Water Model Experiment on the Entrapment of Slag using Polymerization

Manabu IGUCHI1, Yutaka SUMIDA2, Koji MORI1, Tatsuya OHMI1, Yoshiaki UEDA1 and Keiji NAKAJIMA4

1 Graduate School of Engineering, Hokkaido University, Sapporo, Japan
2 Matsushita Electric Works Ltd., Japan
3 Graduate School of Engineering, Osaka Electro-Communication University, Osaka, Japan
4 Royal Institute of Technology, Sweden

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Abstract
Cold model experiments are carried out to determine the number, size, and surface area of slag droplets generated at a slag-metal interface in a cylindrical bath agitated by bottom gas injection. Acrylic monomer is used to represent slag, and water containing salt and gelatin is chosen to represent metal. Since the slag droplets become solid particles after a while due to polymerization, the quantities mentioned above are readily determined by taking them out of the bath and measuring their diameters with screens. As the average power input per unit mass, \( \varepsilon \) and the density of the metal increased, the total number of slag droplets, \( S_{\text{p32}} \), was in proportion to \( \varepsilon \), whereas the Sauter mean diameter, \( d_{\text{p32}} \), was inversely proportional to \( \varepsilon \). Empirical equations were derived for \( S_{\text{p31}} \) and \( d_{\text{p32}} \). The minimum diameter of slag droplets almost agreed with the diameter of the Kolmogorov micro scale of turbulence.

Key words
Steelmaking, Injection, Entrainment of Slag, Polymerization, Sauter Mean Diameter, Acrylic Monomer

1. Introduction
The relation between the dynamic behavior of a slag-metal interface agitated by injected bubbles and the chemical reactions occurring there is of major importance for the ladle metallurgy and the iron-bath smelting reduction process [1-3]. Slag droplets are entrapped in the metal layer when the injected gas flow rate exceeds a certain critical value. Many investigations on the critical gas flow rate have been undertaken using various cold and hot models [1, 4]; however, information on the number, size and shape of the slag droplets is limited [5].

The shape and size of slag droplets are readily observed using a camera or a high-speed video camera if the model of the metal is transparent. These methods, however, cannot precisely determine the number of slag droplets.

Frohberg et al. [5] used water and liquid paraffin as the models of slag and metal, respectively and measured the length of a slag droplet as it passed through a suction tube having a circular cross-section. Since the inner diameter of the tube is known, the volume of the droplet can be determined, and hence an equivalent diameter is obtained by assuming that the droplet is spherical in shape. It was possible to detect slag droplets of diameters ranging from 1mm to 10 mm with this equipment. About 5000 droplets were collected to determine the number probability distribution function. The shape and total number of the slag droplets, however, could not be precisely determined, just as with the visual inspection method.

Nishikawa et al. [6] conducted a cold model experiment on slag entrapment using water and bee’s wax. A cylindrical water bath was agitated with an impeller instead of gas injection. Solidified wax droplets ranging from five hundred to two thousand in number were taken out of the bath for each run, and their shape and size were determined with a microscope.

In order to aid in determination of size and shape, acrylic monomer was used as a model of slag and deionized water mixed with gelatin and salt as a model of metal because the acrylic monomer solidified due to polymerization. The gelatin had the effect of preventing the coalescence of slag droplets. The density of the metal, \( \rho_{\text{m}} \), was adjusted by changing the salt content. Benzoyl peroxide (BPO) of 50% purity was added into the acrylic monomer to initiate and promote polymerization. The effects of gas flow rate, \( Q_g \), and the density of metal on the entrapment of slag droplets were primarily investigated.

2. Experiment
Figure 1 shows a schematic of the experimental apparatus. The bath diameter, \( D \), the inner diameter of the nozzle, \( d_n \), the thickness of the slag and metal layers, \( H_s \) and \( H_m \), the gas flow rate, \( Q_g \), and the physical properties of the slag and metal were considered as influential parameters for the entrapment of slag.

The temperature of the bath was kept at 303 K with a thermo-controller. The physical properties of slag and metal at 303 K are given in Table 1. The density of solidified slag is 1.20g/cm³, which is larger than \( \rho_{\text{m}} \) for the metal model employed in this experiment. It should be noted that the evaluation of the diameter and surface...
area of slag droplets was made using solidified slag droplets. As the slag droplets solidified, they shrank to 0.949 times as large as their original size. Thus the diameter and surface area in the liquid phase must be multiplied by 1.06 and 1.12, respectively. Hereafter, in this description the word “model” is deleted for the sake of simplicity.

