Physical and CFD Modeling of the Effect of Top Layer Properties on the Formation of Open-Eye in Gas-Stirred Ladles With Single and Dual-Plugs

Eshwar Kumar Ramasetti,* Ville-Valtteri Visuri, Petri Sulasalmi, Tuomas Palovaara, Avishek Kumar Gupta, and Timo Fabritius

In secondary steelmaking, the optimal size and position of open-eye is important for effective alloying practice. In the current work, the effect of the top layer thickness and density on the formation of open-eye in a gas stirred ladle was investigated. A one-fifth scale water model of 150-ton ladle was established with single and dual plug configurations for the physical modeling measurements. Air, water and three different oils were used to simulate the argon, liquid steel and slag in the water model, respectively. A transient Computational Fluid Dynamics (CFD) model based on Eulerian Volume of Fluid (VOF) approach was developed for numerical modeling of the fluid flow behavior. The physical modeling results show that the relative open-eye area decreases from 46.7 to 5.6% when top layer thickness is increased from 0.75 to 7.5 cm using a gas flow rate of 7.5 NL min⁻¹. The effect of the number of plugs on the open-eye area for the same range of top layer thickness mentioned above was also studied. The relative open-eye area generated due to the gas injection through the dual plugs decreased from 49.9 to 5.8%. To study the effect of top layer properties, rapeseed oil, castor oil and paraffin oil were employed for studying the effect of density and dynamic viscosity on the open-eye formation. The results revealed that a larger open-eye is formed when the density is increased. Furthermore, it was found out that the density of the upper phase dominates the open-eye formation while dynamic viscosity has only minor effect. The results obtained from numerical simulations and physical modeling were found to be in good agreement.

1. Introduction

In order to attain homogenous distribution of alloying elements and temperature in the liquid steel, and remove inclusions, argon gas stirring has been extensively used in the steel refining process. Bubbles are formed due to the injection of argon gas at immense-speed through the nozzle located at the bottom of the ladle. These rising bubbles enter the liquid steel and accelerate upwards forming a turbulent plume and, subsequently, a circulatory movement of steel within the In plant practice, this serves to homogenize the chemical composition of alloying elements and temperature.

In the meantime, the bubbles move upwards and break the slag layer forming an open-eye as shown in Figure 1. In certain processes, the formation of open-eye is desirable. For instance, in alloying processes, the formation of open-eye is formed which together with steel flow give rise to formation of slag droplet at the edge of the open-eye, thereby, intensifying the reduction reactions. The similar phenomenon is exploited in desulfurisation process as well. On the hand, formation of the open-eye exposes the molten steel to the atmosphere, which causes heat losses and oxygen absorption to the steel. Thus, proper understanding of formation of the open-eye is vital for process control and quality of the steel.

During the past years, the open-eye formation in a gas stirred ladle has been a subject of many studies. Many physical and numerical modeling studies have been conducted to study the fluid flow behavior and open-eye formation in the gas stirred ladle. Yonezawa and Schwerdtfeger found the open-eye to be highly dynamic by performing measurements in a water model. The results concluded that the open-eye increases with increase with gas flow rate. Krishnapisharody and Irons performed measurements in a cylindrical water model ladle to study the open-eye formation. In the study a quantitative description, taking into account the effect of gas flow rate, bath height and top phase thickness and properties (density and viscosity), for the open-eye area was developed via dimensional analysis. The results showed that the open-eye area increases with escalation of gas
flow rate in all the cases. The open-eye area decreased when the top phase thickness increased. The increase in the size of the open-eye with increasing height of water bath was also founded from the results, although the enlargement is not linear. The results also showed that the systems with less dense top phase systems have smaller open-eyes than denser top phase systems.

Amaro-Villeda et al.\cite{9} studied the effect of slag thickness on the open-eye area and mixing time in the water model ladle. The slag thickness was varied in order to study its effect on open-eye area and mixing time in a single plug system with a constant flow rate. The decrement of open-eye area with increase in slag thickness was observed. Maruyama and Iguchi\cite{10} also performed cold model experiments in cylindrical vessel of mercury-silicon oil system to study the effect of slag properties on open-eye area. The results showed the open-eye decreases with increase in the slag thickness and density of the slag has effect only when the thickness of slag is greater than the critical value on the open-eye size.

