In the present investigation, the scheme chosen is based on the assumption that the tundish is working on continuous operation due to which fluid (molten steel) profile is steady moreover, adhesion of small inclusions to the wall, inclusion breakage and coalescence were not taken into account and these effects can cause a reduction of the inclusion separation efficiency by approximately 10% from those obtained in real situations.

References

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