Characteristics of Poorly-Wetted Two Spheres Penetrating into a Water Bath

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Abstract
The purpose of this study is to investigate the dynamic behavior of a pair of spheres with different wettabilities penetrating into a water bath. The visualization technique employs a high-speed camera. An air cavity is formed behind the spheres under certain conditions. The maximum cavity depth and the time required for the cavity to break up are measured and compared with their respective empirical equations proposed previously for a single poorly-wetted sphere. These two quantities can be correlated in terms of the Froude number similitude.

Key words
Desulfurization, Sphere, Wettability, Air Cavity, Cavity Depth, Surface Tension

1. Introduction
Solid-liquid impact phenomena have been investigated by many researchers [1-3]. The first study on the splash when throwing an object into a liquid bath started a century ago with a paper of Worthington and Cole [4]. They used single-spark photography to visualize the dynamic behavior of a polished sphere and a roughened sphere impacting into the bath. Since then, the solid-liquid impact has attracted the interest of researchers in many engineering fields.

The research of the dynamic behavior of a single sphere penetrating into a liquid bath is an intriguing subject in some practical applications, e.g., military projectiles, ship slamming, landing of fly boats, steelmaking process, and so on. In the steelmaking processes, for example, enhancement of the efficiency of desulfurization is of practical importance for clean steel production [5-7]. To effectively introduce fine particles such as CaO particles into a molten iron bath and then disperse them in the whole bath is a very important technique. The wettability between the particle and molten iron is usually poor. According to previous papers of one of the authors, bubbles attach preferably to a solid body of poor wettability [8, 9]. This fact indicates that the dynamic behavior of a poorly-wetted solid sphere penetrating into a molten iron bath is different from that of a wetted solid sphere.

Shimamoto et al. investigated the dynamic behavior of a single wetted or a single poorly-wetted solid sphere penetrating into a water bath [10]. The density of the sphere was greater than that of water. When the wetted solid sphere penetrates into the water bath, an air cavity does not form behind it. The air cavity, however, formed behind the poorly-wetted solid sphere. Shimamoto et al. [10] measured the maximum cavity depth and break-up time of the air cavity, and proposed empirical equations for the two quantities. Tanaka et al. studied the hydrodynamic drag of a poorly-wetted single sphere and the effect of the surface roughness on the hydrodynamic drag [11]. They used low density spheres.

Most of the previous investigations on a solid sphere penetrating into a liquid bath use a single sphere. In the real refining processes, many fine particles are fed into a molten iron bath. Information on many particles penetrating simultaneously into the bath is very limited. We therefore previously investigated the dynamic behavior of a pair of spheres in contact with each other [12]. In this study, we focused on the effect of the horizontal clearance between a pair of spheres on the dynamic behavior of the spheres.

2. Experimental Procedure
Figure 1 shows a schematic of the experimental apparatus. The size of the transparent vessel is 360mm × 400mm in cross-section and 440mm in height. The materials of the sphere are transparent acrylic resin and transparent glass. The diameter of the sphere, dp, the density of the sphere, ρp, the original equilibrium contact angle of the small droplet on the sphere in the air, θc, and the contact angle after coating a water-repellent are shown in Table 1. Figure 2 shows a photograph of spheres submerged in a water bath. The surface of a poorly-wetted sphere is covered with air. Figure 3 shows a water droplet placed on a wetted sphere and that on a poorly-wetted sphere. The volume of the water droplet is 5mm³ and the material of the sphere is acrylic resin. The wettability of a sphere was conventionally evaluated in terms of the contact angle. It is recognized that a solid is wetted by a liquid for θc less than 90 deg., whereas it is poorly-wetted for θc ≥ 90 deg.
Accordingly, the wettability of the original sphere is good. The water-repellent coated on the sphere changed the wettability from good to poor. The contact angle of the sphere after coating was 144 deg. The horizontal clearance between a pair of spheres, \( \delta \), was varied from 0 to 2 \( d_p \). Experiments were carried out under the following conditions.