Valentin et al.\cite{15} performed CFD simulations to evaluate the effect of gas flow rate on the flow pattern, open-eye size and mixing phenomena in a steel making ladle. The results from the simulation results of Liu et al.\cite{16} show that the gas flow rate has a great effect of open-eye formation and there is a huge deformation of slag layer at very high gas flow rates. The simulation results of Li et al.\cite{17} showed that the diameter of open-eye changes from 0.43 to 0.81 m when flow rate of argon

| Table 1. Various investigators and their specific area contribution to gas stirred ladle system. |
|---|
| SI No. | Reference | Physical model | Numerical model | Main investigations |
| 1 | Liu et al.\cite{4} | X | X | Open-eye formation and behavior, slag entrainment |
| 2 | Yonezawa & Schwerdtfeger\cite{5} | X | | Open-eye size, spout height of the gas plume, development of non-dimensional correlation to measure open-eye size |
| 3 | Krishnapisharody and Irons\cite{6} | X | | Formation of open-eye for different gas flow rates, bath heights and slag properties |
| 4 | Krishnapisharody and Irons\cite{7} | X | | Development of extended model to measure dimensionless open-eye size |
| 5 | Guo and Irons\cite{8} | X | | Height and width of spout were measured in the water model |
| 6 | Amaro-Villeda et al.\cite{9} | X | | Effect of slag layer thickness on open-eye area and mixing time |
| 7 | Mazumdar et al.\cite{10} | X | X | Effect of gas flow rate on open-eye formation and mixing time, development of correlations to measure the dimensionless area |
| 8 | Peranandhanthan et al.\cite{11} | X | X | Effect of gas flow rate on open-eye formation and mixing time, development of correlations to measure the dimensionless area |
| 9 | Wu et al.\cite{12} | X | | Effect of gas flow rate, bath height and slag thickness on open-eye area |
| 10 | Thuman et al.\cite{13} | X | | Open-eye formation and slag entrainment |
| 11 | Lv et al.\cite{14} | X | | Effect of gas flow rate, bath height and slag thickness on open-eye area |
| 12 | Valentin et al.\cite{15} | X | | Effect of gas flow rate on open-eye formation and mixing time |
| 13 | Liu et al.\cite{16} | X | | Effect of gas flow rate on fluid flow, open-eye formation and interface behavior |
| 14 | Li et al.\cite{17} | X | | Effect of gas flow rate on the open-eye and slag/steel interface |
| 15 | Li et al.\cite{18-21} | X | X | Effect of gas flow rate on bubble movement, interface behavior using LES approach |
| 16 | Liu et al.\cite{22} | X | X | Modelling of slag-steel-gas three phase flows |
| 17 | Qing et al.\cite{23-25} | X | | Fluid flow, mass transfer, slag-steel interfacial behavior and mixing time. |
| 18 | Liu et al.\cite{26} | X | | Fluid flow analysis, axial velocity and turbulent kinetic distribution. |
| 19 | Joo et al.\cite{27} | X | | Fluid flow analysis, mixing time, and porous plug location. |
gas varied from 100 to 300 NL min \(^{-1}\) for a 220-ton ladle. Li et al.\(^{[18–21]}\) developed a mathematical model using large eddy simulation (LES) to investigate the bubble movement and slag layer behavior in a water model of argon stirred ladle. Liu et al.\(^{[22]}\) investigated the effect of gas flow rate and slag thickness on the open-eye size, bubble movement and mixing time in water model ladle through both physical and numerical modeling. The effect was slag layer thickness was investigated by varying from 20 to 40 mm and 50 mm for a constant flow rate in single-plug-stirred system. The results showed the slag layer thickness has large influence on the open-eye area. The open-eye area would increase quickly when slay layer thickness decreases and vice-versa, although the increment is not linear. Qing et al.\(^{[30–32]}\) investigated the fluid flow, mass transfer, slag-steel interfacial behavior and mixing time in industrial gas stirred ladle. Liu et al.\(^{[33]}\) investigated the effect of various forces, bubble sizes and bubble injection frequencies on the flow analysis in the gas-stirred ladle. The results of axial velocity and turbulent kinetic energy are compared for Euler-Lagrange approach and Euler-Euler approach. Joo et al.\(^{[34]}\) investigated the fluid flow and mixing time in the ladle for different porous plug locations and tracer injections points. Recently, Liu et al.\(^{[36]}\) has reviewed the research into the gas stirring in ladle metallurgy carried out over few decades. The summary of various investigators and their specific contribution to understanding open-eye behavior in ladles is shown in the Table 1. 

Over the past decade, the studies were mainly focused on investigating the effect of gas flow rate on the open-eye formation, and relatively few studies on the effect of slag properties (density, dynamic viscosity and upper layer thickness) on the open-eye size through both physical and numerical modeling. In the present work, the simulation results of open-eye size are provided and validated with experimental data obtained from a physical model. The work focused on studying the effect of slag thickness and slag density on open-eye size in both single and dual plug configurations. The work also focuses on the development of the CFD model with the Eulerian VOF approach to track the slag/steel/air interface behavior for the gas-stirred ladle.

