J Vis (2010) 13:289–292
DOI 10.1007/s12650-010-0054-x

SHORT PAPER

Y. Ueda · M. Tanaka · T. Uemura · M. Iguchi

Water entry of a superhydrophobic low-density sphere

Received: 10 May 2010 / Revised: 8 August 2010 / Accepted: 31 August 2010 / Published online: 19 September 2010

1 Introduction

In a steelmaking process, the micro particles such as calcium oxide (CaO, desulphurization chemical) should be effectively injected into a molten iron bath (solid-liquid impact) and dispersed in the whole bath to enhance the efficiency of desulphurization or dephosphorization. However, the injected particles attract gas bubbles due to the poor wettability with molten iron so that the dispersion in the bath could be inhibited. To achieve the effective dispersion of the injected particles, we need to investigate the dynamic behavior of the air cavity formed by the liquid entry of a particle.

Pioneering work of solid-liquid impact can be found in Worthington and Cole (1897, 1900) who used single-spark photography to examine the air cavity formed by the vertical entry of a sphere into water. Recently, with the progress of a high-speed camera, several kinds of articles virtually investigate the air cavity formed by a superhydrophobic high-density sphere entering into water (see Duez et al. 2007) together with mathematical formulation within an inviscid framework (see Aristoff and Bush 2009; Duclaux et al. 2007; Lee and Kim 2008; Yan et al. 2009). This paper virtually demonstrates the water entry of a superhydrophobic lower density sphere than water and adopts the previous analytical model to the low-density sphere on the time evolution of the cavity shape by Duclaux et al. (2007) and Aristoff and Bush (2009).

2 Experimental setup and visualization procedure

The growth and pinch-off of the air cavity due to the entry of a superhydrophobic low-density sphere into water is demonstrated experimentally. The low-density sphere, having a density $\rho_p = 851$ or 920 kg/m^3 and a diameter $d_p = 12.7$ mm, is freely released, by putting off the power supply of the vacuum pump, at a certain height ($40 \leq h \leq 200$ mm) from a static water surface level in a transparent acrylic cubic vessel (300 mm each). After freely released, the sphere impacts on the water surface and forms the air cavity behind it. The sphere presently used is a lower density than the water so that the sphere naturally broaches from a certain depth of the dive. Several kinds of the cavities formed by the entry of the dewetting sphere are recorded with a high-speed camera whose frame rate is 500 frames/s with the shutter speed of 250 μs for the resolution 1,024 × 1,260 pixels.

Y. Ueda (✉) · M. Tanaka · M. Iguchi
Division of Materials Science and Engineering, Hokkaido University, Hokkaido 060–8628, Japan
E-mail: y-ueda@eng.hokudai.ac.jp

T. Uemura
Department of Mechanical Engineering, Kansai University, Osaka 564–8680, Japan

3 Results and discussion

A coating of water-repellent material dewets a solid surface. Indeed, an air-layer is observed to cover the surface of a hydrophobic sphere immersed in water (see Tanaka et al. 2008a). As shown in Aristoff and Bush (2009), Duez et al. (2007) and Tanaka et al. (2008b), the entry of the hydrophobic sphere into water is known to form the air cavity whereas the non-coating (smooth surface) sphere seems not to form it. The resulting air cavity can be observed at the pinch-off event in various kinds of patterns, which are dependent on a released height of the sphere (see the top side of Figs. 1, 2), i.e., the distinct ripple can be observed on the cavity surface when the sphere is released at the higher position than $h \geq 120$ mm. Figure 4 shows a video sequence of the water entry of the hydrophobic sphere from the onset of the impact. Unlike the previous experiments adopting the high-density sphere [see e.g., Figs. 7–8 of Duclaux et al. (2007) or Figs. 5–7 of Aristoff and Bush (2009)], the low-density sphere pinches off the air cavity at the shorter depth and attracts minimal air on the rear surface because of rapid deceleration of the sphere in water (see the last of Fig. 4 and compare the pinch-off point between Fig. 3 and the top side of Figs. 1 and 2). According to Duclaux et al. (2007) and Aristoff and Bush (2009), the water entry of the high-density sphere would form the cavity surface from around the separation point due to a pressure drop at the impact. In contrast, the low-density sphere experiences a lower pressure drop which could result in a closure of the air cavity before the cavity has fully grown (i.e., a growing velocity of the cavity in the radial direction could be weak).

