Formation of Slag ‘eye’ in an Inert Gas Shrouded Tundish

Saikat CHATTERJEE and Kinnor CHATTOPADHYAY*

Process Metallurgy and Modeling Group, Department of Materials Science and Engineering, University of Toronto, 184 College Street, Toronto, Ontario, M5S 3E4 Canada.

(Received on January 7, 2015; accepted on March 26, 2015)

Inert gas shrouding is a common practice in tundish metallurgy and has manifold benefits. However, there are a few detrimental aspects associated with it, and one of them is the formation of an exposed ‘eye’ around the ladle shroud which results in higher heat losses, and more importantly re-oxidation of the liquid steel and inclusion formation. Hence, it is essential to gain proper insights about the formation, and evolution of slag ‘eye’s in tundishes so as to improve the operations, and enhance liquid metal quality. In the present work, the behavior of slag ‘eye’ in tundishes have been simulated using the finite volume based program ANSYS-FLUENT 15. The mathematical modeling was performed using the Volume of Fluid (VOF) method, and discrete phase method, coupled with the standard k-ε turbulence model. The predictions from mathematical modeling were validated against one-third scale water model experiments. Although the present numerical results over-predicted the experimental results by ~17%, they are well within reasonable limits considering the complexity, and stochastic nature of the problem.

KEY WORDS: slag ‘eye’; tundish; mathematical modeling; physical modeling; volume of fluid; discrete phase modeling.

1. Introduction

There are mainly three regions in any gas-stirred vessel such as ladle or tundish viz., a recirculating liquid zone, a two-phase gas-liquid plume, and a raised spout region. The region of the spout which is open to the atmosphere is somewhat circular in shape and hence it is named as the spout ‘eye’. The spout ‘eye’ in a metal-slag-gas system can be called as the slag ‘eye’ because the ‘eye’ appears as a result of displacement of the slag layer from its initial position. The different regions inside a tundish along with the slag eye have been schematically shown in Fig. 1. The slag ‘eye’ can alternatively be called as the plume ‘eye’ or the exposed ‘eye’. Although the gas-liquid plume generates turbulence which improves the kinetics of the reactions at the metal-slag interface, there can be oxygen and nitrogen pickup from the atmosphere which is detrimental to the quality of steel.

Moreover, slag entrainment and re-oxidation of liquid metal can produce harmful inclusions. Heat losses from the slag ‘eye’ can lead to drop in melt temperatures as well.

