Mathematical Modeling of the Tundish of a Single-Strand Slab Caster

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The production of quality steel from a casting machine is dependent on a large number of interlinked process parameters of ladle, tundish and casting operations. Continuous casting tundishes provide an important link between the ladle and the caster and the parameters of liquid metal in the tundish get affected by both up-stream and down-stream processes.

In this paper, the variation of tundish temperature under the influence of various operating parameters is numerically simulated using a mathematical model. A two-dimensional mathematical model, based on coupled fluid flow and heat transfer, is developed to simulate the tundish operation. The model accounts for turbulent fluid flow and dynamic level changes in the tundish. The model is validated with data published in the literature as well as with data obtained during the plant campaign. Simulation of the tundish operations demonstrates the capability of the model in capturing process dynamics correctly. The effect of a few important process parameters on the tundish outlet temperature is also studied.

KEY WORDS: tundish; continuous casting; fluid flow; superheat control; casting speed.

1. Introduction

With increasing emphasis on the production of consistent quality slabs at higher casting speeds, it has become mandatory to focus on making improvements at every stage of the casting process. Slab quality is directly affected by various intermediate operations, viz., ladle operations, tundish operations, transfer operations and finally, mold and caster operations.1) Tundish operations, subject of the present study, greatly affect steel quality. Apart from its primary function of being an intermediate vessel for regulating flow to the caster, the tundish performs several other important functions including that of a refining vessel. In this direction, it is necessary to quantify the effect of various operating parameters on the performance of the process. One way to do this is through direct measurement through process sensors. However, this method has its limitations since not every parameter of interest can be measured, and even if it is possible to measure these, it may not be economical or feasible to conduct measurements on a regular basis. It is well known that mathematical models play a major role in not only filling up this gap, but also enabling better understanding of the process, the effect of various parameters (including their interactions) on the performance of the process, and also, assisting in process control.

To produce good quality slabs, it is important to have a properly designed tundish with appropriate flow-control devices (dams, weirs, baffles, pour pads, striker pads, shrouds, well etc.). A properly designed tundish should aim at increasing liquid residence time, prevent short-circuiting and promote inclusion removal.1) In recent years, physical and mathematical models have been successfully used as an aid to assess fluid flow and heat transfer conditions in the tundish for various design and operating conditions.2–16) In the case of the tundish, steel flows in from the ladle and flows out into the continuous casting mold—thus, the tundish acts as a buffer of liquid steel. In the tundish, a constant head of liquid steel is maintained (through manual or automatic control) and adequate residence time is provided to enable inclusions in steel to float out. The flow control devices are designed to assist in this direction. In addition, these devices are also employed to reduce turbulence in the tundish from the incoming ladle stream. There are several examples in the literature that highlights these aspects of tundish operations.2–16)

In most of the previous studies, tundish operations have been analyzed under steady state conditions. However, in practice, the tundish operation is rarely under steady state. Frequent changes in casting speed as well as changing conditions of the incoming stream from the ladle make the tundish operation transient. Transient thermal and flow conditions affect both the residence time distribution and the temperature of the liquid metal in the tundish. Thus, the prediction of dynamic variation of the temperature in the tundish as a function of various parameters is extremely important. As stated earlier, there are only few studies in literature where transient phenomena have been considered. Sahai and coworkers17) have studied the effect of variable temperature in the incoming liquid stream, ladle or grade
change operations, etc., on the temperature in the tundish. Besides these, the effect of ladle changeover on transient tundish temperature has also been looked into.

The level of liquid steel in the tundish (generally measured as weight) is seen to fluctuate with time and this disturbs the process—fluid flow, inclusion flotation as well as heat transfer. Obviously, the reason for this behavior is the variation in the input and the output conditions of the tundish. In addition, during the period between the end of a heat and the start of the next (changeover period in a sequence), the liquid level continues to fall until the next ladle begins to feed the tundish. All these events introduce a considerable level of transients into the process disturbing the flow behavior as well as the thermal state. Therefore, the control of superheat becomes difficult due to all the complex interactions. To the authors’ knowledge, the important aspect of level change in the tundish has not been treated satisfactorily. Besides this, mathematical models have largely been used to provide qualitative information about the plant operation in the past. Its effective uses in prediction and control of the plant operation is yet to be demonstrated.

