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Experimental and Numerical Investigation of Slag Thickness Effect on the Formation of Slag Eye in a Water Model of a Steel Making Ladle

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Abstract

In secondary steelmaking process, gas stirring is extensively used to homogenize the chemical composition of alloy elements and the removal of inclusions. During the process, gas is injected through a porous plug into the steel bath creating a buoyant bubble plume. The plume generates a recirculation flow pattern in the ladle, and the rising bubbles break the slag layer creating a slag eye at high gas flow rates. In the current work, the behaviour of the slag eye area for different slag layer thickness heights is been investigated through experimental measurements and CFD simulations. A 1/5-scale water model of 150-ton ladle was established for the experimental measurements and for studying the effect of slag thickness on the slag eye area. The physical modelling results show that the slag eye area changes from 227.6 to 27 cm^2 when slag layer thickness height was increased from 0.75 to 7.5 cm for a gas flow rate of 3.5 NL/min. The mathematical model developed was based on the Eulerian Multiphase Volume of Fluid (VOF) approach and standard $k-\varepsilon$ turbulence model was used for solving the turbulent liquid flow. The simulation results of slag eye area showed a good agreement when compared to the experimental results measured.

Keywords: Ladle metallurgy, computational fluid dynamics, multi-phase flows, slag eye and volume of fluid (VOF) model.

Introduction

Gas stirring is largely used during the steel production process to obtain a homogenous distribution of alloying elements and temperature in the molten steel, and for the removal of inclusions. When gas is injected into the molten steel from the bottom of the ladle, a slag eye is generated by breaking the slag layer. The role of slag layer behaviour is very important in refining the liquid metal, as the contact between slag and liquid metal has been noticed to be more around the slag eye than other areas in the ladle the ladle (1). Figure 1 presents a schematic illustration of the gas-stirring process in a ladle. The investigation of the slag/liquid metal/gas interface behaviour in this process is very important for the production of steel.

Over the past few decades, the formation of slag eye in a gas stirred ladle has been the subject of a number of works. The studies have been conducted to investigate the flow characteristics, slag eye formation and mixing time in the gas stirred ladle through physical modelling measurements (2–6) and numerical simulations (7–12). Xie and Oeters (2) measured the flow velocity distribution, turbulent kinetic energy and its dissipation rate in a ladle with liquid Wood's metal. Liu et al. (3) conducted physical measurements in a water model ladle for slag eye area for different gas flow rates in single and dual-plug system. Yonezawa and Schwerdtfeger (4) measured the slag eye area using mercury and silicon oil as metal and slag in water model ladle. The physical modelling measurements on the formation of slag eye in a 1/5-scale water model ladle were conducted by Wu et al. (5). The investigations included the effect of slag viscosities and gas flow rate on slag eye size. Krishapisharody et al. (6) concluded that the slag eye area increases with increase in the gas flow rate and decreases with increases in slag layer thickness heights from his measurements.

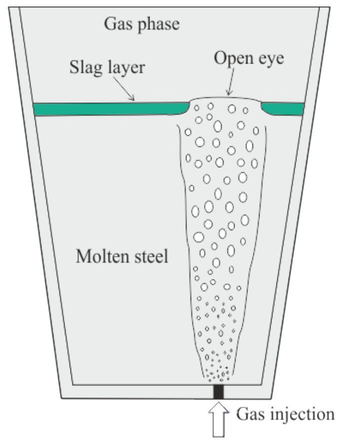

Figure 1. Schematic gas stirring process in a ladle

In numerical simulations, many mathematical models were developed using Eulerian and Lagrangian approaches. Li et al. (7) developed a transient mathematical model for simulating bubble-steel-slag-top gas four-phase flow for argon stirred ladle. To describe the bubble movement Lagrangian discrete phase model (DPM) was used and volume of fluid (VOF) model to observe the formation of slag eye. Liu et al. (8) developed the model based on volume of fluid (VOF) approach to investigate the effect of gas flow rate and plug location on the slag eye area. Cloete et al. (9) and Ramirez-Argaez (10) also performed simulations using VOF model in studying the influence of design variables on the flow analysis and slag eye in a ladle.