There has been a lot of active research in the area of slag ‘eye’ formation due to inert gas purging in the steel ladles for the last few years. Mazumdar and Guthrie1) presented a comprehensive review on all the research related to slag ‘eye’ formation till 1995. Several other studies were performed in the following years. Yonezawa and Schwerdtfeger2) systematically investigated the formation of the open spout on slag covered metallic melt using a video photographic technique. First of all, they carried out cold model experiments using mercury, silicon oil and nitrogen to mimic the metal, slag, and the purged gas phases respectively and followed up with plant experiments in a 350 t steel ladle where argon gas was purged. The measured spout ‘eye’ areas at different operating conditions were converted to dimensionless areas and compared to the dimensionless Froude number in order to find a functional relationship using regression analysis. It was observed that the results of the plant experiments did not match those predicted from the correlations. Moreover, the correlations did not include the effect of the other operating variables such as metal height, gas pressures, viscosity, and density of the fluids, etc. Subagyo et al.3) argued that the expression of dimensionless spout area used by Yonezawa and Schwerdtfeger2) was not justified physically. Hence, they considered a new parameter, which was a ratio of the spout ‘eye’ area to the spout area, and claimed that they were able to obtain better agreement between their calculated results and the experimental data of Yonezawa and Schwerdtfeger.3) Mazumdar and Evans4) suggested that that Froude number should be
expressed as $U_p^2/gH$ instead of $Q^2/gh^3$ in gas stirred ladle systems since the former leads to more meaningful ratios of inertial to gravitational forces. Mazumdar and Evans\(^5\) carried out theoretical analysis to develop an expression correlating the plume ‘eye’ area and operating variables from the basic principles of ladle hydrodynamics. Their relationship described the experimental data of Yonezawa and Schwerdtfeger\(^2\) fairly well. They concluded that a single functional relationship would not work for different gas-stirred systems unlike that suggested previously by Subagyo \textit{et al.}\(^3\). However, they stated that a single correlation was valid for different nozzle dimensions which was against that claimed by Yonezawa and Schwerdtfeger.\(^2\) Iguchi \textit{et al.}\(^6\) developed an expression for the spout ‘eye’ area considering all the physical properties of gas and liquid phases which was not done earlier. They also performed water model experiments and compared their own experimental results with those of Yonezawa and Schwerdtfeger\(^2\) and the accuracy was ±60%. Krishnapisharody and Irons\(^7\) carried out physical modeling and proposed a mechanistic model for the slag ‘eye’ formation in a ladle considering a thin slag layer. They considered both conical and cylindrical shapes of plumes, and recommended new correlations which they believed to be much better than those developed in earlier works. Krishnapisharody and Irons\(^3\) performed water model experiments to study the formation of spouts on the bath surface in gas stirred ladle systems. The experimental data was used to correlate the spout dimensions to the operating variables, namely, the gas flow rate and heights of water and oil layers. Non dimensional representations of the spout height revealed that factors such as the diameter of the ladle, size, and type of gas injector and physical properties of the gas-liquid system did not play any major role in the spout formation. Later on, Krishnapisharody and Irons\(^8\) carried out some dimensional analyses and modified their earlier correlations\(^7\) which were based on a mechanistic model. Their model computed the ‘eye’ size from the primary operating variables of the ladle and proved to be reliable in a variety of multi-phase systems. Li \textit{et al.}\(^10\) developed a three phase mathematical model to study the formation of exposed ‘eye’s in gas stirred ladle systems. Multiphase Volume of Fluid (VOF) method was used to simulate the behavior of the slag layer. The relationship between non-dimensional areas of slag ‘eye’ and the modified Froude number was in good agreement with the experimental data reported in the literature. Since the significant deformation of slag layer occurred during gas stirring operation, the thickness of slag became thin near the slag ‘eye’ and thick near the ladle wall, respectively. The downward flow velocity of steel at the slag ‘eye’ periphery might be affected significantly by flow rate of Ar gas. Therefore, when the downward flow velocity would be larger, the more emulsification of slag could be expected. Wu \textit{et al.}\(^11\) carried out water modeling and cold metal model experiments to estimate the size of the slag ‘eye’ and found out that viscosity and interfacial tensions between the two liquids have no or minor effect on the open ‘eye’ size. They used mass balances and other equations to obtain relations for the open ‘eye’ sizes which agreed well with the experimental results. They concluded that their equation obtained for the cold metal model is a good way to estimate the critical gas flow rate to form an open ‘eye’ in an industrial ladle. However, they did not obtain good results from their water model studies because the equation did not have any term considering the density difference between the two liquids, water and liquid metal. Peranandhanthan and Mazumdar\(^12\) performed physical modeling to estimate the slag ‘eye’ area in bottom purged ladles. They concluded that the slag ‘eye’ area increased as the gas flow rate and depth of bulk liquid were increased. On the contrary, the size of the exposed ‘eye’ decreased with increasing thickness of the upper buoyant phase. Physical properties of the slag phase affected the area of the ‘eye’. They developed a new simple correlation which included three important parameters viz., Froude number, Reynolds number and density ratio, which could effectively predict the slag ‘eye’ area in both aqueous and industrial scale ladle systems under a wide range of operating variables and upper slag phases. Mazumdar and Guthrie\(^13\) reported on the input energy dissipation by an upper buoyant phase in gas stirred ladle systems. They mentioned that several factors like thickness of the slag layer and its properties like viscosity and density, significantly affect the exposed ‘eye’ areas. A thicker slag phase would result in the formation of a smaller exposed ‘eye’ and so is the case with a highly viscous slag phase. A highly viscous slag phase would tend to dissipate more energy due to frictional effects and viscous dissipation within, resulting in a smaller slag ‘eye’ opening. Llanos \textit{et al.}\(^14\) developed a three dimensional three phase mathematical model to study the fluid dynamics in slag covered gas stirred ladles. The Volume of Fluid (VOF) model was employed to simulate the interaction between phases considering the surface tensions. A good agreement was obtained between the physical and mathematical modeling results, where the VOF model showed to be a powerful tool to simulate ladle gas stirring operations. Krishnapisharody and Irons\(^15\) recently showed the behavior of the slag ‘eye’ in a ladle considering a thick slag phase. The critical gas flow rate for which there is no slag ‘eye’ formation was estimated in their work. Their models reproduced the experimental data reasonably well except in the intermediate range of $0.7 < A_p/A_p < 2$. Chattopadhyay \textit{et al.}\(^16\) recently studied the formation of slag ‘eye’ in inert gas shrouded tundishes. A numerical model was developed where only two phases, viz., water and gas bubbles were considered. The water was modeled as a continuous phase fluid, whereas the gas bubbles were modeled using the lagrangian discrete phase method. The slag ‘eye’ was considered to be located in the region where the local surface velocity was approximately ten times higher than the average surface velocity of the tundish. The numerically predicted area of the slag ‘eye’ was validated against full scale water model experiments and the error ranged between 12–25%. Moreover, the slag phase in the physical model was modeled using the polyethylene beads which formed a discontinuous phase unlike the real slag phase. This was an oversimplified representation of reality. The drawback of their model was that it did not consider the upper buoyant slag phase present on the top of bulk liquid phase and used only DPM to model the interaction of the gas phase with bulk liquid. Various researchers \textit{et al.}\(^6,7,12,13,15\) have suggested that the variation in properties of the slag phase such as thickness, viscosity, density, \textit{etc}. can have
significant effect on slag ‘eye’ area. Hence, it is difficult to predict the slag ‘eye’ areas precisely without considering the slag phase.