The current work was undertaken to develop a mathematical model to simulate heat transfer and fluid flow in a tundish of LD2, Tata Steel. The main objective of this study was to develop a transient mathematical model of the tundish of a single strand caster, and employ it to predict the temperature of liquid steel in the tundish (from the entry to the exit).

2. Development of Mathematical Model

Figure 1 shows a schematic diagram of a tundish of a single strand slab caster having two dams and a striker pad. The flow field inside the tundish is frequently unsteady and turbulent, where the liquid level can change with time (especially in those cases having manual control) due to the difference between the input and the output flow of liquid steel. The transport process is dynamic due to the time dependent inflow conditions at the tundish inlet (i.e., rate of change of ladle weight), outflow conditions at tundish outlet (i.e., change in casting speed) and amount of mass accumulated. The thermal field inside the tundish depends on the fluid flow, varying temperature of the liquid steel stream coming from the ladle, heat losses through refractory lining and heat losses from top surface of liquid steel and slag. The transport process in the tundish also involves mixing and homogenization due to turbulent fluid flow conditions. Apart from these, fluctuating level of steel in the tundish can have a significant effect on the turbulent field. To quantify the effect of each of the process parameters separately, a comprehensive mathematical model was developed in the present work. The model accounts for turbulent fluid flow and heat transfer conditions in the tundish as well as keeps track of the fluctuating liquid steel domain as a function of time. The geometry of the tundish and heat loss through the refractory/steel shell are also considered in the model.

The Reynolds averaged Navier–Stokes (RANS) equation and continuity equations were employed for modeling the turbulent fluid flow conditions. The standard $k–\varepsilon$ model was used for handling turbulence. The model used the integral form of the governing equations for an arbitrary moving control volume with pressure and velocity components as dependent variables. The space conservation law was satisfied ensuring a fully conservative computational procedure. The equations employed in the model are capable of handling moving boundaries. Non-orthogonal grids were used to represent the complex geometry of the tundish. Thus, the model is capable of handling geometrical complexities involving different combinations of dams, weirs and striker pads. The heat transfer involves both solid domains (refractory lining, dam, weirs and steel shells), as well as liquid domain. A conjugate heat transfer methodology was employed to model thermal transport in both solid and liquid regions simultaneously. The details of the model formulations are described in the following section.

2.1. Governing Equations

The transport phenomena in the tundish are governed by the conservation of mass, momentum and energy. Additionally, turbulent flow is accounted for through the use of the $k–\varepsilon$ model where $k$ is the turbulence kinetic energy and $\varepsilon$ is the rate of dissipation of kinetic energy. In the formulation of the model, the following assumptions were invoked: (1) The transport processes are 2-dimensional, (2) The flow is described by the conservation equations for an incompressible Newtonian fluid with constant properties, and (3) The two-equation ($k–\varepsilon$) model is used to estimate turbulent flow using the constants reported by Launder and Spalding. For two-dimensional, unsteady and incompressible fluid flow calculations, the conservation equations for all transport variables in a Cartesian coordinate is written as follows:

$$\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho (u_i - v_b) \phi - \Gamma_\phi \frac{\partial \phi}{\partial x_i} \right) = S_\phi \ldots \ldots (1)$$

where, $\phi$ denotes the transport variable, $x_i$ is the $i$-th Cartesian space coordinate, $u_i$ is the $i$-th Cartesian velocity component, $\rho$ is the density of the fluid, $\Gamma_\phi$ is the diffusivity of $\phi$, $v_b$ is the boundary velocity and $S_\phi$ is the source term of $\phi$. The values of $\phi$, $\Gamma_\phi$ and $S_\phi$ for all transport equations applied in the model are presented in Table 1. The constants used in Table 1 have the following values:

$$\sigma_1 = 1.0, \quad \sigma_2 = 1.3, \quad c_{1e} = 1.44 \quad \text{and} \quad c_{2e} = 1.92 \ldots \ldots (2)$$
For the sake of simplicity, the equations are given here in the Cartesian coordinate system, but the computations were performed using Curvilinear boundary-fitted grids.