### 2. Model Description

#### 2.1. Model Description

The fluid flow and turbulent properties in the ladle can be described by continuity equation, momentum equation and turbulence models, which can be written as follows:\(^{[25]}\)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \mu_i)}{\partial x_i} = 0
\]  

Continuity equation

\[
\frac{\partial (\rho \mu_i)}{\partial t} + \frac{\partial (\rho \mu_i u_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + F_i + F_{vol}
\]

Momentum equation

where \(F_i\) is the body force in the case of gas blowing in the ladle and \(F_{vol}\) is the volume force which the source term for surface tension, given by

\[
F_i = \alpha \rho g_i
\]

\[
F_{vol} = \sigma \frac{\rho_k \nabla a_i}{2 (\rho_i + \rho_j)}
\]

The effective viscosity \(\mu_{eff}\) in Equation (2) was determined by solving the standard \(k - \varepsilon\) turbulence model, which introduces additional conservation equations for turbulent kinetic energy

| Parameters | Values |
|------------|--------|
| Diameter of the bottom of the ladle | 273.3 mm |
| Diameter of the top of the ladle | 298.4 mm |
| Height of the ladle | 755 mm |
| Top layer thickness | 7.5 to 75 (varies) mm |
| Effective height filled with water | 520 mm |
| Porous plug diameter | 8 mm |
| Plug radial position | 0.54R |

Table 2. The dimensional parameters of water model for both experiments and simulation.
The auxiliary relationships are:

\[ \mu_{\text{eff}} = \mu_i + \mu_t \]  \hspace{1cm} (8)

where

\[ \mu_t = \frac{\rho C_i k^2}{\varepsilon} \]  \hspace{1cm} (9)

The constants \( k \) and \( \varepsilon \) used in the present study were recommended by Launder and Spalding.\(^{23}\)

The Eulerian VOF model can be used to track the interface between the phases by solving single set of momentum equation. In this work, the tracking of the interfaces between liquid steel/slag/top-gas is accomplished using this model. The governing equation can be written as follows:

\[
\frac{1}{\rho_q} \frac{\partial}{\partial t} \left( \alpha_q \rho_q \mathbf{u} \right) + \nabla \cdot \left( \alpha_q \rho_q \mathbf{u} \mathbf{u} \right) = \mathbf{S}_t + \sum_{p=1}^{n} \left( \bar{m}_{pq} - m_{gp} \right)
\]  \hspace{1cm} (10)

where \( m_{pq} \) and \( \bar{m}_{pq} \) represent the mass transfer from phase \( p \) to \( q \) and phase \( q \) to \( p \) in unit time and volume, respectively; \( a_q \) is the volume fraction of phase \( q \); \( \rho_q \) is the density of phase \( q \); \( \mathbf{S}_t \) is the source term taken as 0 in Fluent software. The volume fraction of main phase is not calculated in Fluent software, while it can be acquired by the Equation (9). When the volume fractions are summed the following equation is satisfied:

\[ \sum_{q=1}^{n} a_q = 1 \]  \hspace{1cm} (11)

3. Materials and Methods

3.1. Physical Modeling Studies

An industrial ladle with a nominal capacity of 150 tonnes was used as prototype to design the water model with geometric scale factor of 1:5. Palovaara et al.\(^{24}\) introduced the water model for investigating the effect of gas flow rate on the open-eye area and mixing time in the ladle. The model was used later for validating CFD simulations\(^{25,37}\) as well as for studying the vibrations induced by gas-stirring.\(^{38}\) The dimensions of the water model are presented in Table 2.

In the physical model, a porous plug was not employed, but a simple circular plug with same area as the porous plug was used instead. Air was injected into the water bath through simple circular plugs with diameter of 8 mm located at the bottom of the vessel. The gas flow rate was measured relative to NTP condition (20°C, 1 atm). The position of the plugs is presented in Figure 2.

The water model was filled with tap water up to a height of 520 mm from the bottom wall. The top layer thickness was varied from 7.5 to 75 mm in the water model to study the effect of top layer thickness on the open-eye area. The employed range of top layer thicknesses correspond to slag layer thicknesses of 37.5 to 375 mm in the 150 t ladle. The physical modeling setup is shown...
in Figure 3. To represent the liquid metal, argon gas and slag, water, air, and oil were used, respectively. For simulating top slag, three different oils (paraffin oil, rapeseed oil, and castor oil) were employed. The physical properties of the materials used are shown in the Table 3. Based on the colour difference between the water and oil, the movement of open-eye was predicted by mounting the video camera on the top of the water model. ImageJ software was used to measure the open-eye area by processing the recorded images taken by the camera. The measurements were conducted for several top layer thicknesses and gas flow rates.