It was possible to overcome these drawbacks by considering the effect of the slag phase on slag ‘eye’ area in the present work. The VOF model was used to model the slag phase along with other models as explained earlier. The use of VOF model enabled us to track the interface between the bulk liquid and upper slag phases precisely. The use of DPM and standard \( k-\varepsilon \) models along with the VOF model was a novel way to study the formation of slag ‘eye’ in tundish. Unlike Chattopadhyay et al., the predictions for slag ‘eye’ radius in present work is much more reliable as contours of the ‘eye’ formed on the surface are not determined based on oversimplified assumptions. Lower values of percentage errors obtained in the present study also support the fact that present predictions are much more robust.

Chattopadhyay et al. also observed that the exposed ‘eye’ formed around the ladle shroud was primarily because of reversed flows created on the bath surface. The bubble column formed just beneath the ladle shroud and it was not conical, unlike that observed in bottom purged ladles.

From the above discussions it is clear that a lot of researchers have modeled exposed ‘eye’s in gas-stirred ladle systems, but none of them ever tried to simulate it in a tundish except Chattopadhyay et al. Hence, it is important to get more insights related to slag ‘eye’ formation in a tundish. Most of the researchers, who performed mathematical modeling in ladles, used three phase (VOF) mathematical models to simulate exposed ‘eye’ formation. In this study, the formation of the ‘eye’ was modeled by using the discrete phase method, and VOF method in synergy. In addition, the turbulent fluid flow was modeled using the standard \( k-\varepsilon \) model.

2. Physical Modeling

A one-third scale water model was used to physically simulate the process of slag ‘eye’ formation in a tundish. A schematic diagram of the physical model is shown in Fig. 2. The liquid steel and argon gas phases were simulated by using water and compressed air respectively, whereas the slag phase was simulated by using mineral oil.

The steady state height of water was kept at a fixed level of 0.167 m. Based on Froude’s similitude, the water inflow rate was kept at 0.01 m\(^3\)/min. The layer of mineral oil was 0.01 m thick whereas its density and viscosity were 870 kg/m\(^3\) and 0.017 Pa.s respectively. The immersion depth of the ladle shroud was 0.02 m. Compressed air was injected from the top of the ladle shroud, at volumetric flow rates ranging between 2 to 12% of water entry flows. The bubble plume, top slag layer movements, and measurements of the slag eye sizes were visualized by using high definition video photography.

3. Mathematical Modeling

The standard \( k-\varepsilon \) model of Launder and Spalding was used to model turbulence, whereas the Volume of Fluid (VOF), and the discrete phase methods were used to simulate the multiphase flows in the liquid and the gas phases respectively. As a result, equations related to these models had to be solved along with the equations for conservation of mass and momentum. The SIMPLE\(^2\) algorithm was used for pressure-velocity coupling and the second order upwind scheme was used for momentum, \( k \) and \( \varepsilon \) equations.

