Model Experiment on the Dispersion of Fine Particles in a Molten Metal Bath Agitated by Plunging Jet

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Cold model experiments were carried out to understand the dispersion of particles introduced into a water bath and a mercury bath by a plunging jet. The particles were uniformly dispersed in the whole bath in a short time regardless of the density and diameter of the particles under the conditions considered. The results imply that small particles can also be uniformly dispersed in molten steel baths by using a plunging jet. Two time scales were introduced to characterize the dispersion of particles. One is time for the plunging jet to reach the bottom wall of the vessel. The other is time for the particles to uniformly disperse in the whole bath. Empirical equations for the two time scales were derived.

KEY WORDS: steelmaking; powder injection; desulfurization; plunging jet.

1. Introduction

In current desulfurization processes powder is commonly introduced into molten metal together with carrier gas. It is rather difficult to push each powder into the molten metal when the powder is not wetted by the metal. This is because the surface tension force dominate the intrusion process when the diameter of the powder is very small. In order to avoid the demerit of carrier gas injection, the KR method is widely used to enhance the efficiency of the desulfurization. The efficiency of this process is not necessarily high because the entrainment of powder into molten metal is still rather difficult even using the centrifugal force.

In this study the authors focused on the possibility that a plunging jet may be useful for efficient entrainment of powder into a molten metal bath. The flow fields in a bath generated by a single plunging jet can be classified into four types, as shown in Fig. 1.

(a) Type NB: No bubble is entrained into the bath.
(b) Type 1: Small bubbles are entrained.
(c) Type 2: Both small bubbles and large bubbles are entrained. Accordingly, the probability distribution function of bubble diameters has two peaks.
(d) Type 3: Mainly large bubbles are entrained.

Type NB appears when the plunging jet is laminar as well as its flow rate is very small. Types 1, 2, and 3 appear when the plunging jets are laminar, transitional, and turbulent, respectively. Therefore, small bubbles are generated when the surface of the plunging jet is smooth, while large bubbles are formed when the surface is rough.

The type of bubble dispersion pattern can be controlled by changing the flow rate of a plunging jet and the distance between the nozzle exit and the bath surface. This fact suggests that fine particles used for desulfurization can also be entrained into a molten metal bath by using a plunging jet. Model experiments were carried out in this study by using water and mercury. Three kinds of particles having different
2. Experiment

2.1. Experimental Apparatus and Procedure for Water Bath

Figure 2 shows a schematic of the experimental apparatus for a water model. Two cylindrical vessels made of transparent acrylic resin were placed in the vertical direction. The diameter of the upper vessel was 20.0 cm, while the diameter of the lower vessel, $D_1$, was 15.0 cm, 20.0 cm, and 30.0 cm. Water was filled to a predetermined depth in each vessel. A cylinder of a diameter, $D_c$, of 4.7 cm was placed on the bath surface of the lower vessel. The initial aspect ratio, $H_i/D_1$, was 0.25, 0.5, and 1.0, where $H_i$ is the initial bath depth. The volume of the plunging jet, $V_p$, is given by

$$V_p = \pi D_c^2 H_i/8$$

The initial velocity of plunging jet at the bath surface, $u_i$, ranged from 139 to 346 cm/s. The diameter of the plunging jet at the bath surface, $d$, ranged from 0.75 to 1.5 cm.

Measurements were carried out under the following four conditions, as shown in Table 1.

| Run | Density (g/cm³) | Average diameter of particle (mm) |
|-----|----------------|----------------------------------|
| (1) | no particle    |                                  |
| (2) | 0.02           | 3.6                               |
| (3) | 0.04           | $40 \times 10^{-3}$               |
| (4) | 0.40           | 6.0                               |

Table 1. The density and diameter.

2.2. Experimental Apparatus and Procedure for Mercury Bath

Figure 3 shows a schematic of the experimental apparatus for a mercury model. The lower test vessel made of transparent acrylic resin had a diameter, $D_1$, of 14.6 cm and a height of 30 cm. Mercury was filled to a depth of 7.3 cm. The initial aspect ratio, $H_i/D_1$, was therefore 0.5. A cylindrical vessel of an inner diameter of 1.8 cm (without bottom) was placed on the mercury bath, and water was filled between the two cylindrical vessels, so that bubbles dispersed in the mercury bath could readily be observed. The mercury plunges into the mercury bath without contacting the water placed on the mercury bath because it passes through the smaller cylindrical vessel, reaches the bottom wall of the vessel, and spreads along the bottom wall. As suggested from the water model experiments shown later, the mercury thus introduced into the mercury bath would also rise inducing highly turbulent flow and arrive at the interface between the mercury and water layers at approximately the same time everywhere in the bath. Accordingly, the water layer would not affect the motion of the flow in the mercury bath. Water was also filled between the cylindrical test vessel of $D=14.6$ cm and a vessel of square cross-section which enclosed the cylindrical vessel. This is intended to decrease the distortion effect as much as possible.