Valentin et al. (11) conducted physical measurements on industrial ladle in studying the influence of gas stirring on formation of open-eye and mixing phenomena and validated with simulation results. Ramasetti et al. (12) performed a wide range of both experiments and simulations in investigating the effect of gas flow rate on the flow characteristics and slag eye area with single and dual plug configuration in a water model ladle. Mazumdar et al. (13) made an extensive literature research in summarizing the studies done on fluid flow, mixing time and slag/steel/gas interface behaviour through physical modelling studies, mathematical modelling studies and combined physical and mathematical modelling studies.

Over the past decade, the majority of the studies were focused on the studying the effect of gas flow rate on the slag eye area and relatively few studies on the effect of slag properties on slag eye area. The purpose of this study is to perform experiments and simulations to attain a better understanding of the effect of slag layer thickness on the slag eye area. As for the physical modelling part, the water model is of 1/5 scale of a 150-ton steelmaking ladle. For the numerical simulations part, the Eulerian VOF approach is used to track the slag/steel/air interface behaviour for the gas-stirred ladle.

Model Formulation

The standard conservations for mass and momentum were solved.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \qquad (2)$$

where $\vec{v}$ is the fluid velocity vector, ρ is the density, p is the pressure, $\vec{g}$ is the gravitational acceleration vector and $\vec{F}$ is the additional force vector.

The Eulerian volume of method (VOF) model which is able to solve two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each fluid throughout the domain is used to represent the interface behaviour of slag, steel and gas layer in the ladle. The governing equations can be presented as follows:

$$\frac{1}{\rho_Q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla.\left(\alpha_q \rho_q \vec{v}_q\right)\right] = 0 \qquad (3)$$

where the volume fraction of primary phase α_q is calculated from the constraint which is equal to unity.

The standard $k - \varepsilon$ turbulence model is to model turbulence, which solves the control equations for turbulent kinetic energy and turbulent dissipation rate.

Turbulent kinetic energy, k:

$$\rho\left(\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G - \rho\varepsilon \qquad (4)$$

where G is the generation term due to the mean velocity gradients,

$$G = \mu_t \frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (5)$$

Turbulent dissipation rate, ε:

$$\rho\left(\frac{\partial \varepsilon}{\partial t} + u_i \frac{\partial \varepsilon}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + \frac{\varepsilon}{k}\left(C_1 G - C_2 \rho \varepsilon\right) \qquad (6)$$

where C_1, C_2, C_μ, σ_k,σ_ε are the empirical constants, whose values are 1.38, 1.92, 0.09, 1.0 and 1.3 respectively.

Experimental Details

A 1/5 scale water model of 150-ton ladle was established to study the effect of slag layer thickness on the slag eye. On the top of water model, a video camera was placed to observe the formation of slag eye. Air was injected through the porous plug located at the bottom of the nozzle for stirring rate of 3.5 NL/min and for different slag layer thickness ranging from 7.5 to 75 mm. Water and rapeseed oil were used to simulate the molten steel and slag layer respectively. The details of the material properties and geometry parameters are shown in Table 1.

Parameters	Value
Height of the water model	755 mm
Water level depth	520 mm
Bottom diameter	273.3 mm
Top diameter	298.8 mm
Plug diameter	8 mm
Radial position of the plug	0.54 R
Density of water	997.2 kg/m^3
Dynamic viscosity of water	0.000891 Pa·s
Density of rapeseed oil	907.2 kg/m^3
Dynamic viscosity of oil	0.0778 Pa·s
Density of air	1.258 kg/m^3
Dynamic viscosity of air	1.846 × 10^{-5}

Table 1. Geometry and thermal physical properties for both experiments and simulations.

Computation Details

The computational domain and mesh of the gas stirred ladle is shown in Figure 2.