The standard \( k-\varepsilon \) model was used in the present work to model the turbulence. Here, \( \varepsilon \) is the rate of turbulence energy dissipation, while \( k \) stands for the kinetic energy per unit mass, and is related to the time averaged-velocity \( \bar{u}_i \) as follows:

\[
k = \frac{1}{2} \sum_i \bar{u}_i^2 \tag{1}
\]

The two extra equations for \( k \) and \( \varepsilon \) that need to be solved are as follows:

\[
\frac{Dk}{Dt} = \frac{v_i}{\sigma_k} \nabla^2 k + G_k - \varepsilon \tag{2}
\]

\[
\frac{D\varepsilon}{Dt} = \frac{v_i}{\sigma_\varepsilon} \nabla^2 \varepsilon + \frac{\varepsilon}{k} (C_1 G_k - C_2 \varepsilon) \tag{3}
\]

The parameter \( G_k \) is the rate of production of \( k \) and is given by the following equation:

\[
G_k = v_i \left[ \frac{\partial}{\partial x_j} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] \frac{\partial \bar{u}_i}{\partial x_j} \tag{4}
\]

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

\[
\mu_t = \frac{C_p \rho k^2}{\varepsilon} \tag{5}
\]

\[
\mu_{eff} = \mu + \mu_t \tag{6}
\]

The values for the constants in the standard \( k-\varepsilon \) model recommended by Launder and Spalding\(^3\) which are \( C_1 = 1.44, C_2 = 1.92, C_p = 0.09, \sigma_k = 1 \) and \( \sigma_\varepsilon = 1.3 \), and were used in the present work without any modification.

The VOF formulation\(^7\) relies on the fact that two or more fluids (or phases) are not interpenetrating. For each additional phase added in the system, a variable, the volume fraction of the phase, is introduced in the computational cell. The volume fractions of all phases sum to unity in each control volume. The fields for all variables and properties are represented as volume-averaged values. Thus, the variables and properties in any given cell are either purely represen-
tative of one of the phases, or representative of a mixture of the phases, depending upon the volume fraction values.

For tracking interfaces between phases, continuity equations such as Eq. (7) for the volume fraction of one or more phases are solved.\(^{23}\)

\[
\frac{1}{\rho_f} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_f) + \nabla (\alpha_q \rho_f \mathbf{u}_q) \right] = S_{\alpha_q} \quad \text{......... (7)}
\]

The volume fraction for the primary phase is not solved, rather it is computed based on the following constraint:

\[
\sum_{q=1}^{n} \alpha_q = 1 \quad \text{.......................... (8)}
\]

In the discrete phase modeling\(^{20}\) 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. There can be exchange of momentum, mass, and energy of the dispersed phase with the fluid phase. The particle or droplet trajectories are computed individually at specified intervals during the fluid phase calculation. The dispersed secondary phase can affect the flow in the primary phase and for that two way turbulence coupling needs to be used. In the two way turbulence coupling, as the trajectory of a particle is computed, a track of the momentum gained or lost by the particle stream that follows the trajectory is kept, and these quantities are then incorporated in the subsequent continuous phase calculations. Thus, while the continuous phase always impacts the discrete phase, we can also incorporate the effect of the discrete phase trajectories on the continuum phase. This two-way coupling is accomplished by alternatingly solving the discrete and continuous phase equations, until the solutions in both phases have stopped changing.\(^{23}\) The basic equations involved in discrete phase modeling are as follows:

\[
\frac{du_p}{dt} = \frac{18 \mu C_d \text{Re}}{2Re d^2} - u_{rel} + \frac{g(\rho_p - \rho)}{\rho_p} \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt} u_{rel} \quad \text{.............. (9)}
\]

\[
\text{Re} = \frac{\rho d}{\mu} \quad \text{..................................... (10)}
\]

\[
u_{rel} = u - u_p \quad \text{................................. (11)}
\]

\[
C_D = a_1 + \frac{a_2}{\text{Re}} + \frac{a_3}{\text{Re}^2} \quad \text{.............................. (12)}
\]

The two major assumptions considered during the mathematical modeling of the three phase gas-liquid-oil flows in the tundish were:

a. The liquid (water) in the shroud was an incompressible and Newtonian fluid.

b. The fluid flow within the shroud was predominantly bubbly and the discrete bubbles formed at the entrance move down the shroud along with the down-flowing water. The maximum volume fraction of gas in the shroud was not more than 10%, so, the assumption of bubbly flow holds true.

Very fine mesh was necessary to obtain higher accuracy of the results. Considering this fact, the one-third scale tundish was chosen to develop this model. Around three million eight hundred thousand \((3.8 \times 10^6)\) cells were generated inside the domain. In this model, the phenomena considered were: fluid flow, turbulence, discrete phase motion and multiphase flow. A small time step of \(10^{-5}\) s was chosen to efficiently track the formation of the exposed ‘eye’. Gas injections of 2%, 4% and 6% by volume through the ladle shroud were considered, and were modeled as discrete gas bubbles using the discrete phase model. For the VOF model, the primary phase was taken as water and the secondary phase was taken as mineral oil \((\text{density} = 870 \text{ kg/m}^3, \text{viscosity} = 0.017 \text{ Pa.s and interfacial tension} = 0.0425 \text{ N/m})\). In reality, a third phase of air is present on the top of the slag, but it was not be considered here, to simplify the problem.