Nitrogen gas was injected into the bath through a centered single-hole nozzle. The gas flow rate was adjusted between 20 and 80 cm³/s with a mass flow controller. The inner diameter of the nozzle was 2 mm, and the thicknesses of the slag and metal layers, $H_s$ and $H_m$, were kept at 30 mm and 70 mm, respectively, and the weight percent of gelatin was 5%. The concentration of BPO was 1, 2, or 3% and metal density values were 1.037, 1.073, and 1.127 g/cm³, as shown in Table 1. For the sake of simplicity, these $\rho_m$ values have been represented as 1.04, 1.07, and 1.13 g/cm³ in Fig. 3 and the following figures.

The interfacial tension, $\sigma_{slag}$, and kinematic viscosity of metal, $\nu_m = (\eta_m/\rho_m)$, also change slightly depending on the density of the metal. However, these parameters were not responsible for the slag droplets and subsequent disintegration into smaller droplets, because the gas flow rate, $Q_g$, was much larger than the critical value, $Q_g,cb$ for the initiation of slag droplets.

Preliminary measurement was made to determine the solidification time of the acrylic monomer. Figure 2 shows variations in the viscosity of slag with respect to time, respectively. The viscosity of slag was measured with an oscillating-plate type viscometer. The moment at which BPO was added into the slag was defined as $t=0$ min. The initial temperature was almost constant at 303 ± 1 K. At this relatively constant temperature, polymerization did not begin until approximately $t=3$ min.

According to previous investigations using the same experimental conditions as shown here [8, 9], fluid flow initially at rest in the bath was found to reach steady state within 1 min.

Visual inspection of the movement of slag droplets in the bath revealed that the entrapment of slag also reached an equilibrium state at around $t=3$ min. Therefore, it was concluded that the history of the viscosity of slag had no effect on the generation of slag droplets.

In Fig. 2, there is no measured value plotted after $t=17$ min for BPO = 1%, for example, because the solidification of slag droplets started around this time. The same was true for other BPO concentrations. Gas injection was therefore stopped before solidification of the slag droplets, those piled up on the bottom surface of the bath would stick together or coalesce, thus it is impossible to count them.

The diameter of solidified slag droplets ranged from 0.0025 cm to 2 cm. The mass probability distribution function was measured using screens with thirty different meshes. On the basis of this function, the number and surface area probability distribution functions then were derived.

Slag droplets whose diameters were larger than approximately 5 mm were not perfectly spherical in shape, whereas those with diameters less than 5 mm could be satisfactorily regarded as being spherical in shape.

It was confirmed beforehand that the density of slag which contains BPO was not time-dependent but remained constant before solidification.

3. Experimental Results and Discussion

3.1 Yield of slag droplets

Total amounts of slag and BPO for BPO = 1, 2, and 3% were 368.1, 375.8 and 381.8 g, respectively. Figure 3 shows the yield of slag droplets for three different BPO concentrations as a function of gas flow rate and the density of metal. As $Q_g$ and $\rho_m$ increase, the slag droplets form more easily. For example, when $\rho_m = 1.13 g/cm^3$, almost 100% of slag was transformed into droplets. On the other hand, when $\rho_m = 1.04 g/cm^3$ the amount of slag droplets formed was relatively small, and the remaining slag solidified while sticking on the side wall or on the bottom wall of the vessel.

In what follows, the number and the total surface area of slag droplets will be determined for the slag droplets per 100 g.

3.2 Reproducibility of the formation of slag droplets

Figure 4 shows the probability distribution function of the surface area of slag droplets per 100 g for $Q_g = 60 cm^3/s$, BPO = 2%, and $\rho_m = 1.07 g/cm^2$. It is clear that the reproducibility of slag formation is good.

3.3 Probability distribution functions for the mass, number and surface area of slag droplets

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An increase in \( Q_g \) also is an increasing function of slag droplets per 100g, \( M_{dp} \), against the droplet diameter, \( d_p \). The density of metal hardly affected the peak value of the function, \( M_{dp} \). It is interesting to note that in a range of \( d_p \) smaller than the droplet diameter at which the peak value, \( M_{dp} \), appears, the probability distribution function for \( \rho_m = 1.13\text{g/cm}^3 \) is much larger than those for other \( \rho_m \) values. This feature is clear on the number probability distribution function of slag droplets shown in Fig. 6.

### 3.4 Total number and total surface area of slag droplets per 100 g

Figure 7 shows the total number of slag droplets, \( N_{p,t} \). It is worth noting that a small increase in \( \rho_m \) brings about a great increase in \( N_{p,t} \). For example, \( N_{p,t} \) exceeded \( 2 \times 10^5 \) for \( \rho_m = 1.13\text{g/cm}^3 \). As \( \rho_m \) increases, slag droplets can stay in the high shear stress region near the slag-metal interface, and hence they have more opportunity to disintegrate into much smaller droplets. This is the reason why \( N_{p,t} \) increases as \( \rho_m \) increases.

