Criticality of Sampler Locations in Inert-gas Shrouded Tundishes during Open Eye Events and Unbalanced Throughputs

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The standard sampling practice involves procuring lollipop samples from an opening on tundish floor close to the stopper rods. Analyzing these samples gives us an overall idea about the chemistry of steel and inclusions in the tundish. A mathematical model was built using computational fluid dynamics to determine the inclusion paths in cases of balanced and unbalanced throughput casting of steel. The calculated trajectories showed that the inclusions are mostly concentrated near the ladle shroud where the tundish open eye (TOE) forms. In order to investigate the effect of TOEs on the chemistry of steel, the ideal sampling location was determined from the mathematical model.

KEY WORDS: tundish open eye; mathematical modeling; Discrete Phase Modeling; inclusion tracks; sampler location.

1. Introduction

Recently, the study of tundish open eye formation (TOE)1–4 has become a popular topic of research at ArcelorMittal Dofasco and the Process Metallurgy and Modelling Group at the University of Toronto. TOEs are believed to be a major cause of reoxidation of liquid steel in tundishes. Reoxidation gives rise to harmful inclusions which in turn result in clogging of SENs. To a steel plant, it means inferior product quality, loss of productivity, and ultimately bad for their bottom line. Researchers at ArcelorMittal Dofasco and University of Toronto have now turned their attention towards investigation of TOEs from both experimental, and modeling perspectives, in conjunction with plant trials. The problem has been analyzed from a variety of aspects including numerical simulation,1,2,3 physical modeling4 and fundamental laws of physics.4

The observations from physical and mathematical models in previous research1–4 have provided us with valuable insights into the field of open eye formation. However, plant trials are required to better understand the phenomenon and fine tune the numerical models. It is cumbersome to carry out controlled plant trials, and obtain proper results on the account of adverse conditions such as high temperatures, and lack of visibility due to opacity of steel/slag or the vessel itself.

Nonetheless, few researchers in the past have performed experimental studies on sampling techniques. Ericsson5 observed that Argon protected samplers have desirable filling velocities and lower slag entrapments compared to conventional samplers. Ruby-Meyer et al.6 were able to come up with few important conclusions from their work. They supported Ericsson’s claim and stated that an Argon blowing sampling device was much more reliable than conventional sampling since the former leads to controlled sample filling velocity, less slag/powder entrapment and steel reoxidation. Cooling samples in air resulted in fewer cracks compared to water quenching. Moreover, lollipop-shaped samples were preferred since they allowed better control over location of shrinkages.

Although significant amount of research has been done on different aspects of sampling, no one has tried to investigate the importance of sampling position. The steel plants usually have a standard operating practice for placing the commonly used lollipop samplers. The standard operating practice may be beneficial for a general case. For instance, the standard operating practice for sampling is performed near the stopper rod. Analyzing samples obtained from such a position gives a good idea about the general chemistry of molten steel and inclusions present in the tundish.

However, the sampling position needs to be altered in case of special events such as during the formation of TOEs or the practice of unbalanced throughputs. Hence, the present work was performed to determine the most effective sampling position to specifically study the TOE formation process and its effects. The main purpose of sampling from plant trials is to obtain samples which when analyzed can provide us with details of the process being studied. Inclusions present or formed in a tundish result from a number of sources such as dissolution of refractories, gunning mass, slag entrainment, etc. In the present study, the main objective was to investigate the inclusions generated due to TOE events only.

2. Mathematical Modeling

A mathematical model was developed using the standard $k$-$ε$ turbulence model7 and the discrete phase method,8 coupled with the discrete random walk model.9 The various physical properties and operational parameters are depicted in Tables 1 and 2. Since the alumina inclusions are present mostly as clusters, effective density of the cluster was considered.10

The trajectories of inclusions within the tundish were predicted and new position of samplers were suggested based on these predictions.