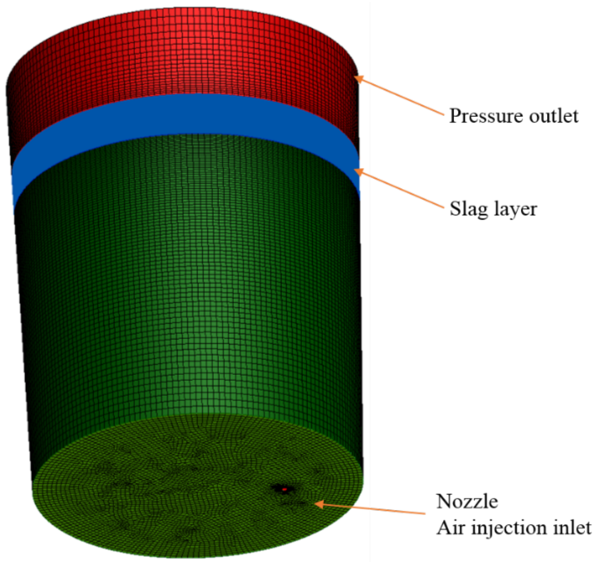

Figure 2. Mesh and boundary conditions

The optimum mesh sizes chosen were about 600,000 cells for a slag layer thickness of 7.5mm and about 1 million cells for 75 mm thickness. The boundary condition at the air injection inlet is taken as the velocity inlet, at the top surface it is taken as pressure outlet condition and no-slip boundary conditions were taken at the ladle walls. The transient multi-phase calculations were carried out by using finite-volume software ANSYS Fluent 18.2. The convergence criteria are set to be 10^{-6} and variable time-step is used by setting Courant number to 1. The data was collected when flow reached steady state at around 20 sec.

Results and Discussion

The effect of slag layer height on the slag eye area for a gas flow rate of 3.5 NL/min was studied through physical modelling and numerical simulations. Figures 3 to 4 displays the comparison of the decrement of the slag eye area of the experimental and simulations results when the slag layer height was increased from 0.75 to 7.5 cm. The slag layer height of 0.75 cm for gas flow rate of 3.5 NL/min generated a slag eye area of 227.6 cm^2 in physical modelling, whereas 235.4 cm^2 from simulation results shown in Figures 3(a) and 4(a).