3.2. Numerical Modeling Studies

The three-dimensional geometric model developed was based on the geometry parameters presented in Table 2. Figure 4 shows the mesh distribution of the gas stirred ladle with two types of plug configurations. The first one is of with single plug configuration with 0.75 cm of top layer height, and the second one is with 7.5 cm top layer height with double plug configuration.

3.3. Initial and Boundary Conditions

The water model is at rest at the initial stage, with no injection of gas (air) from the bottom plug(s). As heat transfer is not within the scope of this work, temperatures changes in the water model were neglected. The velocity inlet boundary condition of the gas (air) is calculated by the flow rates used in the physical modeling by Equation (10).

\[
\nu_l = \frac{Q_l}{A} = \left( \frac{p_s}{p_L} \right) \left( \frac{T_L}{T_S} \right) \frac{Q_S}{A}
\]

where, subscript "L" means the water model operating condition, and "S" is the standard condition, \( T_S = 293.15 \text{ K}, \ T_L = 298.15 \text{ K}, \ p_S = 1 \text{ atm}, \) and \( p_L \) is the total pressure at vessel bottom. A is the bottom plug area, and \( Q_S \) is the air flow rate at standard condition. The total pressure is calculated as

\[
p_L = p_S + \rho g H
\]

where \( \rho \) is the density of the liquid phase, \( g \) is the standard gravity and \( H \) is the bath height.

3.4. Grid Independence Test

The grid independence results for 3.0 cm top layer height configuration are shown below in Figure 5 for a gas flow rate of 5.0 NL min \(^{-1}\). There was a significant change in the slag eye area when the grid was refined from 120,000 to 830,000 cells. On the other hand, further refining of the mesh did not affect the results significantly. Considering this result, the selected optimum grid
size varied from 650,000 cells with 0.75 cm top layer height, 830,000 cells with 3.0 cm top layer height to 1 million cells for 7.5 cm top layer height configurations. The three-phase transient flow simulations were performed using Ansys Fluent 18 software. The Eulerian VOF model with explicit scheme was used to solve the volume fraction equation (Equation 9). The no-slip boundary condition was used at the bottom wall and side walls. Velocity inlet boundary condition was employed for the gas inlet and pressure outlet boundary condition was chosen for the outlet at the top surface. The variable time step $\Delta t$ was used by setting the Courant number to one and the convergence criteria was set to $10^{-6}$ for the residuals of dependent variables. The simulation was stopped and the results were taken once the physical time reached 20 s.

### 4. Results and Discussion

#### 4.1. The Effect of Top Layer Thickness on the Open-Eye Area

In this work, the effect of slag thickness on the open-eye formation was studied. For both single and dual plug systems, six cases were simulated by varying the top layer thickness while the gas flow rate was kept constant. Rapeseed oil was chosen for simulating the slag phase. The total gas flow rate in both systems was 7.5 NL min$^{-1}$ but in dual plug system the gas flow was divided evenly for two plugs. The simulated cases are presented in Table 4.

Figure 6 depicts the fluctuation of the open-eye area for different top layer thickness for period of 20 s. It can be observed that the open-eye area reaches the peak value around 4 s from the injection of gas flow from the nozzle, and then starts to decreases until it stabilizes the fluctuate around the constant level.

The open-eye in the physical model and in the corresponding CFD simulation is shown Figure 7–9 for Cases S1, S3, and S6. According to Figure 7–9. It is obvious that the open-eye area decreases when the top layer thickness is increased. The open-eye formation was not observed to occur when top layer thickness was increased above 7.5 cm. The quantitative results

| Case  | S1   | S2   | S3   | S4   | S5   | S6   |
|-------|------|------|------|------|------|------|
| Top layer thickness [cm] | 0.75 | 1.5  | 3.0  | 4.5  | 6.0  | 7.5  |

| Case  | D1   | D2   | D3   | D4   | D5   | D6   |
|-------|------|------|------|------|------|------|
| Top layer thickness [cm] | 0.75 | 1.5  | 3.0  | 4.5  | 6.0  | 7.5  |

Figure 7. The open-eye in the physical model (left) and in the numerical simulation (right) in Case S1.

Figure 8. The open-eye in the physical model (left) and in the numerical simulation (right) in Case S3.
are presented in a relative form by dividing the measured open-eye area by the area horizontal cross-section of the ladle at the top layer height. The mean relative error between the physical model measurements and CFD results was approximately 5%. The results are collected in Table 5.