2.2. Initial Condition

Before pouring of liquid steel, the tundish was preheated by flame heating. The temperature profile of the refractory at the end of the preheating operation constitutes the initial condition for the model. The initial conditions for the model were obtained through solution of an auxiliary model (described in Appendix I). For fluid flow, the initial conditions were from steady-state analysis. Transient simulations were carried out using these as initial conditions.

2.3. Boundary Conditions

For the momentum equation, the following boundary conditions were imposed:

Free surface: No shear
\[ \tau_s = 0, \quad v = 0 \].................................(3)

Other walls: No slip
\[ u = v = 0 \].....................................(4)

For the heat transfer equation,
Top surface: Convective and radiation heat flux losses
\[ q = h(T_s - T_o) + \varepsilon e(T_s^4 - T_o^4) \].....................(5)

Refractory walls: Convective heat loss
\[ q = h(T_s - T_w) \] ..................................(6)

In Eqs. (5) and (6), \( T_s \) and \( T_w \) are the surface and the ambient temperatures, respectively.

For simulating actual operating conditions of the plant, the inflow rate was calculated using data on the ladle weight, and the outflow from the tundish was calculated from the data on casting speed. The tundish level change was calculated based on variation of ladle weight and casting speed as a function of time. After performing the calculation on the inflow rate, the outflow rate and the level change as a function of time, these were used for specifying the boundary conditions in the tundish model.

2.4. Grid Generation and Solution Methodology

As shown in Fig. 2, the tundish being modeled here has a complex shape and consists of two dams, striker pad. This shape was modeled by dividing the domain into small, regular-shaped sub-domains. Algebraic grids were generated inside these sub-domains. With this strategy, the grid distribution can be easily customized for any tundish geometry.

Table 1. Transport variables.

| Conservation Variable | \( \phi \) | \( \Gamma_\phi \) | \( S_\phi \) |
|-----------------------|--------|-------------|-------------|
| Momentum (j-th component) | \( u_j \) | \( \mu + \mu_t \) | \( \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu + \mu_t \right) \frac{\partial u_j}{\partial x} \) |
| Turbulent kinetic energy | \( k \) | \( \mu + \frac{\mu_t}{\sigma_k} \) | \( \frac{\mu}{\sigma_k} \left( \frac{\partial u_i}{\partial x} + \frac{\partial u_j}{\partial x} \right) \frac{\partial u_i}{\partial x} - pe \) |
| Dissipation rate of \( k \) | \( \varepsilon \) | \( \frac{\mu + \mu_t}{\sigma_e} \) | \( \frac{\varepsilon \mu_t}{k} \left( \frac{\partial u_i}{\partial x} + \frac{\partial u_j}{\partial x} \right) \frac{\partial u_i}{\partial x} - c_\varepsilon D \varepsilon \) |
| Energy \( T \) | \( T \) | \( K / C_p \) | 0 |

Fig. 2. Schematic of calculation domain and grid distribution.

The governing equations were discretized by using the finite volume method on a collocated grid variable arrangement. The convection-diffusion terms were discretized using the upwind scheme and the finite volume equations were developed using a first-order, fully implicit, time discretization scheme. Pressure-velocity coupling was achieved by following the SIMPLE algorithm. The linear equations were solved using the Strongly Implicit Procedure (SIP) of Stone, based on incomplete LU factorization of the coefficient matrix.