A high-speed video camera was used to observe the entrainment of bubbles from the side and bottom of the vessel at 1000 frames/s. A mirror was placed below the vessel. The initial plunging jet velocity, $u_i$, was 183 cm/s and the plunging jet diameter, $d$, was 0.4 and 0.6 cm. The volume of plunging jet, $V_p$, was 110 cm³. The final aspect ratio became 0.545. The physical properties of water, mercury, and molten steel are listed in Table 2.
3. Experimental Results and Discussion

3.1. Particle Dispersion Pattern in Water Bath

Figure 4 shows the dispersion of bubbles and particles in a water bath. The shaded parts in Fig. 4(a) denote the region where bubbles and particles coexist. The bubbles were removed from Fig. 4(a) and the remaining particles are denoted by black points in Fig. 4(a'). The density and size of the particle was 0.02 g/cm$^3$ and 3.6 mm, respectively. Comparison of Figs. 4(a) and 4(a') reveals that bubbles and particles are uniformly dispersed in the shaded region. Consequently, the shaded regions can be regarded as the particle dispersion region. One more example is shown in Fig. 5. The diameter and density of particles are the same as in Fig. 4.

3.2. Bubble Dispersion Pattern in Mercury Bath

Figures 6(a) and 6(b) show photographs of the mercury bath taken from the side and bottom of the vessel. These photographs suggest that bubbles are almost uniformly dispersed in the bath.
3.3. Time Scales Characterizing Dispersion of Bubbles

A plunging jet impinging onto the bath surface descended almost straightly to the bottom by entraining bubbles and the surrounding water (Figs. 7(a) and 7(b)), and then moved in the radial direction along the bottom wall (Figs. 7(c) and 7(d)). Finally, it spread over the whole bath due to the inertial force of the jet and the buoyancy force acting on the bubbles and particles (Fig. 7(f)). The same dispersion pattern was observed under every experimental condition considered.

In order to quantitatively describe the dispersion phenomena, two characteristic time scales were introduced in this study. One is time required for a plunging jet to reach the bottom wall, \( T_b \), after it passed through the bath surface, where subscript b denotes the bottom wall of the vessel. The other is time required for the plunging jet accompanying bubbles and particles to spread over the whole bath. This time was denoted by \( T_a \). In Fig. 7, \( T_b = 0.09 \) s and \( T_a = 0.80 \) s. Measurements of these two time scales were repeated three times under every experimental condition and their mean values were obtained. These time scales, \( T_a \) and \( T_b \), were readily determined from the video images also in the mercury model.

3.4. Time Scale, \( T_b \)

The measured values of \( T_b \) are plotted against \( H_{Li} \) in Fig. 8. A remarkable difference can be seen between the water and mercury baths. The time scale, \( T_b \), is considered to be a function of the diameter of the plunging jet, \( d \), initial plunging jet velocity, \( u_i \), initial bath depth, \( H_{Li} \), and the Reynolds number, \( Re \). The following relationship therefore was assumed.

\[
T_b = \frac{u_i}{H_{Li}} = f(Re) \quad \text{(2)}
\]

\[
Re = \frac{du_i}{v} \quad \text{(3)}
\]

where \( v \) is the kinematic viscosity of liquid. The measured values of \( T_b \) were non-dimensionalized and plotted in Fig. 9. The solid line was drawn through a mean of the measured values.

\[
T_b = \frac{u_i}{H_{Li}} = 0.0045Re^{0.638} \quad \text{(4)}
\]

All the measured values can be approximated by Eq. (4)
within a scatter of ±30%, as shown in Fig. 10.

3.5. Time Scale, $T_a$

The characteristic time scale, $T_a$, has a close relationship with the mixing time in the bath. Figure 11 shows the time scale, $T_a$, against the mixing time, $T_m$. The time scale, $T_a$, increased with an increase in the mixing time. As the mixing time, $T_m$, is closely associated with the plunging time, $T_p$, the mixing time, $T_m$, and the time scale, $T_a$, for the water bath are non-dimensionalized by $T_f$ and are plotted in Fig. 12. The plunging time, $T_p$, is defined as the period from the start of plunging to the end of plunging.