An increase in \( Q_g \) also increases the degree of shear stress in the bath. As a result, \( Q_g \) has the same effect on \( N_{p,t} \) as \( \rho_m \).

The total surface area of slag droplets per 100g, \( S_{p,t} \), also is an increasing function of \( Q_g \) and \( \rho_m \) and reaches up to \( 4000 \text{cm}^2 \) for \( \rho_m = 1.13\text{g/cm}^3 \). The initial interfacial area between stratified slag and metal layers was \( 122.7 \text{cm}^2 \) in the vessel used in this experiment. The incremental interfacial area thus produced due to the formation of slag droplets increased to 30 times as large as its initial value. Since the maximum yield of slag was about 360g under the present experimental conditions, the interfacial area increases up to approximately 100 times as its original value.
3.5 Empirical correlation of total surface area $S_{p,t}$

The concentration of BPO has a negligible effect on the total surface area, $S_{p,t}$, as shown in Fig.8. This means that the generation of slag droplets and their subsequent disintegration into smaller droplets occur and a state of equilibrium is reached within 3 minutes of the start of gas injection.

Next, the experimental results are shown on the total surface area, $S_{p,t}$, for BPO=2% and $\rho_m=1.07\text{g/cm}^3$, because measurements were made most systematically under this condition. The solid straight line in Fig. 8 is drawn through the mean of the measured values, indicating that $S_{p,t}$ is proportional to the gas flow rate, $Q_g$. Also, $S_{p,t}$ increases with an increase in $\rho_m$ for every gas flow rate. The following functional relationship therefore is assumed.

$$S_{p,t} = k\rho_m^mQ_g$$  \hspace{1cm} (1)

where the proportionality constant, $k$, and the index, $m$, are found to be 32 and 4.5, respectively, from a regression analysis.

$$S_{p,t} = 32\rho_m^{4.5}Q_g$$  \hspace{1cm} (2)

The four lines in Fig. 9 are calculated from Eq.(2). The measured values of $S_{p,t}$ for every gas flow rate can be approximated by Eq.(2) within a scatter of $\pm$30%.

The Sauter mean diameter, $d_{p32}$, which is usually used for characterizing the size of slag droplets, is defined as follows:

$$d_{p32} = \frac{\Sigma nd_i^3}{\Sigma nd_i^2}$$  \hspace{1cm} (3)

Since the total mass of the slag droplets is 100g, this equation is transformed into the following form for slag density $\rho_m=1.2\text{g/cm}^3$.

$$d_{p32} = \frac{\Sigma n(6V_i/\pi)}{\Sigma n(S_i/\pi)}$$

$$= 600/(\rho_m S_{p,t})$$

$$= 500/S_{p,t}$$  \hspace{1cm} (4)

Substitution of Eq.(2) into Eq.(4) yields

$$d_{p32} = 15.6\rho_m^{4.5}Q_g^{-1}$$  \hspace{1cm} (5)

Therefore, $d_{p32}$ is inversely proportional to the gas flow rate, $Q_g$.

3.6 Relation between Sauter mean diameter and average power input per unit mass

Under the present experimental conditions an average power input per unit mass, $\varepsilon$, can be approximated by the following equation.

$$\varepsilon = \rho_m g\varepsilon H_Hm/(\rho_m Hm\pi D^2/4) = 4gQ_g/((\pi D)^2)$$  \hspace{1cm} (6)

Combining Eqs.(5) and (6) reveals that $d_{p32}$ is inversely proportional to $\varepsilon$.

On the other hand, Frohberg et al. [5] obtained the following relation under almost the same $\varepsilon$ values as the present ones

$$d_{p32} \propto \varepsilon^{-1}$$  \hspace{1cm} (7)

The index, $-0.3$, is much different from the presently obtained value of $-1$. Since the method of measuring droplet diameter employed by Frohberg et al. [5], cannot detect slag droplets with diameters smaller than 1mm. This might explain the difference in the two indices of $\varepsilon$.

Furthermore, Frohberg et al. [5] suggested that the contribution of smaller bubbles to overall mass transfer should not be overestimated. However, according to the present experimental results, this is not always true.

Chen et al. [10] and Carabrese et al. [11] mechanically stirred baths using an impeller and obtained the following relation [6]

$$d_{p32} \propto \varepsilon^{-0.4}$$  \hspace{1cm} (8)

The volume fraction of slag droplets, $\phi$, in the baths in which they used ranges from 0.1 to 0.5%, and these values
are much smaller than the present values of 3 to 30%. When the volume of slag is small compared to that of metal, power input due to gas injection might be mainly consumed to drive the metal, and hence its contribution to the generation of the slag droplets might be small. The contribution of the power input to the generation of slag droplets is expected to increase as the volume of slag increases.

