Spout Eye Area in Ladle Refining Process

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1. Introduction

Bottom gas injection techniques are extensively used in the steelmaking processes.1–3) Bubbles are successively formed at the exit of the bottom nozzle. They rise upward entraining the surrounding molten metal into their wakes, arrive at the slag–metal interface, and escape from the bath surface into the atmosphere. When the slag layer is thick and the gas flow rate is low, the molten metal carried by bubbles upward into the region near the bath surface moves outward in the radial direction and returns to the molten metal layer. As a result, a recirculating flow is formed outside the bubbling jet. On the other hand, when the slag layer is thin and the gas flow rate is high, the molten metal reaching the slag–metal interface drives the slag away and goes further up to the bath surface. The molten metal contacts directly the gas phase on the bath surface. The cross-section of water and oil on the bath surface became difficult because they are transparent and are highly mixed in a complex manner.11) The data obtained under these conditions were not included in the analysis.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus and the shape of the water column lifted up above the slag–metal interface, where \( V_m \) and \( \Delta H_s \) denote the volume and height of the water column, respectively. The diameter of the test vessel, \( D \), is 20.0 and 50.0 cm. Water was filled in each vessel to a depth, \( H_m \), of 1.5 vessel diameters. Namely, \( H_m = 30.0 \) cm and 75.0 cm for \( D = 20.0 \) cm and 50.0 cm, respectively. Normal pentane or one of three kinds of silicone oils was placed on the water. The physical properties of liquids are listed in Table 1. The thickness of the oil layer, \( H_o \), was varied from 1.0 to 15.0 cm. Air was supplied with a compressor and injected into the bath after removing air pollutants such as oil mist. The air flow rate, \( Q_g \), was adjusted with a mass flow controller. The behavior of the spout eye was observed with a CCD camera and a high-speed video camera from the top of the bath. The images were recorded on a personal computer and then processed to determine the plume eye area. Figure 2 shows an example of the image.

When the thickness of the oil layer, \( H_o \), and the air flow rate, \( Q_g \), exceeded their respective critical values, discrimination of water and oil on the bath surface became difficult because they are transparent and are highly mixed in a complex manner.11) The data obtained under these conditions were not included in the analysis.

3. Experimental Results and Discussion

3.1. Existing Empirical Equations for the Spout Eye Area

Yonezawa and Schwerdtfeger6,9) systematically carried out model experiments using mercury and some kinds of silicone oils to measure the spout eye area. They proposed empirical equations having the following functional relationship.

\[
A_{se}(H_o,H_s) = f \left( Q_g (g H_s^2) \right)^n \tag{1}
\]

where \( A_{se} \) is the spout eye area and \( g \) is the acceleration due to gravity. They found that the spout eye area depends on...
3.2. Derivation of Empirical Equation for Plume Eye

The following empirical equation was derived:

\[
A_w = (2V_m^2 / \Delta H_m)(\Delta H_m / H_m)A_{mc} \tag{9}
\]

where \(V_m\) is the velocity of the molten metal, \(\rho_m\), \(\rho_s\), and \(\rho_g\) are the densities of molten metal, molten slag, and injected gas, respectively, \(u_{inj}\) is the spout eye area, \(A_{mc}\), is the cross-sectional area of the parabolic water column at a height of \(H_m\), i.e., the spout eye area, \(A_{mc}\), is expressed by:

\[
A_{mc} = (4mH_m^2/n)[1/(n/2)]g(\rho_m - \rho_s)H_m/(\rho_m\rho_s) \tag{10}
\]

Equation (10) reduces to a non-dimensional form of

\[
A_{mc} = a_1(\rho_m - \rho_s)H_m/(\rho_m\rho_s) \tag{11}
\]

where \(a_1 = (4m/n)\) and \(a_1 = (4m/n^2)\) are constants. These constants are determined by comparing Eq. (11) with measured values of \(A_{mc}\).