Krishnapisharody and Irons\textsuperscript{[6]} developed a mechanistic model for measuring the dimensionless open-eye size from the fundamental fluid flow considerations. The dimensionless area is expressed in terms of Froude number, which is further modified into the following correlation.

\[
\frac{A^*_e}{C_3} = -4.56 + 15.07(1 - \rho^*)^{-1/2}(Q^*)^{1/3} \left(\frac{H}{h}\right)^{1/2} \tag{14}
\]

where \(A^*_e = \frac{A_e}{C_3}\) (\(A_e\) is the non-dimensional open-eye area and \(H\) is the bath height), \(A^*_p = 1.41(Q^*)^{0.4}\), \(Q^* = \frac{Q}{g^{1/2}h^{1/2}}\) (\(g\) is the gravitational acceleration), \(\rho^* = \frac{\rho_t}{\rho_u}\) (\(\rho_t\) is the density of the top layer and \(\rho_u\) is the density of the water), \(h\) is the height the top layer).

The predicted trend of the dimensionless open-eye area showed in good agreement with the experimental data available from literature. The experimental data collected by various authors and the meanings of the non-dimensional parameters in Figure 10 and 11 can be found in reference.\textsuperscript{[6]}

As for the dual plug system, either one merged open-eye or two separate open-eyes were developed depending on the gas flow rate. Figure 12–14 give a visual illustration of both situations. In Case D1, one large open-eye is created (Figure 12). In Case D3 the open-eyes are barely merged (Figure 13) but in Case D4 two clearly separate open-eyes are formed (Figure 14) due to further increase in top layer thickness. For the given gas flow rate, the top layer height of 4.5 cm represents a critical thickness which can not be exceeded in order to obtain single, merged open-eye. As in the single plug system, the relative open-eye area was calculated for each case from physical model and CFD model. In the case of two separate open-eyes, the areas were summed and the total area was converted into relative form. The relative open-eye areas are presented in Table 6. The mean relative error between the measurement and the CFD results in the dual plug system was approximately 12%. The higher error compared to the single plug system is probably caused by the more complex system where two gas plumes are simulated.

Figure 15a) and b) present the open-eye area as a function of top layer thickness in the single plug system and dual plug system, respectively. It can been seen that the decrement of the

![Image](image-url)

**Figure 9.** The open-eye in the physical model (left) and in the numerical simulation (right) in Case S6.

**Figure 10.** Variation of non-dimensional open-eye area ratio with literature (K & I: Krishnapisharody and Irons;\textsuperscript{[6]} Yonezawa and Schwerdtfeger;\textsuperscript{[5]} Han et al.;\textsuperscript{[34]} a) \(A^*_e/A^*_p\) vs. \((Q^*)^{1/3}(H/h)^{1/2}\). (14)

**Figure 11.** Comparison of the predicted non-dimensional open-eye area ratio with dimensionless groups for gas injection (K & I: Krishnapisharody and Irons;\textsuperscript{[6]} Yonezawa and Schwerdtfeger;\textsuperscript{[5]} Han et al.;\textsuperscript{[34]} b) \(A^*_e/A^*_p\) vs. \((1 - \rho^*)^{1/2}(Q^*)^{1/2}(H/h)^{1/2}\). (14)

**Table 5.** The open-eye area relative the top bath surface area in physical model and CFD model in the single plug system for different top layer thicknesses.

| Case | Relative open-eye area |
|------|------------------------|
|      | S1 | S2 | S3 | S4 | S5 | S6 |
| Physical model [%] | 46.7 | 33.1 | 19.5 | 15.8 | 8.8 | 5.6 |
| CFD model [%] | 48.7 | 34.7 | 21.8 | 16.9 | 9.2 | 5.9 |

![Table 5](table-url)
relative open-eye area with increase in the top layer height follows the same trend as in the single plug system.

The predicted open-eye sizes and trend of reduction of its area with increase in thickness height are similar to the experimental results of Amara-Villeda et al.\cite{9} and Liu et al.\cite{22}

As in the single plug system, the top layer thickness has significant effect on the formation of open-eye, when gas is injected by increasing the number of plugs. From the results, it can be concluded that the top layer thickness has a significant effect on the formation of the open-eye. For industrial practice this means that a thicker slag layer needs to be compensated with a higher gas flow rate. It would be beneficial to use dual plug system when using lower top layer thickness, because it would reduce the deformation of the top layer and larger open-eye is formed by merging of two-slag eyes generated which is better suited for alloying when compared to single plug system. On the other hand, it is not suggested to use dual plug system when using higher top layer thicknesses, because of the weakened plumes through increment of plugs tends to generate smaller open-eyes compared to single plug system, which may not be good for alloying.

4.2. The Effect of Top Phase Properties on the Open-Eye Area

In order to evaluate of the effect of top layer densities on the open-eye area, experiments were conducted using two additional oils, which were chosen based on their density: castor oil (956 kg m\(^{-3}\)) is heavier than rapeseed oil (907.7 kg m\(^{-3}\)), while paraffin oil (880 kg m\(^{-3}\)) is lighter. These results were compared to the measurements conducted using rapeseed oil shown above.