2.5. Preliminary Model Validation

Using the standard \( k-e \) model, the flow for the lid driven cavity was simulated for preliminary validation of the model. The standard wall function treatment was applied at the walls of the tundish. The Reynolds number (Re), based on surface friction velocity and the depth of the cavity, is 6000, which is high enough to ensure turbulent flow. The results of the simulation were compared with those of Rodi’s experimental data on velocity along the mid-vertical plane of the cavity. The predicted normalized velocity profile in the \( x \)-direction along the vertical plane in the middle of the cavity is shown and compared with the experimental data in Fig. 3. It is evident that the predictions from the present model exhibit a good agreement with the experimental data of Rodi.

2.6. Plant Campaign

As a part of this study, plant campaigns were carried out to collect temperature and other operational data from the tundish operation. These data were used as input to the model as well as for tuning and validation of the model. During the plant campaign, the following plant data were collected:

- Discrete temperature measurements at inlet and outlet of the tundish vessel for a complete casting sequence
- Casting speed variations as a function of time
- Tundish weight variations as a function of time
- Ladle weight variation as a function of time
2.7. Thermo-physical Properties

Table 2 shows the thermo-physical properties used as input to the model. The effective refractory properties are calculated to account for different refractory layers/lining at the tundish steel shell. The material properties are taken from the literature. Although the conservation equations adequately represent the physics of turbulent flow with heat transfer, there are several parameters, which are dependent on plant conditions and are not explicitly known. These parameters need to be estimated from the measured data, so that there is minimum mismatch between the measured data and model prediction.

2.8. Tuning of the Model with Plant Data

This section describes the strategies adopted for tuning and validation of the tundish model with plant data. For the tundish model, the tuning parameters are (a) heat transfer coefficients \( h \) and (b) emissivity \( \varepsilon \) from various surfaces. These parameters are estimated using measured discrete temperature data from the plant for one complete sequence consisting of six ladle heats. The parameters are tuned through trial and error until a best mean fit is obtained between the measured and the predicted temperatures. After tuning, temperature predictions from model showed good agreement with plant data as seen in Fig. 4. The final values of the tuned parameters are as follows:

- Heat transfer coefficients \( h \):
  - Tundish side surface: \( h = 5 \text{ W/m}^2\text{K} \),
  - Tundish bottom surface: \( h = 2 \text{ W/m}^2\text{K} \),

- Emissivity \( \varepsilon \):
  - Tundish side surface: \( \varepsilon = 0.8 \),
  - Tundish bottom surface: \( \varepsilon = 0.1 \),
  - Liquid steel: \( \varepsilon = 0.001 \).

The tuned value of emissivity from liquid steel is very low. This is because of the fact that the loss from the top is negligible. In fact, the low value of loss from the top is due to several sub-processes such as exothermic heat generation due to solidification of slag and so on. These sub-processes are not accounted for directly in the model. Nevertheless, its influence is seen indirectly through the low value of emissivity from the top surface.

3. Simulations of Tundish Operation

3.1. Comparison of Model Prediction with Discrete Temperature Measurement

The tuned mathematical model is used to simulate the tundish operation. For this purpose, plant data from two complete sequences, case 1 and case 2, are used. These sequences consist of five and four ladle changes, respectively. Figures 5 and 6 show fluctuations in the tundish weight and casting speed as a function of time for case 1. Using this information, the transient level changes and inlet boundary conditions are computed. Besides these, the tundish inlet temperature, measured at the plant, is used as thermal boundary conditions at the inlet. Model predictions were compared with measured discrete tundish outlet temperatures. Figure 7 shows the comparison of model prediction with the plant measurements for case 1. It is readily seen that the model predictions compare well with the plant.
measurements and are within ±5°C. The model was further used to simulate another set of plant data (case 2). Figure 8 shows the comparison of predicted temperature with the plant measurements for case 2. For this case also, model predictions are in good agreement with the plant measurements.