3.3. Determination of \(a_1\) and \(a_2\) in Eq. (11)

At first, Eq. (11) was compared with the data on the spout eye area measured by Yonezawa and Schwerdtfeger\(^8\) in Fig. 3. They used mercury and silicone oil as models for molten steel and molten slag, respectively. The measured values of \(A_{mc}/H_m^2\) decreased linearly with an increase in \(2g(\rho_m - \rho_s)H_m/(\rho_m\rho_s)\), until it reaches approximately 0.7. The following empirical equation was derived:

\[
A_{mc}/H_m^2 = 0.600 - 0.652[2g(\rho_m - \rho_s)H_m/(\rho_m\rho_s)] \tag{12}
\]

Equation (12) can satisfactorily approximate the measured values. Consequently, the adequacy of Eq.(11) was verified.
when \( 2g(\rho_m - \rho_g)H/(\rho_g u_m^2) \) is small.

3.4. Empirical Equation Applicable in Wider Range of \( 2g(\rho_m - \rho_g)H/(\rho_g u_m^2) \)

The measured values shown in Fig. 3 were re-plotted on a semi-logarithmic scale in Fig. 4. The solid line was drawn through the mean of the measured values. It is expressed by

\[
\log[A_u] = -0.222 - 0.741\{2g(\rho_m - \rho_g)H/(\rho_g u_m^2)\},
\]

\[
[A_u < \pi D^2/4] \ldots \ldots (13)
\]

Equation (13) can approximate the measured values obtained by Yonezawa and Schwerdtfeger within a scatter of \( \pm 60\% \). Such relatively small deviation is caused because most parameters influencing the flow phenomena in the bath are adequately taken into consideration in Eq. (13).

When \( H \) is small and gas flow rate is high, Eq. (13) reduces to

\[
A_u/H^2 = 0.600 - 1.023\{2g(\rho_m - \rho_g)H/(\rho_g u_m^2)\} \ldots \ldots (14)
\]

The functional relationship of Eq. (14) is the same as that of Eq. (12) but Eq. (14) underestimates the spout eye area.

3.5. Comparison of Empirical Equations with Presently Measured Values of Spout Eye Area

Figure 5 shows the presently measured values of the spout eye area. Equation (13) can also approximate the measured values within a scatter of \( \pm 60\% \). It should be stressed that Eq. (13) is valid even for a density ratio, \( \rho_m/\rho_g \), of approximately unity, although Eq. (13) was originally derived for \( \rho_m/\rho_g \) of approximately 14.

Figure 6 shows a comparison of Eq. (4) with the presently measured values of the spout eye area. Equation (4) can approximate the measured values less accurately than Eq. (13). This is probably because the physical properties of gas and liquids are not considered in Eq. (4).

4. Conclusions

The spout eye area, \( A_{se} \), was measured using cold models. Water and silicone oil were modeled for molten steel and molten slag, respectively. An empirical Eq. (13) was derived for spout eye area, \( A_{se} \). The presently measured values of \( A_{se} \) and those by Yonezawa and Schwerdtfeger were approximated by this equation within a scatter of \( \pm 60\% \). This equation is superior to the existing empirical equations. The reason lies in the fact that the presently proposed equation adequately includes many parameters such as the physical properties of gas and liquids that were not considered in the existing equations.

**Nomenclature**

- \( A_{se} \): Spout eye area (cm²)
- \( D \): Bath diameter (cm)
- \( d_{in} \): Inner diameter of nozzle (cm)
- \( g \): Acceleration due to gravity (cm/s²)
- \( H_0 \): Initial depth of molten metal layer (cm)
- \( H \): Initial thickness of molten slag layer (cm)
- \( Q_f \): Gas flow rate at the nozzle exit (cm³/s)
- \( u_{m,cl} \): Mean rising velocity of molten metal on the centerline of bubbling jet (cm/s)
- \( z_0 \): Distance from the nozzle exit to the vertical position at which gas holdup is 50% (cm)
- \( \rho_g \): Density of injected gas (g/cm³)
- \( \rho_m \): Density of molten metal (g/cm³)
- \( \rho_s \): Density of molten slag (g/cm³)

**REFERENCES**

1) 100th and 101st Nishiyama Memorial Seminar, ISIJ, Tokyo, (1984).