2.1. Standard $k$-$ε$ Turbulence Model

The standard $k$-$ε$ model by Launder and Spalding7 was used to model the turbulence. Here, $ε$ is the rate of turbulence energy dissipation, while $k$ stands for the kinetic energy dissipation rate.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Steel</th>
<th>Argon</th>
<th>Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density$^a$, kg/m$^3$</td>
<td>6 977</td>
<td>0.267</td>
<td>5 000</td>
</tr>
<tr>
<td>Viscosity, kg/m·s</td>
<td>0.006</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$Density of Argon calculated at a temperature of 1 550°C using ideal gas law
energy of turbulence per unit mass, and is related to the time averaged-velocity $\bar{\mu}$ as follows:

$$k = \frac{1}{2} \sum_i \bar{u}_i^2$$  \hspace{1cm} (1)

The two extra equations for $k$ and $\epsilon$ that need to be solved are as follows:

$$\frac{Dk}{Dt} = \frac{\nu_v}{\sigma_k} \nabla^2 k + G_k - \epsilon \hspace{1cm} (2)$$

$$\frac{D\epsilon}{Dt} = \frac{\nu_v}{\sigma_\epsilon} \nabla^2 \epsilon + \frac{\epsilon}{k} (C_1 G_k - C_2 \epsilon) \hspace{1cm} (3)$$

The parameter $G_k$ is the rate of production of $k$ and is given by the following equation:

$$G_k = \nu_v \left[ \frac{\partial \bar{v}_i}{\partial x_j} \frac{\partial \bar{v}_i}{\partial x_j} \right] \frac{\partial \bar{v}_i}{\partial x_j} \hspace{1cm} (4)$$

Finally, the turbulent and the effective viscosities are calculated by making use of the following relations:

$$\mu_t = \frac{C_\mu \rho k^2}{\epsilon} \hspace{1cm} (5)$$

$$\mu_{eff} = \mu + \mu_t \hspace{1cm} (6)$$

The values for the constants in the standard $k-\epsilon$ model recommended by Launder and Spalding: $C_1 = 1.44$, $C_2 = 1.92$, $C_{\mu} = 0.09$, $\alpha_l = 1$ and $\alpha_\epsilon = 1.3$, were used in the present work without any modification.

### 2.2. Discrete Phase Model

In the discrete phase modeling procedure, the fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets, through the previously calculated flow field in a Lagrangian frame of reference. Two-way coupling considering the effects of continuous and discrete phases on each other is accomplished by alternately solving the discrete and continuous phase equations, until the solutions in both phases have stopped changing. The basic equations involved in discrete phase modeling are as follows:

$$\frac{d u_{rel}}{dt} = \frac{18 \mu C_D \Re}{24 \rho_p d_p^2} u_{rel} + \frac{g(\rho - \rho_p)}{\rho_p} + \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt} u_{rel} \hspace{1cm} (7)$$

$$\Re = \frac{\rho d_p u_{rel}}{\mu} \hspace{1cm} (8)$$

It is important to consider the dispersion of particles due to presence of a highly turbulent flow of the continuous phase. This has been done by using a stochastic tracking model, which incorporates the effect of instantaneous turbulent velocity fluctuations on particle trajectories using stochastic methods.

The instantaneous fluid velocity is given by:

$$\bar{u} + u'(t) \hspace{1cm} (11)$$

### 2.3. Discrete Random Walk Model

The interaction of a particle with a succession of discrete stylized fluid phase turbulent eddies is simulated in the Discrete Random Walk (DRW) model. Each eddy is characterized by:

(a) A Gaussian distributed random velocity fluctuation, $u'$, $v'$ and $w'$ so that

$$u' = \zeta \sqrt{\bar{u}^2} \hspace{1cm} (12)$$

where, $\sqrt{\bar{u}^2}$ is the local RMS value of velocity fluctuations. Assuming isotropy, the values of RMS fluctuating components are defined from known values of kinetic energy, $k$, as follows:

$$\sqrt{u^2} = \sqrt{v^2} = \sqrt{w^2} = \sqrt{2k/3} \hspace{1cm} (13)$$

(b) A time scale, $\tau_e$.