3.2. Comparison of Model Prediction with Continuous Temperature Measurements

Apart from the discrete temperature data, used to show the predictive power of the model in the previous section, one set of continuous temperature data at the tundish outlet was collected for case 2 during the plant campaign. This special measurement was obtained from a thermocouple placed inside the stopper rod. Continuous temperature measurements have an advantage over discrete measurements as it provides accurate trends in temperature variations during the progress of a sequence casting. The model was used to simulate this sequence. Figure 9 shows the comparison of model predicted temperature at the tundish outlet with plant data from continuous temperature measurement. The results show that the model not only captures the trend of temperature variation accurately but also provides an excellent quantitative match with temperature data. Such an agreement between predictions and measurement demonstrates the capability of the model in capturing the process dynamics related to flow and thermal transients in the tundish.

4. Effect of Key Process Parameters on Flow and Thermal Fields

As seen in the previous section, the model could clearly depict the process transient in terms of outlet temperature. In this section, results of the parametric study are summarized. The validated model is used to quantify the effect of some important process variables on thermal and flow transients and eventually on outlet tundish temperature. Prior to describing the effect of process parameters, typical thermal and flow patterns inside a tundish are described. Figure 10 shows the stream traces of the flow field inside the tundish vessel. It is important to note here that the flow field in a tundish is actually 3-dimensional. The present 2-dimensional model, therefore, provides only a good overall qualitative idea of the flow pattern. At the entry point, the flow pattern exhibits the formation of two cells on both sides of the inlet shroud due to the effect of the inlet jet. A plug flow can be noticed at the top leading to the outlet port. As expected, for the design under consideration, the flow pattern shows the presence of two dead zones behind two dams.

Figure 11 shows isotherms for this case. It clearly shows the presence of cold steel between the dams as well as near
the walls. In contrast to this, there is only a marginal variation in temperature in the stream going through the top portion. This signifies the presence of an actively mixed region at the top. In subsequent sections, the effect of two important process parameters, namely, the tundish preheat temperature and the temperature of the inlet stream from the ladle, are studied with the help of the mathematical model.

The importance of the former is on uses of cold tundish, which have been considered in several plants. With the help of the mathematical model, it is possible to quantify its effect on the tundish outlet temperature. Secondly, the variation in temperature of the inlet stream leads to the variation in temperature of the tundish outlet stream. For the purpose of control of the tundish outlet temperature, it is extremely important to correlate it with temperature variation of the inlet stream.

4.1. Effect of Tundish Preheat Temperature

Preheating of the tundish affects the initial heat absorbed by the refractory during continuous casting. In order to quantify its effect, two simulations were performed. In the first case, a cold tundish was used (without preheating). In the second case, a normal tundish was used (with preheating). Figure 12 shows the effect of these conditions on the tundish outlet temperature. It is noted that the effect of preheating is significant during the initial 15–20 min of the casting. Although overall trends of temperature drop are similar in both cases, the temperature drop for cold tundish is more compared to preheated tundish. For the case of cold tundish, the initial drop in the outlet temperature is due to the chilling effect as cold refractory absorbs a large quantity of heat. Subsequently, the refractory temperature rises with the progress in sequence casting and the influence of cold tundish diminishes in later stages. The temperature increases until the transient effect dies out; after this, the temperature starts to decrease at a slower rate. Although the difference between the two cases lasts for nearly two hours, the significant difference is only in the initial phase of sequence casting. It is important to note that preheat does not have significant effect from the 2nd heat onwards. The sharp drop during the first heat in case of the use of cold tundish can be readily compensated by providing extra temperature in the ladle for the first heat. This point is further illustrated in the subsequent section, where the role of the temperature of incoming ladle stream on the tundish outlet temperature is investigated.