4. Results and Discussion

The exposed ‘eye’ formed in the one-third scale water model for gas injection at flow rates varying from 2 to 12% of water entry flows are shown in the Fig. 3 below. It can be easily observed that the size of the slag ‘eye’ increases as the rate of gas injection is increased. After the start of the gas injection, the exposed ‘eye’ was formed in about 2 seconds and the size of the ‘eye’ became stable after \(~6–8\) seconds.

Many researchers had carried out similar experiments and/or theoretical analyses to obtain the size of the exposed ‘eye’ in the case of ladles. However, there was no significant theoretical or experimental analysis done for slag ‘eye’ in tundishes except for the work of Chattopadhyay et al.\(^{16}\) A few important points that need to be noted in all the previous work related to ladles are (i) ladles have a completely different geometry compared to the tundish (ii) moreover, the gas injection technique in ladles is bottom-blown, whereas, it is mostly through ladle shroud for the tundish. Thus, it is logical to consider that the mechanism of gas flow, and the liquid/gas interactions in tundishes is different from that of ladles. In case of a tundish, the gas bubbles coming through the ladle shroud moves downward to the base of the tundish first. The bubbles may or may not touch the

Fig. 3. Formation of exposed ‘eye’ around the shroud in the one-third scale water model for gas injection at (a) 2% (b) 4% (c) 6% (d) 8% (e) 10% and (f) 12%, of water entry flows.
bottom of the tundish depending on the flow rates of gas injection, and then float up because of buoyancy, creating a two phase gas-liquid zone or the bubble plume. When the gas flow-rates are large enough, the bubbles raise the melt towards the top, recirculatory flows are developed, and the slag layer is subsequently pushed away radially at the melt-slag interface, creating an open ‘eye’. This mechanism is quite different from the case of ladle where the bubbles of the bottom-blown gas raises the bulk metal and creates the open ‘eye’. Additionally, the shape of the bubble plume in a tundish is different than that in a ladle.

Although the operations in ladle and tundish are different, it is worthwhile to check if the correlations developed for the slag ‘eye’ in ladles can be used to predict the area of slag ‘eye’s in a tundish. All the previous work were carried out under different operating conditions. One of the most important parameter which affects the slag ‘eye’ area is the ratio of the slag height to the melt height. The ratio of slag height to bath height in the present water model experiment was 0.01 m/0.167 m = 0.05988. The Eqs. (13)–(15) list the correlations from earlier studies\(^2,3,15\) which had similar slag height to bath height ratios. These correlations were used to estimate the slag ‘eye’ area based on the operating variables from the one-third scale tundish, and compared against experimental measurements.

\[
\log \left( \frac{A_e}{Hh} \right) = -0.69897 + 0.90032 \log \left( \frac{Q^2}{gh^2} \right) - 0.14573 \left[ \log \left( \frac{Q^2}{gh^2} \right) \right]^2 + 0.01560 \left[ \log \left( \frac{Q^2}{gh^2} \right) \right]^3
\]

for \(0.01 < \left( \frac{Q^2}{gh^2} \right) < 10^2\) and \(d = 0.5 \text{ mm} \)

\[\text{.................................(13a)}\]

\[
\log \left( \frac{A_e}{Hh} \right) = \log \left( \frac{Q^2}{gh^2} \right) - 0.45593 + 0.83275 \log \left( \frac{Q^2}{gh^2} \right) - 0.14732 \left[ \log \left( \frac{Q^2}{gh^2} \right) \right]^2 + 0.01789 \left[ \log \left( \frac{Q^2}{gh^2} \right) \right]^3
\]

for \(0.01 < \left( \frac{Q^2}{gh^2} \right) < 2000\) and \(d = 0.1 \text{ and } 1.5 \text{ mm} \)

\[\text{.................................(13b)}\]

\[
\frac{A_e}{(h + H)^2} = (0.02 \pm 0.002) \left( \frac{Q^2}{gh^2} \right)^{0.3756 \pm 0.0136}
\]

\[\text{.................................(14)}\]

\[
A_e/A_p = 0.91 - 0.12(1 - \rho^*)(Q^*)^{0.64} h^*
\]

\[\text{.................................(15a)}\]

where,

\[
Q^* = \frac{Q}{\rho^* g H^2}
\]

\[\text{.................................(15b)}\]

\[
h^* = \frac{h}{H}
\]

\[\text{.................................(15c)}\]

\[
A_p = 1.41(Q^*)^{0.4} H^2
\]

\[\text{.................................(15d)}\]