3.7 Empirical correlation of peak value of the distribution function of surface area of slag droplets, $S_{g,g}$, and peak diameter at which $S_{g,g}$ appears

The peak value of surface area, $S_{g,g}$, and peak diameter, $d_{g,g}$, are shown together in Fig. 10 as functions of the density of metal, $\rho_m$. In the present $\rho_m$ region, $\rho_m$ has negligible effects both on $S_{g,g}$ and $d_{g,g}$. This result is different from the dependence of $S_{g,g}$ on $\rho_m$. The reason seems to be explained by the fact that the generation of slag droplets whose diameters are smaller than $d_{g,g}$ is affected significantly by $\rho_m$, and the contribution of these slag droplets to $S_{g,g}$ is not negligible.

Changes in $S_{g,g}$ and $d_{g,g}$ with respect to gas flow rate, $Q_{g}$, are shown in Fig. 11. $S_{g,g}$ is an increasing function of $Q_{g}$, whereas $d_{g,g}$ decreases with $Q_{g}$. All the measured values of $S_{g,g}$ are shown together in Fig. 12. They are almost in proportion to $Q_{g}$ just as $S_{g,g}$. On the contrary, $d_{g,g}$ decreases in inversely proportional to $Q_{g}$, as can be seen in Fig. 13. Therefore, the following empirical correlation can be derived.

$$S_{g,g} = 9 Q_{g}$$  \hspace{1cm} (10)

$$d_{g,g} = 11.6 Q_{g}^{-1}$$  \hspace{1cm} (11)

3.8 Diameter of energy containing eddy and Kolmogorov micro scale of turbulence

The diameter of an energy containing eddy, $d_{\varepsilon}$, is given by [11]

$$d_{\varepsilon} = Au'_{rms}^{3}/\varepsilon$$  \hspace{1cm} (12)

where $A$ is the proportionality constant having a value of the order of unity and $u'_{rms}$ is the root-mean-square value of the turbulence component of liquid velocity in the mainstream direction. Provided that the Sauter mean diameter, $d_{s,32}$, has a linear relationship to $d_{\varepsilon}$, $u'_{rms}$ should be independent of $Q_{g}$ because $d_{s,32}$ is inversely proportional to $\varepsilon$ or $Q_{g}$. As the volume fraction, $\phi$, is relatively large, this situation might occur due to strong interaction between the metal and slag droplets. Whether this relation holds or not under the presence of a large amount of slag droplets must be left for a future study.

The Kolmogorov micro scale of turbulence, $d_{k}$, is defined as
\[ d_k = \left( \frac{\nu_m}{\varepsilon} \right)^{1/4} \tag{13} \]

Substitution of Eq.(6) into Eq.(13) gives \( d_k = 0.02 \text{cm} \) under the experimental condition depicted in Fig. 5, being almost in agreement with the minimum diameter of slag droplets generated in the bath.

3.9 Consideration of previously published volumetric coefficients

According to investigations of a volumetric inclusion removal coefficient, \( k_{vi} \), in a tundish [13], \( k_{vi} \) depends on \( \varepsilon^{0.3} \) for small \( \varepsilon \) values. When \( \varepsilon \) is large, slag droplets are formed and then \( k_{vi} \) is proportional to \( \varepsilon \). In addition, Asai et al. [14] reported that the volumetric mass transfer coefficient, \( k_{vm} \), between slag and metal is proportional to \( \varepsilon \) in the presence of slag droplets.

The volumetric inclusion removal coefficient, \( k_{vi} \), is defined as the product of the inclusion removal coefficient, \( k_i \), and the total interfacial area between slag droplets and metal, \( S_{p,t} \). Also, the latter, \( k_{vm} \), is defined as the product of the mass transfer coefficient, \( k_m \), and the total interfacial area, \( S_{p,t} \). If the present empirical equation of \( S_{p,t} \) is valid for the two cases, the inclusion removal coefficient, \( k_i \), and mass transfer coefficient, \( k_m \), would be independent of \( \varepsilon \).

4. Conclusions

Polymerization of acrylic monomer was employed to investigate the entrainment of slag into metal. Using solidified slag droplets, the number, total surface area, Sauter mean diameter, and other quantities were determined. It should however be noted that the diameter and surface area of the slag droplets before the solidification should be multiplied by 1.06 and 1.12, respectively, because the slag droplets shrink during the solidification.

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