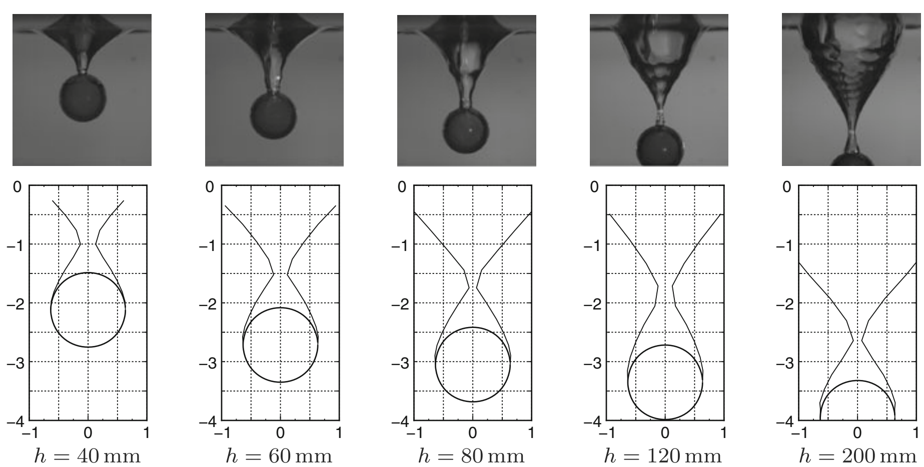

Fig. 1 Air cavity shapes, at pinched off, formed by the water entry of a superhydrophobic low-density sphere ($d_p = 12.7$ mm and $\rho_p = 851$ kg/m^3). *Top* photograph, *Bottom* analytical model of Duclaux et al. (2007)

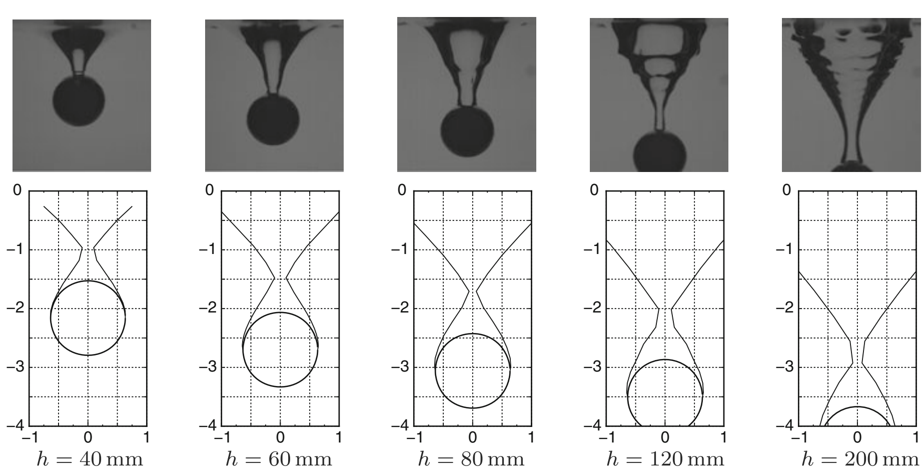

Fig. 2 Air cavity shapes, at pinched off, formed by the water entry of a superhydrophobic low-density sphere ($d_p = 12.7$ mm and $\rho_p = 920$ kg/m^3). *Top* photograph, *Bottom* analytical model of Duclaux et al. (2007)

Fig. 3 Cavity due to a high-density sphere ($\rho_p = 2360$ kg/m^3) is cited from Fig. 7 of Duclaux et al. (2007)

Fig. 4 A video sequence of the water entry of a hydrophobic sphere from the onset of the impact to the pinch-off in the case of $d_p = 12.7$ mm, $d_p = 851$ kg/m^3 and $h = 160$ mm

