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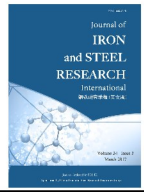

Size analysis of slag eye formed by gas blowing in ladle refining

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ABSTRACT

The formation of slag eye in a gas stirred ladle was studied through cold models and industrial trials. In the cold model, water and sodium tungstate solution were employed to simulate liquid steel, and silicon oil was employed to simulate slag. The simulation results revealed that the gas flow rate and bath height had strong effects on the slag eye size. In particular, the thickness of slag layer played a strong role in the slag eye size. In addition, the slag eye could not be formed when the thickness of the top layer was more than 4 cm in water-silicone oil model. Besides, the section area of vessel had a great impact on the slag eye size. Industrial trials results showed a similar trend that the gas flow rate was very significant on the slag eye size. The predictions of the existing models showed larger predictions deviations compared with the experimental data. Moreover, a new model without fitting parameters was developed based on force balance and mathematical derivation, and verified by the experimental data. The new model provides the prediction with small deviations by comparing with the data acquired from cold models and industrial trials.

Symbol List

A—Area of section $A''B$, cm^2;
A_e—Slag eye size, cm^2;
A_0—Section area of vessel, cm^2;
A_p—Plume size, cm^2;
A_e^*—Dimensionless slag eye;
A_p^*—Dimensionless plume;
d—Nozzle diameter, mm;
D_0—Ladle diameter, cm;
D_e—Slag eye diameter, cm;
D_p—Plume diameter, cm;
$\boldsymbol{Fr}$—Froude number;
$\boldsymbol{Fr}^*$—Densimetric Froude number;
g—Acceleration of gravity, $cm \cdot s^{-2}$;
h_0—Upper phase (slag) thickness without gas blowing, cm;
h—Upper phase (slag) thickness with gas blowing, cm;
H—Depth of bulk phase fluid in ladle, cm;
$\boldsymbol{j}$—Unit vector in vertical direction;
K_1, K_2—Constants;
$\hat{\boldsymbol{n}}$—Unit normal vector;
P_a, P_b—Pressures at top and bottom, respectively, of control volume, Pa;
Q—Gas flow rate, $cm^3 \cdot s^{-1}$;
s—Ratio of thickness of top phase to depth of bulk phase;
U_0—Velocity of downward flow in control volume, $cm \cdot s^{-1}$;
U_p—Plume velocity (average rise velocity of two-phase mixture), $cm \cdot s^{-1}$;
U_{pmax}—Maximum of plume velocity, $cm \cdot s^{-1}$;
$\boldsymbol{v}$—Component of velocity vector;
$\boldsymbol{V}$—Velocity vector;
W—Mass of water contained in control volume, g;
α, β, γ—Constants;
θ—Vertical angle of downward flow in control volume;
μ_s—Kinematic viscosity, $cm^2 \cdot s^{-1}$;
ρ_o—Density of oil, $g \cdot cm^{-3}$;
ρ—Density of water, $g \cdot cm^{-3}$;
ρ_s—Density of upper liquid, $g \cdot cm^{-3}$;
ρ_m—Density of bulk phase liquid, $g \cdot cm^{-3}$;
$\Delta\rho$—Difference between top liquid and bulk liquid, $g \cdot cm^{-3}$;
Ψ—Gas fraction in plume;
χ—Numerical value.

1. Introduction

Argon gas stirring is widely employed in ladle refining process. Generally, argon gas is introduced into ladle by using bottom blowing[1]. For bottom blowing, gas scatters many bubbles in the process of rising in liquid steel. Besides, the bubbles transfer potential energy to liquid steel during rising,

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forcing liquid steel movement and thus forming a gas-liquid plume. Under moderate condition, such as large plume velocity and thin slag layer, the plume will overcome potential energy difference between liquid slag and liquid steel, revealing a bare liquid steel surface which is referred to as "slag eye".

