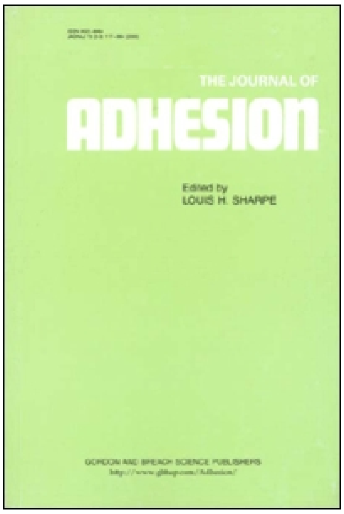

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Bouncing Bubbles

Frédéric Vincent[a]; Anne Le Goff[a]; Guillaume Lagubeau[a]; David Quéré[a]
[a] Physique et Mécanique des Milieux Hétérogènes, UMR 7636 du CNRS, ESPCI, Paris, France

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Frédéric Vincent
Anne Le Goff
Guillaume Lagubeau
David Quéré
Physique et Mécanique des Milieux Hétérogènes,
UMR 7636 du CNRS, ESPCI, Paris, France

We discuss here soap bubbles hitting a bath of water and bouncing off the surface. We first describe the characteristics of this event, that is, the bubble deformation during impact and the contact time associated with the rebound. Then we propose a tentative scenario for understanding this behavior, which stresses the importance of the transient film of air between the bubble and the bath, preventing the coalescence from taking place.

Keywords: Non-wetting; soap bubbles

1. INTRODUCTION

Adhesion and wetting are fields closely related to each other [1]. If two solid plates stuck together with a liquid glue are separated, a crack can propagate either along the solid (adhesive failure) or within the liquid (cohesive failure). In the first case, the minimum energy required for propagating the crack arises from the creation of solid/vapor and liquid/vapor interfaces and suppression of a solid/liquid frontier, while cohesive failure just implies the creation of two liquid/vapor interfaces. Hence the latter scenario will be favored if the liquid totally wets the considered solid. Conversely, a zero-wetting situation will induce a non-adhesive behavior. Such a

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Address correspondence to David Quéré, Physique et Mécanique des Milieux Hétérogènes, UMR 7636 du CNRS, ESPCI, 10 rue Vauquelin, Paris F-75005, France. E-mail: david.quere@ESPCI.fr

situation has attracted a lot of attention in the recent years, and it can be achieved by a Leidenfrost effect (liquid on a very hot plate) or with super-hydrophobic materials (such as lotus leaves or duck feathers) [2].

In all these cases, the key fact is the existence of a film of gas between the substrate and the deposited liquid, which prevents the contact (and thus both wetting and adhesion). When one tries to bring two liquids into contact, such a film generally exists only temporarily, and it can be interesting to make it more permanent. "Special" conditions favor this, allowing us to observe a delay in adhesion or in coalescence between the two bodies. Coffee drops hitting a coffee pool often roll for a few seconds at the surface of the pool, which results from the presence of fatty chains in the coffee solution [3], or from a temperature difference between the drop and the bath [4]. It was also recently demonstrated that shaking a bath of oil can stabilize oil drops above the surface as long as shaking is maintained [5]. Here we show that for large and relatively slow objects, such as centimeter-size soap bubbles approaching a bath of quiescent water, the air film is persistent enough for preventing the coalescence of the bubble, as proved by its rebound. We analyze a few characteristics of this phenomenon, and compare our results with recent findings obtained with drops.

Soap bubbles were made from a commercial dishwashing solution (measured surface tension $\gamma = 25\,\mathrm{mN/m}$), by blowing in a ring first drawn out of the solution. Varying the diameter of the ring allowed us to change the bubble radius. Then, the bubbles were thrown towards the surface of a large bath of water, owing to a flow of air. Using pure water, or the same surfactant solution as the one used for making the bubble did not affect our observations. In Figure 1, we show what happens as a bubble (radius $R = 1.1\,\mathrm{cm}$) hits the water surface at $V = 65\,\mathrm{cm/s}$, where it is observed to bounce off, after deforming (without coalescing) during a time, τ, on the order of a