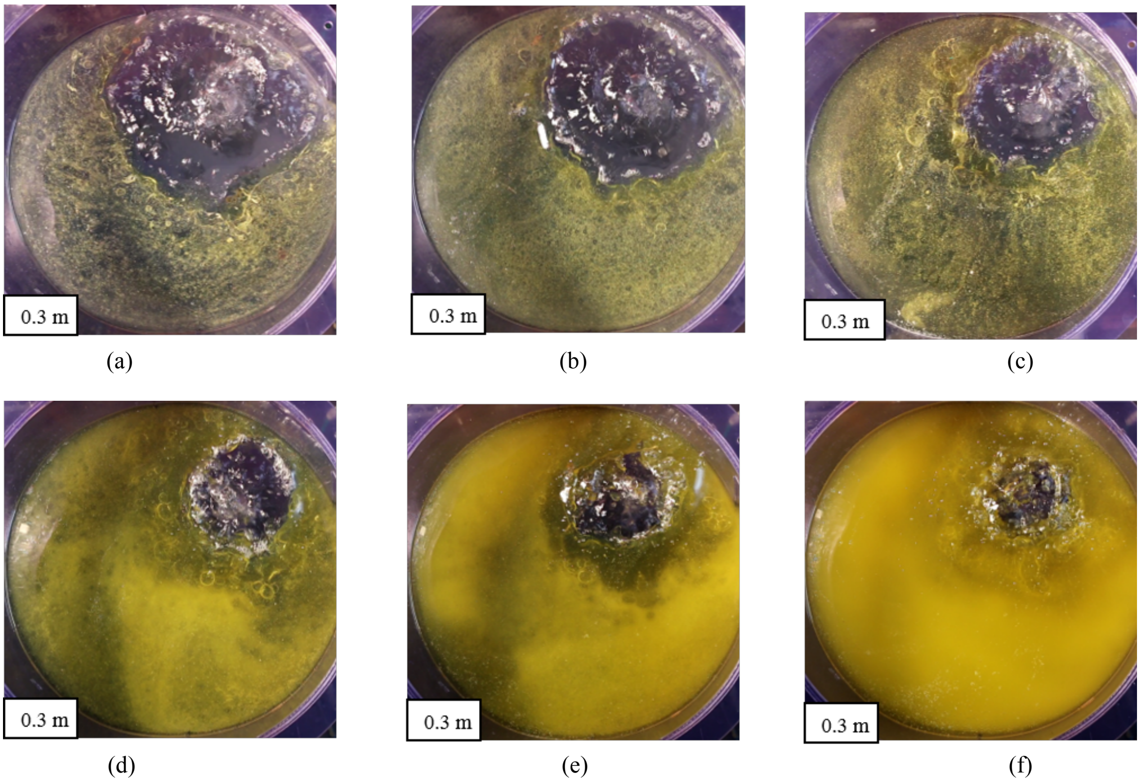

Figure 3. The experimental results of slag-eye size variation when slag layer height is increased from 0.75 to 7.5 cm (a) 0.75 cm (b) 1.5 cm (c) 3.0 cm (d) 4.5 cm (e) 6.0 cm (f) 7.5 cm