In total, 18 experimental and CFD cases (three oils and three gas flow rates for single and dual plug systems) were conducted in order to study the effect of density of the top phase. The top layer thickness of 3.0 cm was constant in every case. Again in the dual plug system, the gas flow was divided evenly for both bottom plugs. The summary of the simulated cases is presented in Table 7.

The experimental and simulation results for the cases PS2, RS2, and CS2 are shown in Figure 16. It can be seen that the open-eye size increases with increase in the density of the top layer. The smallest open-eye was formed when the low-density oil (paraffin oil) was employed. The densest oil
(castor oil) produced the largest open-eye. The relative area for the paraffin oil case was 15.1% and 16.1% for the physical model and CFD model, respectively. In the castor oil case, the corresponding relative areas were 23.4% and 24.0%. The similar results for cases PD2, RD2 and CD2 are presented in Figure 17. It can be seen that for the densest oil one merged open-eye is formed but with the low-density oils two separate open-eyes are formed. The results imply that a high slag density might enable a large open-eye at this injected gas flow rate, which might be advantageous for alloying.

Table 6. The percentage of open-eye area relative the top bath surface area in physical model and CFD model in the dual plug system for different top layer thicknesses.

| Relative open-eye area | Case |
|------------------------|------|
|                        | D1   | D2   | D3   | D4   | D5   | D6   |
| Physical model [%]     | 49.9 | 35.5 | 21.9 | 16.2 | 9.9  | 5.8  |
| CFD model [%]          | 51.9 | 37.8 | 24.5 | 18.2 | 10.4 | 6.5  |

Figure 15. Percentage of open-eye area relative to the bath top surface area as function of top layer thickness in a) single plug system and b) in dual plug system.

Figure 16. The simulation results of open-eye size in single plug system for different top layer properties: paraffin oil (on the left) rapeseed oil (in the middle) and castor oil (on the right).
Table 7. Cases for simulating the effect of the top layer properties on the open-eye area.

| Single plug system | Gas flow rate [NL min⁻¹] | Oil         | Dual plug system | Gas flow rate [NL min⁻¹] | Oil         |
|--------------------|--------------------------|-------------|------------------|--------------------------|-------------|
| Case               |                          |             | Case             |                          |             |
| PS1                | 1.5                      | Paraffin oil| PD1              | 0.75 + 0.75              | Paraffin oil|
| PS2                | 3.5                      | Paraffin oil| PD2              | 1.75 + 1.75              | Paraffin oil|
| PS3                | 7.5                      | Paraffin oil| PD3              | 3.75 + 3.75              | Paraffin oil|
| RS1                | 1.5                      | Rapeseed oil| RD1              | 0.75 + 0.75              | Rapeseed oil|
| RS2                | 3.5                      | Rapeseed oil| RD2              | 1.75 + 1.75              | Rapeseed oil|
| RS3                | 7.5                      | Rapeseed oil| RD3              | 3.75 + 3.75              | Rapeseed oil|
| CS1                | 1.5                      | Castor oil  | CD1              | 0.75 + 0.75              | Castor oil  |
| CS2                | 3.5                      | Castor oil  | CD2              | 1.75 + 1.75              | Castor oil  |
| CS3                | 7.5                      | Castor oil  | CD3              | 3.75 + 3.75              | Castor oil  |

**Figure 18a** and b) present the open-eye area as a function of gas flow rate for different oils in the single plug system and dual plug system, respectively.

The experimental and simulation results seen in Figure 15 and 16 show that the systems with denser top layer generate larger open-eye when compared to systems with less dense top layer, which is somewhat counterintuitive (one would expect that a less dense phase should be easier to push aside and enable a larger open-eye). Nevertheless, the predicted behavior of open-eye sizes with respect to top layer properties were consistent with the experimental results of Krishnapisharody and Irons[6] and Wu et al.[12] It can be seen from the equations that they have derived from the dimensional analysis that open-eye area increases with the density. Krishnapisharody and Irons[6] also performed similar kind of measurements on studying the effect of top layer density and viscosity using less dense paraffin oil and denser motor oil on the open-eye size. Moreover, Krishnapisharody and Irons[6] concluded that the change in the open-eye size was

Figure 17. The simulation results of open-eye size in single plug system for different top layer properties: paraffin oil (on the left) rapeseed oil (in the middle) and castor oil (on the right).
attributed mainly to the differences in density of the top layer, while the dynamic viscosity of the top layer player plays virtually no role. Wu et al.\textsuperscript{12} also performed measurements for studying the open-eye size using water model experiments. Their results indicate that the gas flow rate as well as the height of the lower and top liquids have a strong impact on the open-eye size, while the viscosity of the top layer and the interfacial tension have only little effect on the open-eye size.