4.2. Effect Ladle Steel Temperature

In this case, the effect of the ladle steel temperature on the tundish outlet temperature was studied using the model. To illustrate this issue, two simulations were carried out. These two cases were similar in all respects except that, in one case, the ladle steel temperature for the 2nd heat of the sequence was 10°C higher compared to the other case. The difference was deliberately kept in the 2nd heat of the sequence as this allowed sufficient time for the transient effects of tundish preheating to die down. Figure 13 compares the predicted outlet tundish temperature for these two cases. It is readily seen that the temperature increase in the ladle is reflected in the outlet tundish temperature. However, there is a time lag before the effect of the difference in ladle temperature on outlet tundish temperature is fully reflected. The time lag is because of the mixing of the incoming liquid stream from the ladle with the remaining liquid of the previous sequence. Similarly, at the end of the second sequence, it takes some time in the third heat before the effect of the higher ladle temperature of the second heat is completely diminished. However, except for the time lag, the direct correspondence between the ladle temperature and the tundish temperature is readily evident. This information can be effectively used to prescribe ladle temperature under a variety of conditions. This includes prescribing the ladle temperature for the first heat in case of the use of cold tundish, for the last heat of the sequence and for the cases with unusual delays.

5. Summary and Conclusions

A comprehensive process model for fluid flow and heat transfer in the tundish was developed with a capability to capture the transient process dynamics. The model is based on a conjugate thermal analysis of the tundish, accounting for simultaneous heat transfer through the liquid steel, refractory, steel shell and dams. This model is checked for numerical correctness by comparing model predictions for laminar as well as turbulent fluid flow conditions cited in the literature. As a part of this study, plant campaigns were undertaken to collect plant data for the tuning and validation of the model. Using the plant data, the tundish model was tuned. The tuned model was used to simulate tundish operations during several sequence casting and the predicted tundish temperature at the tundish outlet compared well with measured plant data. Using the tundish model, effect of a few important process parameters on the tundish outlet temperatures were studied. The potential of the model for control of tundish superheat was also highlighted.

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edged.

Nomenclature

- \( p \): Density (kg/m\(^3\))
- \( k \): Turbulent kinetic energy (m\(^2\)/s\(^2\))
- \( \varepsilon \): Dissipation rate of \( k \) (m\(^2\)/s\(^3\))
- \( T \): Temperature (°C)
- \( K \): Thermal conductivity (W/m\(^2\) K)
- \( C_\rho \): Specific heat of material (J/kg K)
- \( U_j \): Velocity in \( j \)-direction (m/s)
- \( f \): Variable
- \( P \): Pressure (N/m\(^2\))
- \( x_j \): \( j \)-direction

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Appendix

Before pouring of liquid steel, the tundish is preheated
by flame heating. The temperature profile of the refractory
at the end of the preheating operation constitutes the initial
condition for the model (Eq. (1) in conjunction with Table
1). This was obtained through an auxiliary model, which is
described below. Due to low thermal conductivity and large
thickness of the refractory, the heat flow through the refrac-
tory during preheat is assumed to be one dimensional along
the thickness. Accordingly, the heat flow is represented by
the following governing equations:

\[
\rho C_\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) \tag{1a}
\]

with the following initial and boundary conditions:

Initial condition:

\[
T = T_0 \quad (t=0) \quad \text{at all } x \tag{2a}
\]

Boundary conditions:

\[
T = T_1 \quad \text{at } x = 0 \quad \text{(Inner surface of refractory)} \tag{3a}
\]

\[
T = T_2 \quad \text{at } x = 1 \quad \text{(Outer surface of refractory)} \tag{4a}
\]

During the plant campaign, temperatures of the inner as
well as outer surface of the tundish were measured by an
optical pyrometer. These data were used to specify the tem-
perature boundary conditions, i.e., \( T_1(t) \) and \( T_2(t) \) of Eqs.
(3a) and (4a). Temperature distribution in the refractory at
the end of the preheating operation was estimated through
the solutions of Eq. (1a). This temperature profile was used
as initial refractory temperature for the main model.