The following empirical equation was derived.

$$
\frac{T_a}{T_f} = 0.043 \left( \frac{T_m}{T_f} \right)^{1.94} \quad \text{...............(5)}
$$

The measured values of $T_a/T_f$, both for the water and mercury baths, are plotted in Fig. 13. Equation (5) was slightly modified to give

$$
\frac{T_a}{T_f} = 0.046 \left( \frac{T_m}{T_f} \right)^{1.66} \quad \text{...............(6)}
$$

All the measured values can be approximated by Eq. (6).
within a scatter of ±40%. According to the water model experiment, the dispersion pattern of fine particles of a mean diameter of 40×10⁻³ mm was the same as that of bubbles. Therefore, fine particles would be dispersed in the mercury bath. This result suggests that fine particles would be dispersed also in molten steel bath because the density of molten steel falls between those of water and mercury.

3.6 Case Study for Molten Metal Bath

The two time scales will be predicted for a case presented in the previous paper. The initial and final bath dimensions, and related quantities are as follows: the bath diameter \( D = 300 \) cm, initial bath depth \( H_i = 100 \) cm, final bath depth \( H_f = 300 \) cm, vertical distance between the bath surface in the upper vessel and that in the lower vessel \( H_s = 600 \) cm, jet diameter \( d = 10 \) cm, plunging time \( T_i = 166 \) s, mixing time \( T_m = 166 \) s. An empirical equation proposed previously by the authors gave a mixing time, \( T_m \), of 129 s for the plunging time of 166 s. This 129 s is acceptable because the estimation error of that equation is ±30%. However, it is physically strange to choose this 129 s because this value is shorter than \( T_i \) of 166 s. We therefore assumed that \( T_m = T_i \). Under these conditions the initial jet velocity, \( u_i \), is 1080 cm/s, the kinematic viscosity of molten steel, \( \nu \), is 0.008 cm²/s, and the Reynolds number, \( Re \), is 1.35×10⁶.

Equation (4) yields
\[
T_i = 0.0045Re^{0.638}H_i/u_i = 3.5 \, \text{s} \quad \text{..........................(7)}
\]

On the other hand, Eq. (6) gives
\[
T_s = 0.046T_i(T_m/T_i)^{1.66} = 7.6 \, \text{s} \quad \text{..........................(8)}
\]

This result suggests that particles entrained into the molten steel bath by a plunging jet are rapidly dispersed in the whole bath.

The total time for all particles enclosed with a cylinder of a diameter of \( D_i \) and initially placed on the bath surface to be entrained into the bath depends on \( D_i \), jet diameter, \( d \), the volume of the particles and so on. Further investigations are necessary for evaluating this period.

4. Conclusions

The behaviors of bubbles and particles introduced into a water bath and a mercury bath by a plunging jet were investigated with a high speed video camera and by eye inspection. Fine bubbles and particles were dispersed uniformly in the two baths by the plunging jet. Two time scales, \( T_i \) and \( T_m \), were introduced to characterize the dispersion of them in the bath. Time required for a plunging jet to reach the bottom of the bath, \( T_b \), was predicted by the following empirical equation within a scatter of ±30%.

\[
T_b u_i/H_i = 0.0045Re^{0.638} \quad \text{.........................(4)}
\]

The other time scale, \( T_o \), denotes time for bubbles and particles introduced into the bath to disperse over the whole bath. The following empirical equation was proposed for \( T_o \).

\[
T_o/T_i = 0.046(T_m/T_i)^{1.66} \quad \text{..........................(6)}
\]

The measured values of \( T_i \) were correlated by Eq. (6) within a scatter of ±40%.

Nomenclature

- \( D \): Bath diameter (cm)
- \( d \): Diameter of plunging jet (cm)
- \( H_i \): Initial bath depth (cm)
- \( Re \): Reynolds number (–)
- \( T_i \): Time for uniform dispersion (s)
- \( T_o \): Time for plunging jet to reach the bottom wall (s)
- \( T_f \): Plunging time (s)
- \( T_m \): Mixing time (s)
- \( u_i \): Velocity of plunging jet on the bath surface (cm/s)
- \( V_p \): Volume of liquid introduced into the lower bath (cm³)
- \( \nu \): Kinematic viscosity of liquid (cm²/s)

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