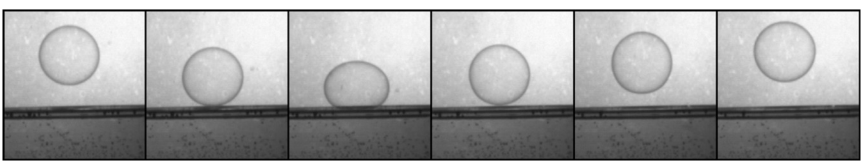

FIGURE 1 Impact and rebound of a soap bubble (radius $R = 1.1\,\mathrm{cm}$) hitting at $V = 65\,\mathrm{cm/s}$ a pool of quiescent water. The time interval between two successive pictures is $14\,\mathrm{ms}$. It is observed that the bubble deforms without coalescing, allowing it to store its kinetic energy, and then takes off. The "contact" time between the bubble and the pool is here 22 ± 2 ms.

few milliseconds. About 40% of the bubbles of this size bounce—the rest just coalesce with the bath—where they eventually form a hemisphere before bursting. For larger bubbles (diameter of about 10 cm), about 90% of them show a rebound (for impact velocities on the order of 10 to 20 cm/s).

2. BUBBLE DEFORMATION AT IMPACT

The kinetic energy of the impinging bubble is stored during the shock, owing to its deformation. Thus, it is observed that the amplitude of this deformation depends on the impact velocity, V, as seen in Figure 2.

We quantify the deformation by the quantity δ, the difference between the radius of the impacting spherical bubble and half the minor axis of its ellipsoidal shape, at maximum deformation. Since inertia of the incoming bubble is expected to favor its deformation while the surface tension, γ, resists it, δ should increase as a function of the Weber number, which compares inertia with surface tension: $We = \rho RV^2/\gamma$, where ρ is the air density. Note that the repartition of the mass in a bubble is not obvious: the mass of air is $4\pi\rho R^3/3$ (denoting ρ as the air density), of the order of 4 mg for a centimeter size bubble; if the water film (of density ρ_w) has a thickness, h, of 1 micrometer, its mass, $4\pi\rho_w hR^2$, is about 1 mg. The mass of large bubbles ($R > 3h\rho_w/\rho$) is thus dominated by the contribution of air, explaining why we used this mass in our definition of inertia in the Weber number.

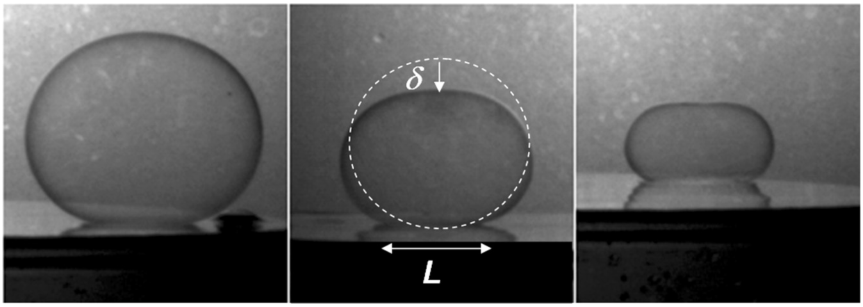

FIGURE 2 Maximum deformation of soap bubbles impacting a water pool without coalescing. The bubble radii R and velocities V are (from left to right) 1.1 cm and 43 cm/s, 0.8 cm and 86 cm/s, and 0.6 cm and 120 cm/s. The corresponding Weber numbers, $We = \rho RV^2/\gamma$, which compare inertia and surface tension, are 0.08, 0.24 and 0.35, respectively: the higher We, the larger the deformation. We quantify the deformation by the bubble flattening δ, and denote as L the contact zone in which the bubble is parallel to the bath.