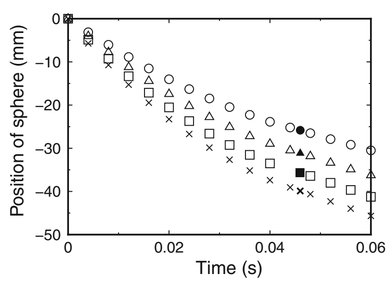

Fig. 5 Position of a sphere ($d_p = 12.7$ mm and $\rho_p = 851$ kg/m^3) entering into water. *Circle* $h = 50$ mm, *Triangle* $h = 80$ mm, *Square* $h = 120$ mm, *Cross* $h = 160$ mm. Data at the pinch-off event is indicated as *solid/bold symbol*

As mentioned in the previous section, the lower density sphere than water is presently used so that the sphere can experience the rapid deceleration (after then, it broaches from a certain depth of the dive). The equation of motion of a hydrophobic sphere entering into water was derived by Lee and Kim (2008) and briefly presented in Aristoff and Bush (2009). Instead of solving the equation of motion to which the solution cannot be analytically obtained, we measure the instantaneous position of the sphere entering into water with the high-speed camera (see Fig. 5). The entering velocity of the sphere is calculated from Fig. 5. As observed in Fig. 5, the low-density sphere experiences the rapid deceleration, whereas the high-density sphere sinks with the constant velocity in water (see Duclaux et al. 2007; and Aristoff and Bush 2009). Duclaux et al. (2007) and Aristoff and Bush (2009), who extended the work of Duclaux et al. (2007) by including the effects of surface tension and aerodynamic pressure on the cavity surface, analytically obtained the evolution of the cavity shape on the basis of the Besant–Rayleigh problem by assuming the diameter of the cavity to be small relative to its length (i.e., the cavity shape is slender, which allows us to treat in 2D). The time evolution of the cylindrical cavity radius R at a given z is approximately described as $R^2 = (d_p/2)^2 + \sqrt{\alpha} v_{p0} d_p t - gzt^2$, where we have used the initial conditions $R\ (t = 0) = d_p/2$ and $\dot{R}(t = 0) = \sqrt{\alpha} v_{p0}$ with α a constant smaller than unity (see Duclaux et al. 2007). In addition, v_{p0} is the entering velocity of a sphere into water ($v_{p0} = \sqrt{2gh}$) and g is acceleration due to gravity. The calculated shapes of the cavity are compared to the experimental photograph in Figs. 1 and 2. It seems that the above equation is no longer valid in the case of the pinch-off position being close to the sphere (i.e., Although Duclaux et al. (2007) and Aristoff and Bush (2009) do not restrict the formulations to a high-density sphere, a low-density sphere pinches off the cavity before the cavity has fully grown, which fails to fulfill the above-mentioned assumption of the cavity shape being slender). To remedy this, the advanced analysis will be required in a three-dimensional problem. We intend to analyze the problem in a future work.

References

Aristoff JM, Bush JWM (2009) Water entry of small hydrophobic spheres. J Fluid Mech 619:45–78

Duclaux V, Caillé F, Duez C, Ybert C, Bocquet L, Clanet C (2007) Dynamics of transient cavities. J Fluid Mech 591:1–19

Duez C, Ybert C, Clanet C, Bocquet L (2007) Making a splash with water repellency. Nat Phys 3:180–183

Lee D-G, Kim H-Y (2008) Impact of a superhydrophobic sphere onto water. Langmuir 24:142–145

Tanaka M, Hashimoto M, Tsujino R, Iguchi M (2008a) Model experiment on the hydrodynamic drag of a poorly wetted sphere penetrating into a molten metal bath. J JSEM 8(3):196–200

Tanaka M, Hashimoto M, Tsujino R, Iguchi M (2008b) Behavior of a poorly wetted low-density sphere penetrating into a water bath (in Japanese). J JSEM 8(3):201–205

Worthington AM, Cole RS (1897) Impact with a liquid surface, studied by the aid of instantaneous photography. Philos R Soc Lond A 189:137–148

Worthington AM, Cole RS (1900) Impact with a liquid surface studied by the aid of instantaneous photography. Paper II. Philos R Soc Lond A 194:175–199

Yan H, Liu Y, Kominiarczuk J, Yue DKP (2009) Cavity dynamics in water entry at low Froude numbers. J Fluid Mech 641:441–461