(a) Single wetted sphere
(b) Single poorly-wetted sphere
(c) Two wetted spheres
(d) Wetted sphere and poorly-wetted one
(e) Two poorly-wetted spheres

Each sphere was kept at the exit of a vertical straight branched brass pipe using a vacuum pump. The spheres were dropped simultaneously onto the bath surface by putting off the power supply to the vacuum pump. The initial height, \( h_0 \), from the bath surface to the bottom end of each sphere was varied from 50mm to 150mm. The initial velocity of the spheres was zero and the impact velocity was ranged from 990mm/s to 1,710mm/s. The impact velocity was obtained from \( v_{p0} = \sqrt{2gh_0} \), where \( g \) is the acceleration due to gravity. The behavior of the spheres penetrating into a water bath was observed with a high-speed camera with a frame rate of 500 frames/s. The shutter speed was 150\( \mu \)s for the resolution 1,024 \( \times \) 1,240 pixels.

It is well known that a cavity is formed behind a single poorly-wetted sphere penetrating into a water bath. We measured the maximum cavity depth, \( H_m \), the brake-up time of the air cavity, \( t_m \), and the angle between the forward stagnation point and bubble separation point, \( \beta \).

### Table 1 Sphere diameter, \( d_p \), sphere density, \( \rho_p \), and contact angles, \( \theta_c \)

<table>
<thead>
<tr>
<th></th>
<th>Acrylic resin</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ( d_p ) (mm)</td>
<td>10.1, 15.0, 20.1</td>
<td>12.5, 15.1, 24.8</td>
</tr>
<tr>
<td>Density ( \rho_p ) (g/cm(^3))</td>
<td>1.17</td>
<td>2.49</td>
</tr>
<tr>
<td>Original contact angle ( \theta_c ) (deg.)</td>
<td>71</td>
<td>33</td>
</tr>
<tr>
<td>Contact angle after coating a water-repellent ( \theta_c ) (deg.)</td>
<td>144</td>
<td>141</td>
</tr>
</tbody>
</table>

**Fig. 2** Photograph of spheres submerged on the bottom wall of the vessel. (left): poorly-wetted sphere, (right): wetted sphere.

**Acrylic solid sphere**

- Good wettability
- Poor wettability

![Acrylic solid sphere](image)

**Fig. 3** Water droplet placed on (a) a wetted sphere and (b) a poorly-wetted sphere

Accordingly, the wettability of the original sphere is good. The water-repellent coated on the sphere changed the wettability from good to poor. The contact angle of the sphere after coating was 144 deg. The horizontal clearance between a pair of spheres, \( \delta \), was varied from 0\( d_p \) to 2\( d_p \). Experiments were carried out under the following conditions.

(a) Single wetted sphere
(b) Single poorly-wetted sphere
(c) Two wetted spheres

**3. Results and Discussion**

### 3.1 Single sphere

**Fig. 5** shows the dynamic behavior of a single wetted or a single poorly-wetted sphere penetrating into a water bath. There exists no cavity behind the single wetted sphere. On the other hand, behind a single poorly-wetted sphere, an air cavity was formed. Duez et al. investigated the threshold velocity for the formation of the cavity theoretically as well as experimentally [13]. The threshold velocity depended on the contact angle as seen in Fig. 6. When the wettability was good in this study, the impact velocity was smaller than the threshold velocity. As a result, an air cavity was not formed behind the sphere. When the wettability of the sphere was poor, the impact velocity was greater than the threshold velocity and, hence, the cavity was formed behind the sphere.
The history of a falling single sphere is shown in Fig. 7. The moment when the sphere impacts onto the bath surface is chosen to be $t = 0$. The falling distance of the single poorly-wetted sphere measured from the initial bath surface was shorter than that of a single wetted sphere due to the existence of the air cavity behind it.

3.2 A pair of wetted spheres

If the threshold velocity proposed by Duez et al. [13] is valid for a pair of spheres, an air cavity does not form behind a pair of wetted spheres in contact with each other ($\delta = 0d_p$). The cavity, however, was formed even in this case (Fig. 8). This is because an air pocket generated behind a pair of wetted spheres triggers the cavity. When the horizontal clearance between a pair of wetted spheres was not zero (for example, $\delta = 0.25d_p$), the cavity was not formed, as shown in Fig. 8. Figure 9 shows the history of a pair of falling spheres together with that of a single wetted sphere. Because a pair of wetted spheres is decelerated by the air cavity, the falling distance of a pair of wetted spheres is smaller than that of a single wetted sphere.