The simplest model we can imagine is energy conservation during impact [6]. On the one hand, this seems natural: the Reynolds number $\rho VR/\eta$ associated with the shock (and defined with the air density and viscosity ρ and η, respectively) is typically 100, so that viscous effects can be ignored. The kinetic energy of the impinging bubble of mass, M, simply writes as: $1/2MV^2$. The increase of surface area, ΔA, associated with the transformation of a sphere into an ellipsoid (denoting δ as the bubble flattening) is $16\pi\delta^2/5$ (a similar formula for a deforming drop would imply a numerical factor $8\pi/5$, but here we have two interfaces which get deformed). The surface energy stored in this deformation is γ ΔA. Hence, energy conservation yields:

$$\delta \approx (5/24)^{1/2} R\, We^{1/2}. \tag{1}$$

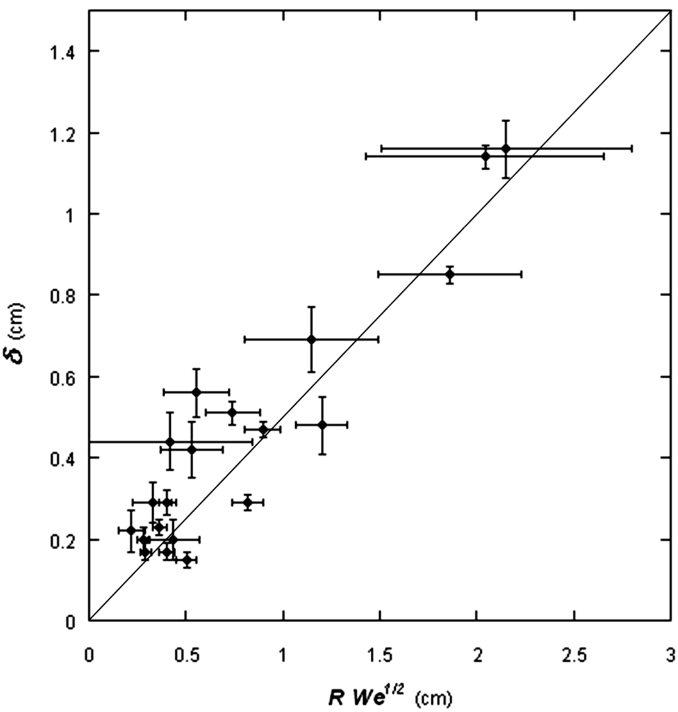

FIGURE 3 Flattening δ of a bubble impacting a pool of water, as a function of the impact velocity; δ is the difference between the initial radius, R, and half the minor axis of the ellipsoidal shape, as defined in Figure 2. The data scatter around the law $\delta = 0.5\, R\, We^{1/2}$ (drawn with a solid line), close to the behaviour expected from Eq. (1).

We compare in Figure 3 our data for the bubble deformation with the prediction of Eq. (1). The data are obtained for bubble radii, R, between 0.6 and 5.7 cm. The Weber number varies by a factor of 50, between 0.007 and 0.34. In this limit of small *We*, it is observed that all the data collapse into a single linear curve, in fair agreement with the expected behavior. The numerical coefficient itself is well described (we took 0.5 in the fit, close to the 0.45 in Eq. (1). In a few cases, the deformation is larger than expected, which could come from neglecting the mass of the liquid shell: if the kinetic energy is larger, we indeed expect a greater deformation. Another source of error comes from the velocity at impact (entering the Weber number): these bubbles are large and thus filmed from quite far away, so that the measurement of small distances (from which the velocity is deduced) can be rather imprecise (up to $\pm 20\%$).

Interestingly, surface energy is not only converted into kinetic energy after impact. We can monitor the maximum height reached by the bubble after take off. We deduce a restitution coefficient (defined as the ratio between velocities after and before rebound) of the order of 0.5 to 0.6, significantly lower than observed at low *We* on bouncing drops [7]. Energy loss mainly comes from the transfer of kinetic into vibrational energy: after taking off, the bubble vigorously oscillates as it rises. We finally note that if the bubble hits the pool with an angle (measured from the normal to the surface), it takes off symmetrically towards the normal (specular reflection).