It is generally believed that gas-liquid plume and slag eye are crucial to refining effect. For example, argon gas stirring improves slag-metal mixing around slag-eye and increases slag-metal contact area, which in turn accelerates slag-metal reaction[2]. Besides, argon bubbles in liquid steel are vacuum chambers, and thus gas-liquid plume has a strong degassing function. In addition, the inclusions attached to gas bubbles easily rise and enter slag, which is helpful to inclusion separation.

However, a violent gas stirring would lead to a high plume velocity. Many researchers thought fast flowing liquid steel would shatter the top slag, forming tiny slag droplets. The slag droplets would be dragged into metal bath by flowing liquid steel, forming inclusions[3,4]. Big size of slag eye would also increase the contact surface between liquid steel and air, which results in re-oxidation and absorbing gas.

Due to above reasons, some studies[5-13] have been performed to describe slag eye size as a function of the gas flow rate and the properties of the melts. These studies are very valuable to understand the formation of slag eye. However, little work was devoted to studying the effect of ladle dimension on slag eye size.

The present work focused on the following three aspects: (1) collecting three series data based on water-silicone oil models, sodium tungstate-silicone oil model and industrial trial; (2) establishing a new model to fit the experimental data acquired from the cold models and industrial trials; (3) checking the existing models and the new model by the experimental data.

2. Experimental

Two water models were adopted in the present study. The experimental setup is shown in Fig. 1. Each model consists of a transparent acrylic cylindrical vessel (with inner diameters of 60 cm and 29 cm, respectively) and a mass flow controlling system. Compressed air was injected into the vessel through a centrally placed nozzle with an inner diameter of 6 mm on the bottom of the cylindrical vessel. Tap water and silicone oil were used to simulate liquid steel and slag layer, respectively. To easily make out the boundary of slag eye, a few drops of Sudan blue was added to the silicone oil. A video camera was employed to catch the dimensions of slag eye.

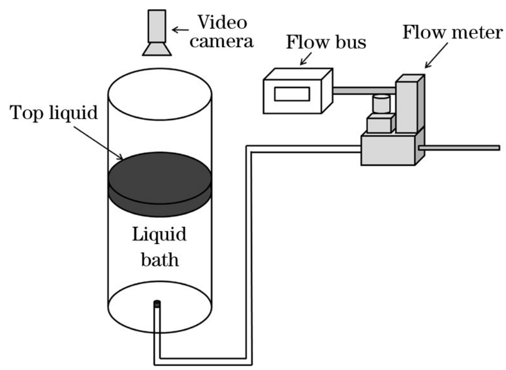

Fig. 1. Experimental setup for cold model.

In another model, sodium tungstate solution and silicone oil were used to simulate liquid steel and slag layer, respectively. The experimental setup was similar to the water model. It has an inner diameter of 18.8 cm and the maximum liquid bath height of 17.2 cm. Similarly, to easily identify boundary of slag eye, a few drops of Sudan blue were added to the silicone oil. Compressed air was employed in this model experiment as well. The gas inlet positioned in the center of the bottom had an inner diameter of 6 mm.

The physical properties of the liquids used in the experiments are listed in Table 1. In a general experiment, the heights of top liquid and bath liquid were accurately measured. A constant gas flow rate was adopted in each experiment. The dimensions of slag eye were recorded when the slag eye reached relatively steady state, which usually took about a few minutes. Both video clips and steady photos were taken. The images were used to determine the dimensions of slag eye by comparing them with the dimensions of the vessel.

Besides, the industrial trials were also carried out to verify the existing models. The diameter of the 120 t ladle is about 3.0 m, and the height of the liquid steel is calculated to be 3.2 m based on the ladle dimensions and the density of the liquid steel (1873 K). After argon blowing for 5 min, the variations of slag eye size with gas flow rate were recorded by an infrared video camera. According to the mass ratio of slag to metal, the thicknesses of the layers were estimated to be about 2－6 cm.

Table 1
Physical properties of liquids used in present study

Liquid	Viscosity/ (mPa·s)	Surface tension/ ($N\cdot m^{-1}$)	Density/ ($kg\cdot m^{-3}$)
Silicone oil	97.0	21.0×10^{-3}	965±4
Sodium tungstate	10.0	90.0×10^{-3}	2000
Water	1.0	7.0×10^{-3}	1000