3.3 A pair of wetted and poorly-wetted spheres

Figure 10 shows the photographs of a pair of wetted and poorly-wetted spheres ($\delta = 0.25d_p$) penetrating into a water bath. A part of the air cavity formed behind the poorly-wetted sphere was pulled toward the wetted sphere because the pressure behind the wetted sphere is lower than that away from it. On the contrary, the wetted sphere was pulled upward by the cavity. Consequently, the falling
distance of the wetted sphere became slightly smaller than that of the poorly-wetted sphere, as shown in Fig. 11. Interaction between a pair of wetted and poorly-wetted spheres disappeared with a further increase in $\delta$.

### 3.4 A pair of poorly-wetted spheres

This subsection deals with the case of a pair of poorly-wetted spheres. When the horizontal clearance between a pair of spheres is zero ($\delta = 0d_p$), the air cavities formed behind each sphere merged (Fig. 12). The falling distance was almost the same regardless of $\delta$ (Fig. 13). That is, the falling distance did not depend on the horizontal clearance between a pair of spheres, $\delta$.

### 3.5 Maximum cavity depth, $H_m$

Shimamoto et al. [10] proposed the following empirical equation for the maximum cavity depth, $H_m$ for a single poorly-wetted sphere.

$$\frac{H_m}{d_p} = 0.595 \text{Fr}^2$$  \hspace{1cm} (1)

$$\text{Fr}^2 = \left[ \left( \frac{\rho_p}{\rho_L} \right) \left( \frac{v_0^2}{gd_p} \right) \right]^{1/2}$$  \hspace{1cm} (2)

where $\text{Fr}^2$ is the modified Froude number, $\rho_p$ is the density of the liquid and $g$ is acceleration due to gravity. Figure 14 shows the relationship between the dimensionless maximum depth of an air cavity, $\frac{H_m}{d_p}$ and the modified Froude number, $\text{Fr}^2$ for a single poorly-wetted sphere. The
data obtained by Shimamoto et al. and Tanaka et al. were also plotted. The solid line indicates the equation proposed by Shimamoto et al. The experimental results for a single poorly-wetted sphere obtained in this study fitted with the empirical equation and the previously obtained results. Figure 15 presents the results for a pair of spheres. The results for a pair of wetted spheres were removed because the mechanism of the formation of the air cavity was different from that of the others. When the horizontal clearance between a pair of spheres was zero, the value of the dimensionless maximum depth was larger than the empirical equation, Eq. (1). However, when the horizontal clearance between a pair of spheres was not zero, the measured values were approximated by Eq. (1).

3.6 Break-up time of the air cavity, $t_m$
Tanaka et al. [14] modified the empirical equation proposed by Shimamoto et al. as follows:

$$v_{p,0}t_m/d_p = 1.18Fr$$  \hspace{1cm} (3)

$$Fr = \left(\frac{v_{p,0}^2}{gd_p}\right)^{1/2}$$ \hspace{1cm} (4)

where $Fr$ is the Froude number. The results for a single sphere can be approximated by Eq. (3) denoted by the solid line (Fig. 16). The measured values of the dimensionless brake-up time of the air cavity formed behind a poorly-wetted sphere were larger than the empirical equation, Eq. (3), as can be seen in Fig. 17. The data however can be correlated in terms of the Froude number similitude.

4. Conclusions
This study investigated the dynamic behavior of a pair of spheres with different wettabilities penetrating into a water bath. The visualization technique employed was a high-speed camera. Main findings can be summarized as follows:
(1) An air cavity was formed in the case of a pair of wetted spheres penetrating into a water bath. This is because an air pocket generated behind a pair of wetted spheres triggers the cavity.

(2) The falling distance of a pair of wetted spheres is smaller than that of a single wetted sphere. This is because a pair of wetted spheres is decelerated by the air cavity.

(3) When the horizontal clearance between a pair of spheres except for a pair of wetted spheres was zero, the measured value of the dimensionless maximum depth was larger than the empirical equation, Eq. (1). However, when the horizontal clearance between a pair of spheres was not zero, the measured values were approximated by Eq. (1).

(4) The measured values of the dimensionless brake-up time of the air cavity for a pair of spheres except for a pair of wetted spheres were larger than the empirical equation, Eq. (3). The data can be correlated in terms of the Froude number similitude.

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