3. CONTACT TIME

Another observation on this phenomenon concerns the "contact" time, τ, of the impact, which can be easily deduced from high-speed images such as displayed in Figure 1. The time τ corresponds to the interval between the moment when the bubble is tangent to the surface of the pool (second image in Fig. 1) and the one when it leaves the bath (just before the fourth image in Figure 1). We display in Figure 4 the variation of this time, which is a fraction of a second for large bubbles, as a function of the bubble radius, for impact velocities between 10 and 100 cm/s (with an average of 60 cm/s). In this logarithmic plot, we find that the contact time rapidly increases with R, as shown by the solid line, which indicates the slope 3/2. These measurements are quite precise, yielding error bars of the order of the dot size: uncertainty in time and radius is ± 1 ms and ± 1 mm, respectively.

Since the impact implies an oscillation, we are tempted to introduce the period of this oscillation. A bubble behaves as a spring of mass M and stiffness 2γ (the factor 2 arises from the presence of two interfaces), with a natural time scale $(M/2\gamma)^{1/2}$ [8]. If we assume that the mass is mainly inside the bubble ($M = 4\pi\rho R^3/3$), we deduce a contact time:

$$\tau \approx (\rho R^3/\gamma)^{1/2}. \tag{2}$$

If the mass is within the water shell ($M = 4\pi\rho_w hR^2$), we rather expect:

$$\tau \approx (\rho_w hR^2/\gamma)^{1/2}. \tag{3}$$

Hence, the contact time should be independent of the impact velocity V. Moreover, it should scale as $R^{3/2}$ for large bubbles ($R > 3h\rho_w/\rho$, on the order of 1 cm) and as R for smaller bubbles. We can see in Figure 4 that the scaling expected from Eq. (2) is indeed well obeyed by the data. The numerical coefficient in Eq. (2) deduced from the data is $\beta = 3.0 \pm 0.2$, comparable with the value found for bouncing drops, which is $\alpha = 2.6 \pm 0.2$ [9]. Note that the latter value is itself larger than the one for a freely oscillating drop (about 2.2), owing to the presence of a substrate below [10].

Comparing bubbles with drops, we could expect on the one hand a smaller coefficient β by about 40% since the stiffness of this "spring"

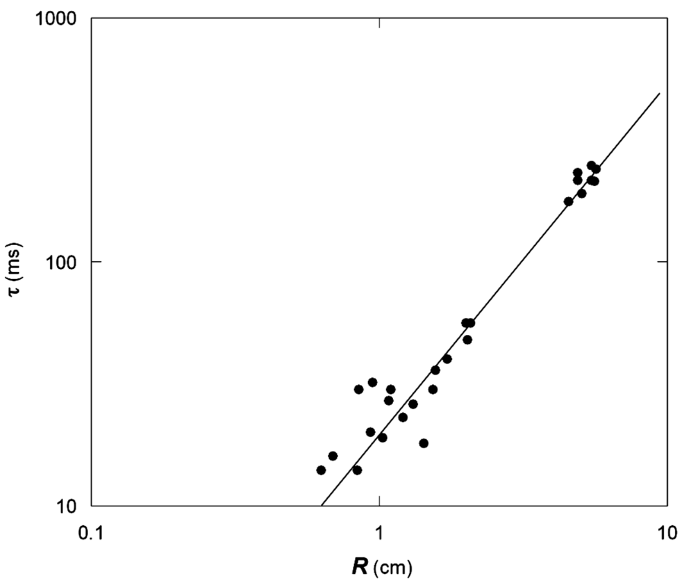

FIGURE 4 Contact time of centimetre size bubbles bouncing off a pool of water, as a function of their size (impact velocities are in the range 10 to 100 cm/s). The full line indicates a slope 3/2, as expected from Eq. (2).

is 2γ, instead of γ for a drop, for which there is only one interface. On the other hand, three facts favor a larger coefficient: (i) Air around the bubble contributes to increase the contact time. As shown by Lamb, if the oscillating globule and surrounding medium are of the same density, the oscillation period is increased for the simplest mode of oscillation by a factor $(5/3)^{1/2}$ (about 1.3), which corresponds to an added mass term [11]. Together with the previous remark, this leads to a coefficient $\beta = (5/6)^{1/2}\,\alpha$, close to α, as observed experimentally. (ii) The actual mass of the bubble is slightly larger than assumed in Eq. (2), since the water shell also contributes to it; as stressed above, this contribution is all the larger since the bubble is small, which in our opinion is the reason for the deviation (or scattering of the data) visible in Figure 4 at small radii. Then, Eq. (3) should be more relevant, imposing a smaller slope in this logarithmic representation (1 instead of 1.5) for the law $\tau(R)$. (iii) For drops, it was observed that the contact time increases (by a factor which can be about 2) as the impact velocity becomes small, which was shown to result from the influence of the drop weight [9]. This could also affect our data at small impact velocities.

