A Water Model Study of Simultaneously Releasing Multi-Particles onto a Molten Metal Bath

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Uniform dispersion of refining agents in a molten iron bath is of practical importance for efficient desulfurization. As a fundamental study of enabling uniform dispersion, a simple method was proposed to simultaneously release multi-particles in the atmosphere. As a first step, two solid spheres of different diameters were released onto a water bath. The dynamic behavior of the spheres entering the bath and associated air cavity formation were observed with a high-speed camera.

KEY WORDS: steelmaking; refining; powder injection; desulfurization; water model; water entry; air cavity.

2. Method of Simultaneously Releasing Multi-spheres

As a preliminary experiment, a dividing junction7) was employed to simultaneously release a pair of spheres of different diameters. Unfortunately, the efficiency of this method was not high because the propagation of pressure wave in the pipe was modulated at the junction. In other words, the pressures at the two exits of the junction did not reach the atmospheric pressure, $p_0$, at the same time. Accordingly, the dividing junction was replaced by a chamber 88 mm ×
88 mm in cross-section and 75 mm in height to decrease the pressure modulation, as shown in Fig. 2. The chamber was chosen by referring to the constant-pressure type nozzle used in the injection metallurgy. This nozzle works through the capacitance effect. A pipe of \( D_1 \) (m) in inner diameter and \( L_1 \) (m) in length was connected to the bottom plate of the chamber so that the bottom end of the smaller sphere is located on the same horizontal plane as the larger one. The larger sphere was directly connected to the hole drilled on the bottom plate.

The density of the acrylic resin, \( \rho_p \), was 1200 kg/m³ and the contact angle of a water droplet placed on an acrylic flat plate was 70°. Thus, the spheres used in this study are wetted by water. A pair of spheres of 10.0 \( \times 10^{-3} \) m and 20.0 \( \times 10^{-3} \) m in diameter were placed as shown in Fig. 2 and then the pressure in the chamber was decreased using a vacuum pump to hold the spheres there. The distance from the bottom of each sphere to the bath surface was 150 mm. The power of the pump was put off to release the spheres. In a strict sense, experimental conditions must be determined in terms of dynamical similitude such as the modified Froude number similitude. Detailed discussion on this subject must be left for a future study and only a releasing method and some experimentally obtained results are introduced here.

The following condition must be satisfied for simultaneous release of a pair of spheres of different diameters.

\[
\frac{\pi}{4} D_1^2 (p_0 - p_r) - \frac{\pi}{4} D_2^2 (p_0 - p_r) > \frac{\pi}{6} d_{p1}^3 \rho_p g \quad \frac{\pi}{6} d_{p2}^3 \rho_p g > 1 \quad \text{........... (1)}
\]

where \( D_1 \) (m) is the smaller hole diameter, \( D_2 \) (m) is the larger hole diameter, \( p_0 \) (Pa) is the atmospheric pressure, \( p_r \) (Pa) is the reduced pressure in the chamber, \( d_p \) (m) is the sphere diameter, and \( g \) (m/s²) is the acceleration due to gravity. The subscripts 1 and 2 for \( d_p \) and \( \rho_p \) denote the smaller and larger spheres, respectively.

### 3. Experimental Results and Discussion

Many trials were taken to examine the possibility of simultaneously releasing a pair of spheres of different diameters by keeping \( D_1 = 3.0 \times 10^{-3} \) m and adjusting the larger hole diameter, \( D_2 \), around 8.7 \( \times 10^{-3} \) m. This \( D_2 \) value was calculated from Eq. (1). About 20% of the trials revealed that the two spheres simultaneously entered a water bath under the best combination of \( D_1 \) and \( D_2 \). Here, simultaneous water entry means that two spheres enter the bath within an interval of 1/600 s (= 1.67 ms). The corresponding distance between the bottom ends of the spheres is less than \( \frac{v_{p0}}{600} \approx 2.86 \times 10^{-3} \) m.

**Figure 3** shows an example of simultaneous water entry of a pair of spheres of different diameters. Here, \( D_1 = 3.0 \times 10^{-3} \) m, \( D_2 = 9.0 \times 10^{-3} \) m, \( L_1 = 10 \times 10^{-3} \) m, \( d_{p1} = 10.0 \times 10^{-3} \) m, and \( d_{p2} = 20.0 \times 10^{-3} \) m. The interval between the successive photographs is 1/600 s. It is already known that an air cavity is not formed behind a wetted single sphere when the impact velocity, \( \eta_0 \), is lower than the critical impact velocity \( \eta_{0c} \) of about 7.3 m/s reported by Duez et al. Although the impact velocity \( \eta_0 \) of 1.71 m/s was much smaller than the critical value, an air cavity was formed behind a pair of spheres. The air cavity is considered to be triggered by an
air pocket formed behind the spheres.\(^7\) Main results can be summarized as follows:

1. The smaller sphere decelerated more rapidly than the larger one. The terminal velocity was lower for the smaller sphere than for the larger one. The reason can be explained in the following.