Furthermore, two additional simulations were performed to understand, which of the top layer properties, density or dynamic viscosity, is dominating the open-eye area formation in the studied ladle. As seen in the Figure 19, there is large difference in open-eye size for rapeseed oil and castor oil top layer properties. Therefore, the two additional simulations were carried out for these two cases to check if dynamic viscosity also has an effect on open-eye size or it is only due to the change in
density. In the first case, the rapeseed oil density and castor oil dynamic viscosity were chosen for the top layer properties. For the second case, the castor oil density and rapeseed oil dynamic viscosity were chosen for the top layer properties. The details for the two simulation cases carried out are shown in the Table 8.

Figure 18 shows with a constant top phase density, there is no significant change in the open-eye size when the dynamic viscosity of the top phase is varied. The relative areas of the open-eye generated in BC1 and TC1 were 21.8 and 21.9%, respectively. In BC2 and TC2 the open-eye areas were 34.1 and 34.2%, respectively. The relative error between the open-eye areas between these cases is almost negligible. Thus, it can be concluded that the change in the open-eye area is primarily dominated by the density of the top phase which is supported by the results of Krishnapishrody and Irons[6] as well as those of Wu et al.[12]

### 5. Conclusions

Numerical simulations were conducted in a one-fifth scale physical model of a 150-ton ladle to study the effect of top layer properties on the open-eye formation with single and dual-plug configurations. In the physical model, water and air were used to represent liquid steel and argon, respectively. Three different oils were employed for simulating the slag phase. The Eulerian Multiphase Volume of Fluid (VOF) model was used to simulate the three-phase flow in the ladle. A comparison of the open-eye formation for different top layer thickness and density between the single and dual-plug configurations was made.

The following conclusions can be drawn from the numerical simulation results:

1) The top layer thickness affected the open-eye diameter and area. In a single plug system, when the top layer thickness was increased from 0.75 to 7.5 cm, the relative open-eye area decreased from 46.7% to 5.6% for a gas flow rate of 7.5 NL min\(^{-1}\).
2) The open-eye did not form when the top layer thickness was increased more than 7.5 cm for gas flow rate of 7.5 NL min\(^{-1}\). At low top layer thickness (0.75 and 1.5 cm), there was strong deformation in the top layer in the single plug system.
3) In dual plug system, the two open eyes merged into larger single open-eye at lower top layer thickness of 0.75 and 1.5 cm for gas flow rate of 3.5 NL min\(^{-1}\) injected from each plug. With higher top layer thickness of 3.0 and 4.5 cm, two separate open-eyes were formed.
4) The top layer density was found to have a significant effect on the area of the open-eye. The top layer with high density (castor oil) generates a larger open-eye when compared to the top layer with low density (paraffin oil). Under the conditions of the work, the dynamic viscosity of the top layer did not have a significant effect on the open eye area.

### Acknowledgements

The authors are grateful for the financial support of the European Commission under grant number 675715-MIMESIS – H2020-MSCA-ITN-2015, which is part of the Marie Skłodowska-Curie Actions Innovative Training Networks European Industrial Doctorate Programme. Furthermore, the Finnish Cultural Foundation is acknowledged for their financial support.

### Conflict of Interest

The authors declare no conflict of interest.

### Nomenclature

- \( \rho \): Density, kg m\(^{-3}\)
- \( u \): Fluid velocity, m s\(^{-1}\)
- \( \mu \): Effective dynamic viscosity, Pa s
- \( g \): Acceleration due to gravity, m s\(^{-2}\)
- \( P \): Pressure, Pa
- \( \mu_e \): Effective turbulent viscosity, Pa s
- \( k \): Turbulent kinetic energy, m\(^2\) s\(^{-2}\)
- \( \epsilon \): Turbulent dissipation rate, m\(^3\) s\(^{-3}\)
- \( \mu_t \): Turbulent eddy viscosity, Pa s
- \( F_i \): Body force, kg/m s\(^2\)
- \( a_q \): Phase volume fraction
- \( G_k \): Generation term
- \( Q \): Gas flow rate, m\(^3\) s\(^{-1}\)
- \( A \): Area, m\(^2\)
- \( A_e \): Non-dimensional eye area
- \( A_p \): Non-dimensional plume area
- \( Q' \): Non-dimensional gas flow rate
- \( \rho^* \): Density ratio of liquids

### Keywords

computational fluid dynamics, ladle metallurgy, multi-phase flows, open-eye, volume of fluid model

Received: February 19, 2019  
Revised: April 30, 2019  
Published online: June 5, 2019