The radii of slag ‘eye’s were calculated from the areas considering ‘eye’s to be circular in shape. The values for radii obtained from earlier correlations and their deviations from present experimental measurements are presented in Table 1. The % error was calculated according to the following formula:

\[
\% \text{ Error} = \left( \frac{\text{experimental measurement} - \text{prediction from previous correlation}}{\text{experimental measurement}} \right) \times 100
\]

\[\text{.................................(16)}\]

### Table 1. Comparison of slag ‘eye’ sizes measured in the present water model study with those estimated from the correlations developed by other researchers.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Investigators</th>
<th>Correlation for slag ‘eye’ Procedure</th>
<th>Experimental conditions considered</th>
<th>Vol. frac. of gas injected</th>
<th>Radius of slag ‘eye’ (m)(^2)</th>
<th>%Error(^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yonezawa and Schwerdtfeger(^2)</td>
<td>(13)</td>
<td>0.013 ≤ h/H ≤ 0.133, 0.05 ≤ Q ≤ 0.7 m(^3)/h</td>
<td>2%</td>
<td>0.0004</td>
<td>99.33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4%</td>
<td>0.0012</td>
<td>98.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6%</td>
<td>0.0022</td>
<td>98.25%</td>
</tr>
<tr>
<td>2</td>
<td>Subagyo et al.(^3)</td>
<td>(14)</td>
<td>0.013 ≤ h/H ≤ 0.133, 0.05 ≤ Q ≤ 0.7 m(^3)/h</td>
<td>2%</td>
<td>0.0061</td>
<td>88.43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4%</td>
<td>0.0079</td>
<td>90.65%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6%</td>
<td>0.0092</td>
<td>92.73%</td>
</tr>
<tr>
<td>3</td>
<td>Krishnapisharody and Irons(^5)</td>
<td>(15)</td>
<td>0.022 ≤ h/H ≤ 0.207 (for thick slags), 0.05 ≤ Q ≤ 0.6 m(^3)/h</td>
<td>2%</td>
<td>0.013</td>
<td>75.27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4%</td>
<td>0.0166</td>
<td>80.36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6%</td>
<td>0.0187</td>
<td>85.25%</td>
</tr>
<tr>
<td>4</td>
<td>Present work</td>
<td>One-third scale water model</td>
<td>h/H = 0.059, 0.012 ≤ Q ≤ 0.036 m(^3)/h</td>
<td>2%</td>
<td>0.0527</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4%</td>
<td>0.0845</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6%</td>
<td>0.1266</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^*\) The shape of slag ‘eye’ was considered to be circular.

\(^\dagger\) % Error = \left( \frac{\text{experimental measurement} - \text{prediction from previous correlation}}{\text{experimental measurement}} \right) \times 100
It is seen from Table 1 that the percentage errors in the estimated slag ‘eye’ radius range from 75.27% to 99.33% which are huge. The percentage errors in the radius obtained from other researchers7,9,11,12) which had different operating slag height to bath height ratios were even larger and hence, are not shown here. This clearly proves the fact that the correlations developed to predict the open ‘eye’ area in ladles can not be used for tundishes.

The temporal evolution of the exposed ‘eye’ for 4% gas injection by volume was obtained from mathematical modeling and is shown in Fig. 4. The shape of the ‘eye’ changed with time, as is evident from Figs. 4(a)–4(c). This phenomenon was captured because of the very small time step used during the simulations. The exposed ‘eye’ started to form after about 0.5 s of gas injection. The area of the ‘eye’ increased with time and became prominent at \( t = 1 \) s. It became stable after 6 s and continued to remain so till \( t = 11 \) s. However, the shape of the ‘eye’ kept on changing and this is quite normal when gas bubbles are displacing a liquid phase. The bubble plume always oscillates with time.

Fig. 4. Temporal evolution of the exposed ‘eye’ due to gas injection at 4% of water entry flows for time interval: (a) 0 to 1.5 s (b) 2 to 5 s (c) 6 to 11 s. (Online version in color.)
and hence the mineral oil layer also keeps on displacing.