4. POSSIBLE CONDITION FOR BOUNCING

It is finally worth wondering how bubbles can bounce on a bath of water, while water drops do not exhibit a similar behavior. The reason might be the (large) size of these objects. As it approaches water, a bubble must remove the air present between the two liquids, which can take longer than τ, the time necessary for deforming and recoiling: then, the bubble will bounce. We denote ε as the distance between the bath and the (bottom of) the bubble. The bubble stops when viscous effects overcome inertial ones: constructing a Reynolds number Re, with the distance, ε, that is, $\rho\varepsilon V/\eta$, we assume that the distance in which the bubble stops is given by Re of order 1. For our parameters, we find that ε should be in the range of 10 to 100 µm. Using backlighting, together with the use of a high-speed camera of high resolution (1200×1600 pixels at 1000 images per second), we could show directly the existence of the air film, and even evaluate its thickness: in Figure 5, for a bubble of radius $R = 1.6\,\text{cm}$ hitting a surface at $V = 70\,\text{cm/s}$, we find a thickness ε of 100 ± 25 microns, of the order of the value expected above. Note that this experiment also confirms that the deformation mainly concerns the bubble: the pool basically remains flat as the bubble impacts it.

We expect a viscous drainage of air, owing to the overpressure inside the film. The latter should just be the Laplace pressure in the bubble, of the order of γ/R. This pressure holds inside the bubble

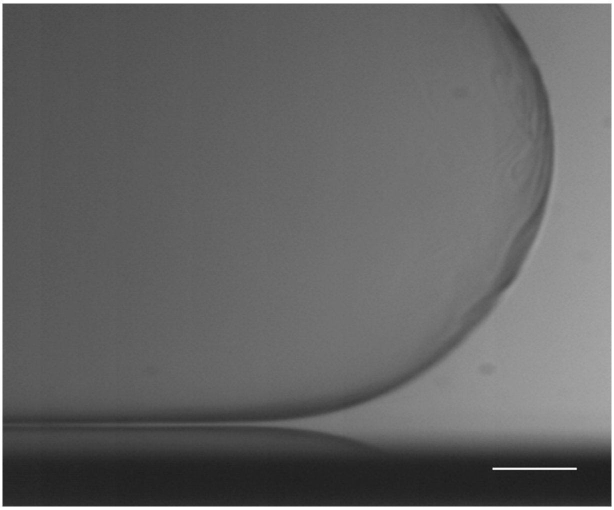

FIGURE 5 Close-up of the bottom of the deformed bubble: backlighting reveals the film of air, which prevents the bubble from coalescing. Its thickness, ε, is here 100 ± 25 micrometers. The bar indicates 1 mm.

but also in the film, since crossing the (flat) interfaces below the bubble does not imply any pressure jump. (Hydrostatic pressure is much smaller, for such bubbles.) The mean velocity, v, of the air flow in the film should be given by a balance between the viscous drag and the pressure gradient, which can dimensionally be expressed as: $\eta v/\varepsilon^2 \sim \gamma/RL$, where L is the length of this film.

As it impacts the bath, the bubble is flattened by a quantity δ, which is given by Eq. (1). The lengths L and δ might be related to each other by the (geometrical) Hertz relationship: $L \sim (\delta R)^{1/2}$. We show in Figure 6 that the length L, easily deduced from figures such as Figure 2, is indeed found to vary linearly with the (measured) quantity $(\delta R)^{1/2}$, as expected from the Hertz relation.