The equation of motion for a single sphere entering a bath was given by Ozawa et al.\(^9\) The Weber number, \(W_e\), for the smaller sphere is given under the present experimental conditions by

\[
W_e = \frac{\rho_p d_p v_p^2}{\sigma} = \frac{1200 \times 10^7 \times 10^{-1} \times (1.71)^2}{73 \times 10^{-4}} = 481 \quad \ldots (2)
\]

and \(W_e = 961\) for the larger sphere. The interfacial effect is therefore negligible and the following approximate equation is obtained.

\[
(\rho_p + k \rho_L) \frac{\pi}{6} d_p^3 \frac{dv_p}{dt} = \frac{\pi}{6} d_p^3 \rho_p g - \frac{\pi}{6} d_p^3 \rho_L g - C_D \frac{\pi}{4} d_p^2 \frac{\rho_p}{2} v_p^2 \quad \ldots (3)
\]

where \(\rho_p\) is the density of water, \(k = 1.5\) is the added mass coefficient,\(^4\) and \(C_D\) is the drag coefficient. The three terms on the right-hand side of Eq. (3) denote the weight of the sphere, buoyant force and drag force acting on the sphere, respectively.

If the entry Reynolds number, \(Re_0\), is greater than about 1 000, \(C_D\) can be assumed to be constant below the bath surface \((C_D = 0.44)\). The entry Reynolds number of the smaller sphere is given under the present experimental conditions by

\[
Re_0 = \frac{v_{p0} d_p}{\nu} = 1.71 \times 10^7 \times 10^{-3} = 17100 \quad \ldots (4)
\]

and \(Re_0 = 37200\) for the larger one. Equation (3) can therefore be solved under the initial condition of \(v_p = v_{p0}\) at \(t = 0\) as:

\[
v_p = \frac{\alpha}{\beta} \left(1 + \frac{v_{p0} - \alpha / \beta}{v_{p0} + \alpha / \beta} e^{-2 \alpha / \beta t}\right)
\]

......(5)

\[
\alpha = \left[\frac{(\rho_p - \rho_L) g}{\rho_p + k \rho_L}\right]^{1/2}, \quad \beta = \left[\frac{3 C_D \rho_p}{4 d_p (\rho_p + k \rho_L)}\right]^{1/2}
\]

......(6)

For \(t \to \infty\) Eq. (5) reduces to

\[
v_p = \frac{\alpha}{\beta} \left[4 (\rho_p - \rho_L) \frac{gd_p}{3 C_D \rho_p}\right]^{1/2}
\]

......(7)

Accordingly, the terminal velocity is an increasing function of \(d_p\). This relationship seems to be approximately valid for water entry of a pair of spheres. The deceleration tendency can be more clearly explained as follows:

Equation (3) reduces to

\[
\frac{dv_p}{dt} = \alpha^2 - \frac{3 C_D \rho_p}{4 (\rho_p + k \rho_L)} v_p^2 d_p \quad \ldots (8)
\]

Deceleration of each sphere was significant at the initial stage of water entry \((t = 0)\). At this stage \(v_p = v_{p0}\) and, hence, Eq. (8) further reduces to

\[
\frac{dv_p}{dt} = \alpha^2 - \frac{3 C_D \rho_p}{4 (\rho_p + k \rho_L)} v_{p0}^2 d_p \quad \ldots (9)
\]

The deceleration therefore increases with a decrease in \(d_p\).

2. The air cavity was elongated near the rear part of each sphere. The size of the elongated part was larger for the smaller sphere than for the larger one (Fig. 4(b)). The reason is that the velocity of the larger sphere is greater than that of the smaller one. The elongated part behind the larger sphere detached earlier than that behind the smaller one (Fig. 4(c)).

3. A pair of spheres departed from each other due to pressure rise between the front parts of the spheres (Fig. 4(b)), just like a pair of spheres of the same diameter.\(^7\) Consequently, the penetration depth of spheres in the bath is considered to be shortened due to simultaneous water entry.

4. Splash was formed mainly behind the larger sphere (Figs. 4(b), 4(c)).

4. Concluding Remarks

The experimental results obtained in this study suggest that simultaneous entry of refining agents in a molten metal bath is not necessarily beneficial for sulfur refining as long as the penetration depth is concerned. Anyway, further experimental investigations based on dynamical similarity are desirable to systematically understand the dispersion of refining agents.

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