Since it was observed from both the physical and mathematical models that the size of the slag ‘eye’ became constant after ~6 s, the simulations were performed for 6 s for all the other gas flow rates. The exposed ‘eye’ formed in the tundish for gas injections varying between 0–6% by volume after 6 s of gas injection are shown in Fig. 5. The red region represents mineral oil while the blue region is water. It is clearly seen that as the volume fraction of gas is increased, the area of the exposed ‘eye’ increases. The numerically predicted area were compared to those obtained from one-third scale water model experiments, and the percentage error was below 17% as shown in Table 2. The % error was calculated according to the following formula:

\[
\% \text{ Error} = \left( \frac{\text{experimental measurement} - \text{mathematical modeling prediction}}{\text{experimental measurement}} \right) \times 100
\]

In reality, there is an upper phase of air, and a fluctuating free surface on top of the slag phase. Since the mathematical model did not consider these factors, it always overpredicted the ‘eye’ radius and hence, area.

Finally, results from real plant observations have been considered, and compared to the results obtained from physical modeling and numerical simulation. The plant measurements were carried out in a four strand delta shaped tundish whose height was 1.02 m. The steady state liquid steel flow rate through ladle shroud was 1.2 tons/min whereas the steady state liquid steel level in the tundish was 0.5–0.6 m. The direct inert gas injection rate was varied from 5–35 litres/min. The areas of the slag ‘eye’ were measured using a HD video camera. Two photographs of slag ‘eye’s are presented in Fig. 6. It can be clearly seen that the size of the slag ‘eye’ increases with increasing gas flow rate, which is similar to the trend obtained from the

**Fig. 5.** Predicted contours of the second phase (mineral oil) in the tundish after 6 seconds of gas injection. (Online version in color.)

**Fig. 6.** Photograph of slag ‘eye’ in a real steel tundish at a gas flow rate of: (a) 8.5 litres/min equivalent to 5% (b) 17 litres/min equivalent to 10%.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Vol. frac. of gas injected</th>
<th>Experimentally measured average slag 'eye' area, (A_1)(^a) (m(^2))</th>
<th>Numerically predicted average slag 'eye' area, (A_2)(^a) (m(^2))</th>
<th>% Error(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2%</td>
<td>0.0087</td>
<td>0.0100</td>
<td>-14.13%</td>
</tr>
<tr>
<td>2</td>
<td>4%</td>
<td>0.0224</td>
<td>0.0262</td>
<td>-16.74%</td>
</tr>
<tr>
<td>3</td>
<td>6%</td>
<td>0.0504</td>
<td>0.0545</td>
<td>-8.22%</td>
</tr>
</tbody>
</table>

\(^a\) The shape of slag ‘eye’ was considered to be circular

\(^a\) % Error = \left( \frac{\text{experimental measurement} - \text{mathematical modeling prediction}}{\text{experimental measurement}} \right) \times 100

\(^a\) \frac{\left(A_1 - A_2\right)}{A_1} \times 100
water model experiments and numerical simulations. One interesting observation from plant measurements is that the slag ‘eye’ was not concentric with the ladle shroud. This may be attributed to the random oscillation of the gas bubble plume in the tundish.

A quantitative comparison of all the slag ‘eye’ areas is shown in Fig. 7. The best way to analyze these data was to compare the non-dimensional areas, i.e. by dividing the absolute values of the slag ‘eye’ area, $A_e$, by the total surface areas of the tundish at the corresponding bath heights, $A_T$. The non-dimensional areas of the tundish were obtained by using the Eqs. (18a) and (18b) for plant trials and present study respectively.

Non-dimensional area of slag eye =

\[
\frac{\text{Absolute area of slag eye at bath height of } 50 \text{ cm}}{\text{Total surface area of tundish at bath height of } 50 \text{ cm}} \quad (18a)
\]

for plant trials

Non-dimensional area of slag eye =

\[
\frac{\text{Absolute area of slag eye at bath height of } 16.7 \text{ cm}}{\text{Total surface area of tundish at bath height of } 16.7 \text{ cm}} \quad (18b)
\]

for physical modeling and numerical simulations

The results obtained from plant, physical model experiments and numerical simulations are compared in Fig. 7. The results from the plant measurements are a bit higher than the results from the experimental and modeling studies performed in the present study. It should be noted that the real process is very stochastic in comparison to the controlled water model experiments conducted in the laboratory. In addition, the results from the plant cannot be relied upon completely because of lack of precision in measurements resulting from oscillating slag ‘eye’s and high temperatures. The observation of slag ‘eye’ area in plant trials is an estimate rather than an exact measurement. Moreover, it is very difficult to measure the slag height accurately, and this can give rise to erroneous results. Hence, comparison of results from operations which were performed under different conditions such as different ratio of slag height to bath height can result in huge errors.

