Note

Spout Eyes Area Correlation in Ladle Metallurgy

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In ladle metallurgical operations, it is common practice to use an inert gas for stirring. The stirring is used to achieve homogenization and to pursue chemical and physical changes. The raised region where the gas discharges from the bath during argon stirring is usually called a spout. Where the spout is uncovered by slag, the region is called the spout eye.¹⁾ The spout region is significance in industrial practice, since it is an important site for slag–metal reactions and the site of undesirable reactions between metal and air. However, there has been relatively little study to elucidate the phenomena.

Recently, Yonezawa and Schwerdtfeger^{1,2)} reported a comprehensive investigation of the spout region. They studied the phenomena with the objectives to determine the dimensions of the spout and the spout eye. Data were obtained from cold model experiments, by using mercury and silicon oil for simulating metal and slag, respectively, and plant measurements on a 350 t ladle. A video camera was employed to measure the spout formation and spout eye area. For measuring the height of the spout, electroresistivity probes were used for the cold model and the dissolved tube length technique for the plant measurements. The results indicated that spout eye formation and spout eye size are highly dynamic, as a consequence of the discontinuous gas discharge at the nozzle and of the subsequent disintegration into bubbles.

Despite their success in measuring spout eyes, both in the cold model experiments and plant trials, they failed to develop an adequate functional correlation between eye area, A_{es} , and operational variables. By employing dimensional analysis technique, they developed the following functional correlation:

$$\frac{A_{es}}{hH} = f\left(\frac{Q^2}{gH^5}\right) \dots\dots\dots(1)$$

where A_{es} is spout eye area (m^2), h is metal height (m), H is slag height (m), Q is gas flow rate at nozzle exit (m^3/s), and g is the gravitational constant (m/s^2). By using polynomial regression technique on the data, Yonezawa and Schwerdtfeger¹⁾ proposed the following empirical equation:

$$\log\left(\frac{A_{es}}{hH}\right) = \alpha_0 + \alpha_1 \log\left(\frac{Q^2}{gH^5}\right) + \alpha_2 \left[\log\left(\frac{Q^2}{gH^5}\right)\right]^2 + \alpha_3 \left[\log\left(\frac{Q^2}{gH^5}\right)\right]^3 \dots\dots\dots(2)$$

where for $0.01 < Q^2/gH^5 < 10\,000$ and $d=0.5$ mm, the values of α_0 , α_1 , α_2 , and α_3 are equal to -0.6987 , 0.90032 , -0.14578 , and 0.01560 mm, respectively, and for $0.01 < Q^2/gH^5 < 2\,000$ and $d=1.0$ and 1.5 mm, the values of α_0 , α_1 , α_2 , and α_3 are equal to -0.45593 , 0.83275 , -0.14732 , and 0.01789 , respectively.

However, as shown in **Fig. 1**, it is clear that this dimensionless correlation does not unify the plant measurements and cold model experiments. Therefore, a more satisfactory correlation is still required.

It is well known that dimensional analysis is a useful tool to develop correlation for complex physical phenomena, which cannot be described by a mechanistic approach. However, the technique works best when coupled with physical insight into the phenomena.

The right-hand side of Eq. (1) is the Froude number. This dimensionless number physically represents the ratio between inertial force and gravitational force. The buoyancy of the gas operating over the height of the steel drives the flow to create the raised spout area, so it is appropriate to use this number. On the other hand, it is hard to justify the physical meaning of the dimensionless number on the left-hand side, *i.e.* A_{es}/hH . Therefore, the following discussion is an attempt to obtain a more appropriate dimensionless number.

It is convenient to define η as a ratio between spout eye area, A_{es} and spout area, A_s ,

$$\eta = \frac{A_{es}}{A_s} \dots\dots\dots(3)$$

The spout area is chosen as a reference because the spout eye area can be no larger than the spout area.

A schematic diagram of gas stirred ladle metallurgy is presented in **Fig. 2**. By simple geometry analysis, the ap-

Fig. 1. Correlation between (A_{es}/hH) and Froude Number for cold model experiments ($d=0.5$, 1.0 , and 1.5 mm) and plant measurements ($d=90$ mm).¹⁾

Fig. 2. Schematic diagram of gas stirred ladle metallurgy.

proximate value of spout area, A_s , is $(H+h)^2 \pi \tan^2 \theta$. Then, Eq. (3) can be rewritten as:

$$\eta \approx \frac{A_{es}}{(H+h)^2 \pi \tan^2 \theta} \quad \text{.....(4)}$$

The present discussion is limited to ladle metallurgy conditions and water models thereof in which the ladle height to diameter is approximately unity,³⁾ the plume is far from the sidewalls, the stirring energy input⁴⁾ is of the order of 10 W/tonne, and the plumes are observed to expand in a conical fashion. Consequently, the value of $\pi \tan^2 \theta$ in Eq. (4) may be assumed to be a constant.

$$\eta \propto \frac{A_{es}}{(H+h)^2} \quad \text{.....(5)}$$

Therefore, the dimensionless number on the right-hand side of Eq. (5) is used to replace the dimensionless number on the left-hand side of Eq. (1) to give

$$\frac{A_{es}}{(H+h)^2} = f\left(\frac{Q^2}{gH^5}\right) \quad \text{.....(6)}$$

A plot of $A_{es}/(H+h)^2$ against the Froude number for measurement data taken from Yonezawa and Schwerdtfeger¹⁾ is presented in Fig. 3. As shown in the figure, there is a merge data points between plant measurement and cold model experiment.

Using this approach we can develop an empirical correlation between spout eye area and operational variables. By employing a linear regression technique on the data, the following empirical correlation was found.

$$\frac{A_{es}}{(H+h)^2} = (0.02 \pm 0.002) \left(\frac{Q^2}{gH^5}\right)^{0.375 \pm 0.0136} \quad R^2=0.915 \quad \text{.....(7)}$$

To test the correlations, the computed values and measured

 Fig. 3. Correlation between $A_{es}/(h+H)^2$ with Froude Number for cold model experiments ($d=0.5, 1$, and 1.5 mm) and plant measurements ($d=90$ mm).

 Fig. 4. Comparison of the calculated value of $A_{es}/(h+H)^2$ with measurement data.

data of $A_{es}/(H+h)^2$ are plotted against the Froude number in Fig. 4. As shown in the figure, there is a reasonable agreement between measured and calculated values. The dependency on nozzle diameter is puzzling, but it should be noted that in Yonezawa and Schwerdtfeger's data¹⁾ there is considerable uncertainty regarding nozzle diameter. Because Eq. (7) is purely an empirical correlation, its applicability is limited to similar ladle metallurgy conditions.

Comparing Eq. (2) to Eq. (7), the latter has advantage on the physical insight basis and its simplicity. It has also been shown that Eq. (7) is better than Eq. (2) in terms of prediction, i.e. the values of standard deviation of Eqs. (7) and (2) are 0.169 and 0.311, respectively.

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