If we finally define the characteristic time of drainage τ^* by the scaling relation $\tau^* \sim L/v$, we find that τ^* should vary as $\eta\delta R^2/\gamma\varepsilon^2$. Using Eq. (1) for the quantity δ, we can thus propose the following scaling law for the drainage time:

$$\tau^* \sim \eta R^3/\gamma\varepsilon^2\, We^{1/2}. \tag{4}$$

Our criterion for non-coalescence (and thus rebound) is $\tau < \tau^*$. In the limit of large bubbles, τ obeys Eq. (2) (as commented earlier, and found

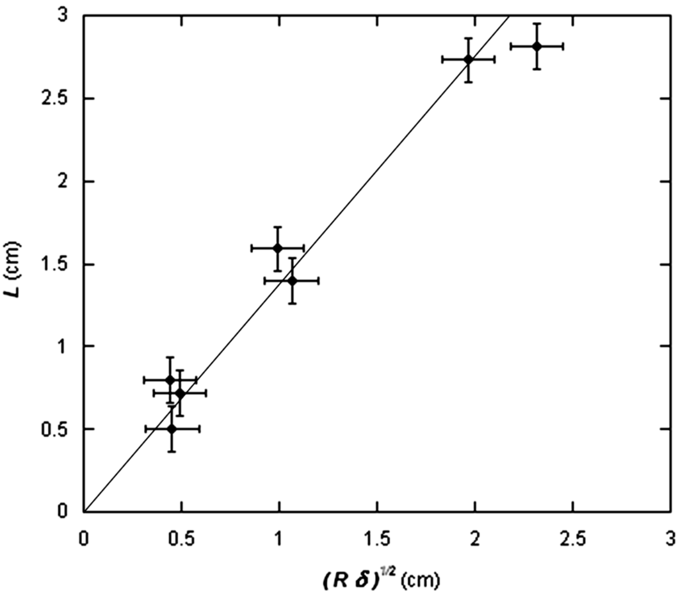

FIGURE 6 Contact length of centimetre size bubbles bouncing off a pool of water, as a function of their flattening, δ. The impact velocity was varied between 10 and 100 cm/s, allowing us to vary both δ and L. The data are found to satisfy the geometric Hertz relationship $L \sim (\delta R)^{1/2}$ and the slope of the solid line is 1.4.

in Figure 4), so that this criterion just writes as:

$$R > \varepsilon / Ca^{1/2}, \tag{5}$$

where $Ca = \eta V/\gamma$ is the capillary number associated with impact. Taking typical values for the different parameters ($\varepsilon = 100\,\mu\text{m}$ and $V = 1\,\text{m/s}$), we find that a bubble might bounce provided that its size is typically 1 cm. Moreover, bubble rebounds should be favored with increasing bubble sizes, which might be studied by establishing a statistics of the bouncing events: Eq. (5) predicts an increase of the probability of rebound, for a critical value $\varepsilon/Ca^{1/2}$, which depends on the characteristics of the impact (particularly on its velocity). Similarly, the detail of the "contact" might be specified: systematic studies of the thickness of the air film (as a function of the bubble size and speed) would be worth doing.

The criterion for bouncing might be different: soap bubbles are often observed to hold at the bottom a drop (which results from the gravitational drainage of liquid inside the soap film). A hanging drop can behave as a nucleator for the coalescence: if its thickness, h, is of the order of ε or larger ($h > \varepsilon$), a contact might be established between the drop and the pool. The criterion would, thus, be mainly related to the velocity of impact: as proposed above, the larger this velocity, the thinner the air film ($\varepsilon \sim \eta/\rho V$), and thus the more likely the coalescence. Following this scenario, an older bubble (for which drainage is more significant) should coalesce more easily.

It would also be interesting to see if rebounds are possible at large Weber numbers, and what their characteristics are. The deformations should become spectacular in this limit, as has been observed with drops. But our preliminary study already shows that the delay in coalescence between two fluid bodies (here a bath and a bubble) can have spectacular consequences, the dynamics of which results from a subtle interplay between inertial effects (owing to the large size of the objects) and viscous ones (related to the thinness of the films). This is often the case in interfacial hydrodynamics, where the coexistence of different scales makes it necessary to take into account different types of dynamics to elucidate the observed behaviors.

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