The timescale actually defines the characteristic lifetime of the eddy. It can be either a constant as:

(i) $\tau_e = 2T_L \hspace{1cm} (14)$

where, $T_L = 0.15k/\epsilon \hspace{1cm} (15)$

(ii) or a random variation about $T_L$:

$$\tau_e = -T_L \ln(r) \hspace{1cm} (16)$$

where $0 < r < 1$.

The second approach yields a better description of the characteristic correlation function of the time scale. The particle eddy crossing time is defined as:

$$t_{cross} = -\tau \ln \left[ 1 - \left( \frac{L_e}{\tau u_{rel}} \right) \right] \hspace{1cm} (17)$$

The particle is assumed to interact with the continuous fluid phase eddy over a time which is smaller out of the eddy lifetime and the eddy crossing time. As soon as this time is reached, a new value of instantaneous velocity is obtained by applying a new value of $\zeta$ in Eq. (12).

### 2.4. Initial and Boundary Conditions

Since both balanced and unbalanced throughputs of steel were modeled, constant velocities of specific magnitudes needed to be considered at the inlet and each outlet. The values of $k$ and $\epsilon$ at inlet were fixed based on previous correlations as:

$$k = 0.01v_0^2 \hspace{1cm} (18)$$

$$\epsilon = 2k^{1.5}/D_m \hspace{1cm} (19)$$

$$C_D = a_1 + \frac{a_2}{\Re} + \frac{a_3}{\Re^2} \hspace{1cm} (10)$$
At the outlets, a low value of turbulent intensity, and hydraulic diameter equal to the outlet diameter were considered. Stationary wall with the no-slip condition was considered for modeling momentum transfer at the solid walls of tundish. The free surface of the liquid steel in the tundish was modeled as a stationary wall with zero shear stress. The particle criteria was set such that inclusions were reflected on striking any solid wall and escaped at the free surface or on reaching the outlets.

3. Results and Discussion

Inclusion trajectories in the tundish were calculated for two cases: with and without Ar flow. The cases without Ar flow represents those in which no TOE forms and are represented in Fig. 1. Since inclusions with bigger sizes can easily float up inside the tundish and are relatively less important, smaller sized inclusions with a diameter of 1–5 μm were considered in the present model. The frontal and top views of inclusion tracks for the case of balanced throughput casting are depicted in Fig. 1(a). The inclusions were concentrated mostly near the central part of the tundish. They either float towards the top surface or float out towards the SENs; the distribution being almost equal on both sides.

There is a striking difference between balanced and unbalanced throughput casting of steel. Unbalanced casting is the practice where the flow rates of liquid steel are different through different SENs. Such a practice is required to adhere to different casting rates that are dictated by downstream operations. In case of an unbalanced throughput casting, the flow of inclusions is concentrated more towards the side of higher throughput rate as shown in Fig. 1(b). Since inclusions follow the flow of the bulk liquid phase, the observations are quite logical.

In our previous work based on a combination of mathematical modeling, water modeling and plant trials, we were able to show that slag eyes or TOEs start to form as the gas flow rate is gradually increased. It is evident that a volume flow rate of gas corresponding to 5 percent of the bulk phase flow rate can certainly generate TOEs. This fact was also observed in our recent mathematical modeling study. 5 percent Ar gas flow rate for the present tundish corresponds to a value of 8 LPM under STP (standard temperature and pressure). Hence, the case with TOE formation was simulated by considering the same value of Ar flow rate. The inclusions formed at the TOEs by reoxidation of steel are usually very small in size. The highly turbulent flow conditions transfer the inclusions away from the top surface and prevent their growth. The small inclusions are readily swept towards the tundish floor or near the SENs. Hence, the inclusion size was considered to be < 5 μm in this case. Both the cases of balanced and unbalanced throughput casting with Ar flow were considered as shown in Fig. 2. Similar to the case of no TOE, the concentration of inclusions is more near the central region of the tundish. Moreover, the inclusions flow preferentially more in the direction of higher throughput rate as shown in Fig. 2(b).