[1] G. Stolte, Secondary Metallurgy, Verlag Stahleisen GmbH, Düsseldorf 2002.
[2] F. Oeters, Metallurgy of Steelmaking, Verlag Stahleisen mbh, Düsseldorf and Springer-Verlag Berlin, Heidelberg 1989.
[3] H. Lachmund, Y. Xie, T. Buhles, W. Pluschkel, Steel Res. 2003, 74, 77.
[4] W. Liu, H. Tang, S. Yang, M. Wang, J. Li, Q. Liu, J. Liu, Metall. Mater. Trans. B 2018, 49, 2681.
[5] K. Yonezawa, K. Schwerdtfeger, *Metall. Mater. Trans. B* 1999, 30, 411.
[6] K. Krishnapisharody, G. A. Irons, *Metall. Mater. Trans. B* 2006, 37, 763.
[7] K. Krishnapisharody, G. A. Irons, *ISIJ Int.* 2008, 12, 1807.
[8] D. Guo, G. A. Irons, *Metall. Mater. Trans. B.* 2002, 33, 377.
[9] A. M. Amaro-Villeda, M. A. Ramirez-Aragaez, A. N. Conejo, *ISIJ Int.* 2014, 54, 1.
[10] D. Mazumdar, J. W. Evans, *Metall. Mater. Trans. B.* 2004, 35, 401.
[11] M. Peranandthan, D. Mazumdar, *ISIJ Int.* 2010, 11, 1622.
[12] L. Wu, P. Valentin, D. Sichen, *Steel Res. Int.* 2010, 7, 508.
[13] M. Thuman, S. Eckert, O. Hennig, J. Björkvall, D. Sichen, *Steel Res. Int.* 2007, 12, 849.
[14] N. Li, L. Wu, H. Wang, Y. Dong, C. Su, *Iron Steel Res. Int.* 2017, 24, 243.
[15] P. Valentin, C. Bruch, Y. Krylenko, H. Köchner, C. Dannert, *Steel Res. Int.* 2009, 80, 552.
[16] H. Liu, Z. Qi, M. Xu, *Steel Res. Int.* 2011, 4, 440.
[17] B. Li, H. Yin, C. Q. Zhou, F. Tsukihashi, *ISIJ Int.* 2008, 48, 1704.
[18] L. Li, Z. Liu, B. Li, H. Matsuura, F. Tsukihashi, *ISIJ Int.* 2015, 55, 1337.
[19] L. Li, B. Li, *JOM* 2016, 68, 2160.
[20] L. Li, Z. Liu, M. Cao, B. Li, *JOM* 2015, 67, 1459.
[21] Z. Liu, L. Li, B. Li, *ISIJ Int.* 2017, 57, 1971.
[22] L. Li, B. Li, Z. Liu, *ISIJ Int.* 2017, 57, 1980.
[23] B. E. Launder, D. B. Spalding, *Comput. Meth. Appl. Mech. Eng.* 1974, 3, 269.
[24] T. Palovaara, V.-V. Visuri, T. Fabritius, *Proc. 7th International Congress on Science and Technology of Steelmaking, 2018.*
[25] E. K. Ramasetti, V.-V. Visuri, P. Sulasalmi, R. Mattila, T. Fabritius, *Steel Res. Int.* 2019, 2, 1800365.
[26] H. Noureddini, B. C. Teoh, L. Davis Clements, *JAOS 1992, 69, 1184.*
[27] H. Noureddini, B. C. Teoh, L. Davis Clements, *JAOS 1992, 69, 1189.*
[28] M. F. Jamil, Y. Uemura, K. Kusakabe, O. B. Ayodele, N. Osman, N. M. N. Ab Majid, S. Yusup, *Procedia Eng.* 2016, 148, 378.
[29] ANSYS Fluent Theory Guide, Release 17, 2016, 85.
[30] Q. Cao, L. Nastac, *Iron Steel Making 2018, 45, 1.*
[31] Q. Cao, L. Nastac, *Metall. Mater. Trans. B* 2018, 49, 1388.
[32] Q. Cao, L. Nastac, *JOM* 2018, 70, 2071.
[33] Y. Liu, M. Ersson, H. Liu, P. Jönsson, Y. Gan, *Steel Res. Int.* 2019, 90, 1800494.
[34] J. W. Han, S. H. Heo, D. H. Kam, B. D. You, J. J. Pak, H. S. Song, *ISIJ Int.* 2001, 41, 1165.
[35] S. Joo, R. I. L. Guthrie, *Metall. Mater. Trans. B* 1992, 23, 765.
[36] Y. Liu, M. Ersson, H. Liu, P. Jönsson, Y. Gan, *Metall. Mater. Trans. B* 2009, 50, 555.
[37] N. Alia, V. John, S. Ollila, *Appl. Math. Model.* 2019, 67, 549.
[38] N. Alia, M. Pylvänäinen, V. Visuri, S. Ollila, *J. Iron Steel Res. Int.* 2019, 1. https://doi.org/10.1007/s42243-019-00241-x