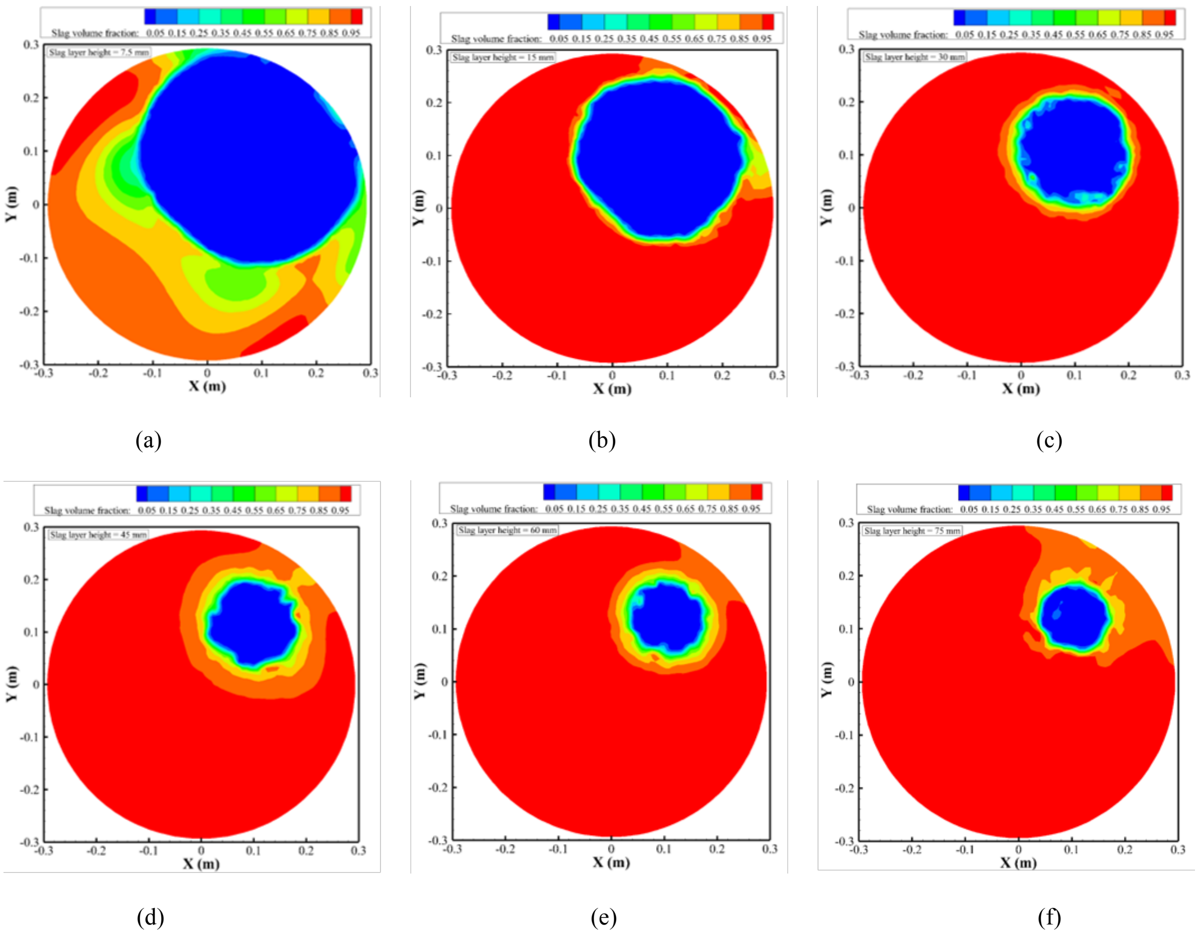

Figure 4. The simulation results of slag-eye size variation when slag layer height is increased from 0.75 to 7.5 cm (a) 0.75 cm (b) 1.5 cm (c) 3.0 cm (d) 4.5 cm (e) 6.0 cm (f) 7.5 cm

The slag eye area reduced to 155.2 cm^2 when the slag layer increased to 1.5 cm, which shows a good agreement to 157.9 cm^2 with simulation results (see Figures 3(b) and 4(b)). When the slag layer heightened to 3.0 cm, the slag eye area downsized to 97.2 cm^2, which was somewhat larger than this value obtained from the simulation results (Figures 3(c) and 4(c)). The slag open eye area shortened from 94.2 cm^2 shown in Figure 3(d) when the slag layer height marked up to 4.5 cm, which was quite congruent with the simulation results (see Figure 4(d)). The slag layer height of 6.0 generated a slag eye area of 37.9 cm^2 in physical modelling and 36.4 from simulations. At a high thickness of slag layer of 7.5 mm, the slag eye area diminished to 27.6 cm^2, which was a satisfactory match with the simulation results of 26.2 cm^2.

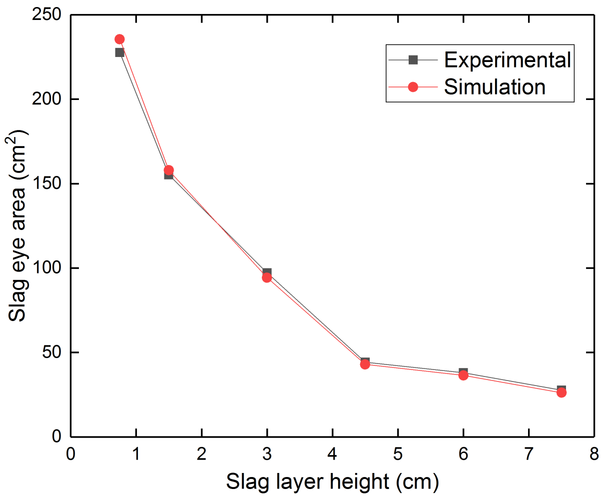

Figure 5. Effect of slag layer height on the slag eye area for both experiments and simulations.

The decrement of the slag eye area when the slag layer height is increased from 0.75 cm to 7.5 cm is shown in Figure 5. The slag eye area decreases from 227.6 to 27.6 cm^2 for physical modelling and 235.4 to 26.2 cm^2 for numerical simulations. The relative percentage error between the experimental and simulation results of slag eye area is around 5.0 %, which is tolerable in view of the complexity of the current case. The predicted slag eye sizes are in good agreement with the shape and size when compared to the simulation results of Li et al. (7) and Li et al. (3).

The mathematical model developed in the current work provides a better understanding of the effect of slag layer height on the slag eye area. This model can be modified for simulating the full-scale industrial ladle for investigating the effect of gas flow rate and slag layer height on the slag eye area, providing information for better alloying purposes.

Conclusions

A one-fifth scale water model was set up to study the effect of slag layer thickness on slag eye formations. A mathematical model based on Eulerian Multiphase Volume of Fluid (VOF) model was developed to study slag interface behaviour in the ladle and validate the experimental results. It was clear from the results that the slag layer has a significant effect on the slag eye area. The slag eye area decreases with increases in the slag layer height for both experiments and simulations. The simulation results of slag eye area agree well with the measured experimental results.

Acknowledgments

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