The present modeling study allows us to observe the transient and steady-state behaviors of slag ‘eye’s in tundishes for gas flow rates ranging from 2 to 12%. Also, the numerical simulation shows us the usefulness of using the VOF and discrete phase models to predict slag ‘eye’ sizes in a tundish. It is believed that the numerically simulated results can be improved significantly by employing better turbulence models like the Reynolds Stress model (RSM) and by simulating steel-slag-Ar gas system instead of water-oil-air system. Moreover, the VOF model can be employed instead of the discrete phase model to simulate the gas phase if calculations for higher flow rates need to be performed where the bubbly flows no longer exist.

5. Summary

On comparing the present water model results with the estimates obtained from the correlations for ladles, it can be concluded that the mechanism of slag ‘eye’ formation in a tundish is different from that in ladles, and hence, a new correlation needs to be developed for predicting the size of slag ‘eye’ in a tundish.

The formation of slag ‘eye’ in an inert gas shrouded tundish was studied systematically using physical and mathematical modeling. The developed mathematical model predicts the slag ‘eye’ area quite well, the error being ~17% of the experimental measurements. This indicates significant improvements of the mathematical model than what was developed by Chattopadhyay et al. earlier.

Coupling of the VOF method with the discrete phase method is a robust technique to simulate complex three phase flows occurring in inert gas shrouded tundishes.

The difference of non-dimensional area of the slag ‘eye’ obtained from the plant trials compared to those obtained from present study increases with increasing gas flow rates. The reason for these deviations may be because of errors in plant measurements at high temperatures.

There is still scope for improvement in the mathematical model and these include the use of better turbulence models, and simulating real steel-slag-Ar gas system instead of water-oil-air system. The effects of various physical properties like slag thickness, viscosity, surface tension and other operating variables like gas flow rates, temperature etc. on slag ‘eye’ formation will be analyzed in the works to follow.

Acknowledgements

The authors would like to thank ANSYS Inc., and SimuTech Group for their support towards the mathematical modeling research performed in this study.

Nomenclature:

- $k$: Kinetic energy of turbulence per unit mass, $m^2s^{-2}$
- $\varepsilon$: Rate of dissipation of $k$, $m^2s^{-3}$
- $U_p$: Plume velocity (average rise velocity of the gas-liquid mixture), $m/s$
- $g$: Acceleration due to gravity, $m/s^2$
- $H$: Depth of bulk phase fluid, $m$
- $Q$: Gas flow rate, $m^3s^{-1}$
- $k$: Depth of upper phase fluid, $m$
- $A_e$: Area of the slag ‘eye’, $m^2$
- $A_p$: Cross-sectional area of the plume, $m^2$
- $A_T$: Total surface area of the tundish, $m^2$
Fluid velocity, $m \, s^{-1}$

Characteristic length, $m$

Time averaged-velocity, $m \, s^{-1}$

Kinematic viscosity of fluid, $m^2 \, s^{-1}$

Empirical constants

Rate of production of $k$, $kg \, m^{-1} \, s^{-3}$

Velocity in the direction $x_i$, $m \, s^{-1}$

Cartesian space coordinate

Turbulent viscosity, $kg \, m^{-1} \, s^{-1}$

Density of the fluid, $kg \, m^{-3}$

Effective viscosity, $kg \, m^{-1} \, s^{-1}$

Viscosity of the fluid, $kg \, m^{-1} \, s^{-1}$

Density of the $q$th fluid in a cell, $kg \, m^{-3}$

Volume fraction of the $q$th fluid in a cell

Velocity of the $q$th fluid in a cell, $m \, s^{-1}$

Source term indicating any non-diffusive or non-convective term

Particle velocity, $m \, s^{-1}$

Drag coefficient

Reynolds number, $\frac{\rho v L}{\mu}$

Particle diameter, $m$

Fluid velocity relative to the particle, $m \, s^{-1}$

Density of the particle, $kg \, m^{-3}$

Constants

diameter of nozzle in ladle, $m$

Non-dimensionalized density difference between the liquid phases

Non-dimensionalized gas flow rate

Non-dimensionalized height of the upper phase fluid

VOF: Volume of Fluid

DPM: Discrete Phase Method

REFERENCES