4. Conclusion

The standard operating practice for sampling is performed near the stopper rod. This has been depicted by marking the regions in black in Fig. 3. The analyses of inclusion trajectories from mathematical modeling allowed the prem-
ent researchers to come up with useful recommendations. In order to capture the effect of TOE on reoxidation and inclusion formation, the sampling should be done close to the ladle shroud as shown in red in Fig. 3. TOEs have been schematically depicted in Fig. 3. Since most of the inclusions formed at the TOE are concentrated near the central part of tundish, it is not worthwhile to perform sampling at regions away from the TOE. It must be ensured that the sampler is positioned deep enough in the liquid steel phase to prevent contamination from the overlying slag phase. For this purpose, use of ladle sampler which are longer in length is recommended from this study. It is expected that analyzing the samples obtained from ‘near-eye regions’ would allow researchers to come up with useful recommendations.

Presently, samplings are being practiced at locations recommended from this study. It is expected that analyzing the samples obtained from ‘near-eye regions’ would allow us to investigate explicitly the effect of TOEs on steel and inclusion chemistry.

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Fig. 3. Proposed sampling position. Case 1- Balanced casting: 3.5 TPM (left) and 3.5 TPM (right), Case 2- Unbalanced casting: 3 TPM (left) and 4 TPM (right). Circular zone around shroud: schematic representation of TOE Black and red samplers: Standard operating location and proposed operating location respectively. (Online version in color.)

Nomenclature

\( k \): Kinetic energy of turbulence per unit mass, \( \text{m}^2/\text{s}^2 \)
\( \overline{u_i} \): Time averaged-velocity, \( \text{m} \text{s}^{-1} \)
\( e \): Rate of energy dissipation, \( \text{m}^2/\text{s}^3 \)
\( \nu \): Kinematic viscosity of fluid, \( \text{m}^2/\text{s} \)
\( C_i, C_2, C_{pa} \sigma \) and \( C_{s2} \): Empirical Constants
\( G_k \): Rate of production of \( k \), \( \text{kg} \text{ms}^{-3} \)
\( x_i \): Cartesian space coordinate
\( v_i \): Velocity in the direction \( x_i \), \( \text{m} \text{s}^{-1} \)
\( \mu_1 \): Turbulent viscosity, \( \text{kg} \text{m}^{-1}s^{-1} \)
\( \rho \): Density of the fluid, \( \text{kg} \text{m}^{-3} \)
\( \mu_s \): Effective viscosity, \( \text{kg} \text{m}^{-1}s^{-1} \)
\( \mu \): Viscosity of the fluid, \( \text{kg} \text{m}^{-1}s^{-1} \)
\( u_p \): Particle velocity, \( \text{m} \text{s}^{-1} \)
\( C_D \): Drag coefficient
\( d_p \): Particle diameter, \( \text{m} \)
\( u_{rel} \): Fluid velocity relative to the particle, \( \text{m} \text{s}^{-1} \)
\( \rho_e \): Density of the particle, \( \text{kg} \text{m}^{-3} \)
\( v_0 \): Velocity at inlet, \( \text{m} \text{s}^{-1} \)
\( D_{in} \): Inlet (ladle shroud) diameter, \( \text{m} \)
\( a, a_2, a_3 \): Constants
\( \bar{u} \): mean fluid phase velocity
\( u(t) \): fluctuating fluid phase velocity component
\( \zeta \): normally distributed random number
\( r \): uniform random number, \( 0 < r < 1 \)
\( \tau \): time scale
\( \tau_e \): particle relaxation time
\( T_L \): fluid Lagrangian integral time
\( L_e \): eddy length scale
\( Re \): Reynolds number, \( \frac{\rho D L \bar{u}}{\mu} \)
\( L \): Characteristic length, \( \text{m} \)
TPM: Tonnes Per Minute
LPM: Liters Per Minute
DPM: Discrete Phase Modelling
TOE: Tundish Open Eye
STP: Standard Temperature and Pressure