Ultra-Hydrophobic Water

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Abstract

When a drop of a viscous fluid is deposited on a bath of the same fluid that is vibrating, it is shown that it coalesces with this substrate or lifts off when the vibration of the surface is larger than g , leading to a steady condition where a drop can be kept bouncing for any length of time, as shown in figure 1. The phenomena that will occur depends on various parameters, such as drop impact acceleration, liquid surface tension, density, dynamic viscosity, gravity, droplet radius and impact speed, bath vibration frequency and amplitude. The effect of different parameters will conclude to a set of conditions which results in a system, called “ultra-hydrophobic water” which plays important role in chemical micro fluidic applications.

Key Words

Ultra-hydrophobic, Soapy Water, Loudspeaker, Vibrator, Small droplets

Introduction

The impact of a liquid drop on a quiescent liquid bath has been widely studied due to its visual appeal and its importance in both natural processes and industrial applications. Physicists found that after a droplet falls on the surface of the same liquid, it will

bounce several times before merging with the liquid. Back in 2005, Couder discovered that upon placing a silicon droplet on the surface of a bath of the same liquid, the droplet will not coalesce under certain conditions and will instead stay on the liquid surface for a period of time. Such a lubricating film can delay or completely avoid coalescence, as shown in figure 2.

This phenomena depends on various parameters such as drop impact acceleration, liquid surface tension, density, dynamic viscosity, gravity, droplet radius and impact speed, bath vibration frequency and amplitude.

In this study, the theory of this phenomenon will be explained both theoretically and using an experimental set up, where different parameters were investigated.

Materials and Methodology

Using high speed cameras, it has been shown that when a liquid droplet falls on the surface of the same liquid, it doesn't submerge immediately; it will bounce several times, go in and come out of the liquid and finally submerge into the liquid. This all happens within a very short period, which is why coalescence is the only observation made at the impact time.

To extend the duration of time during which the droplet will stay

Figure 1: Smaller drops stay (bounce) more and longer on the water surface.

Figure 2: Four steps of sitting a droplet on the liquid surface after impact [1].

Figure 3: Standing waves that decrease the droplet and surface contact time.

on the water and change the liquid surface to a hydrophobic stuff, a vibration must be induced to the liquid surface. With this technique, the droplets will remain on the surface, for a longer time period, without coalescing. Depending on how the experiment is conducted, different observations will occur. Drops may submerge into water, stay immobile on the surface, move on it, or even rotate around its center. This phenomenon happens because of various mechanisms that have been described as follows.

I. Standing waves

The lesser the contact time between the droplet and liquid surface, the longer the duration of time during which the droplet stays on the surface will be. By inducing a sinusoidal vibration with certain frequency to the liquid, standing waves, called Faraday waves, will be produced on every point of the surface and therefore a vertical force with the certain amplitude makes the droplet bounce and reduces the time spent in contact with the surface. A vertical force, at every place, at every moment, prevents the droplet from going into the liquid. Figure 3 shows the mechanism.

The droplet will continue to bounce on the liquid bath if the vibration amplitude is large enough to allow a periodic lift of the droplet where the vibration amplitudes is comparable to the gravity.

II. Air film

In many different studies, it is shown that the two similar liquids can be placed beside each other and be stable without merging and coalescing when a film of another fluid lies on their interface. When a falling droplet of a liquid impacts the surface of the same liquid, a thin layer of air will trap between the two surfaces and works as an elastic pillow, which makes the droplet bounce and not encounter the water surface directly. This layer is maintained by various mechanisms, such as air drag by liquid viscosity, air flow while escaping from the interface and the flow driven by the thermal Marangoni effect (Figure 4). This film produces a frictionless state and lets the droplet float on the liquid surface. Depending on whether this film

simply drains or becomes unstable, air entrainment might occur.

This observation indicates that an air layer exists between the drop and the bath.

III. Coefficient of restitution

An important parameter to explain this phenomenon is the coefficient of restitution,

which is described as a measure of the restitution of a collision between two objects and the amount of the kinetic energy remains for the object to rebound from one another vs. the amount lost as heat, or work done deforming the objects. It is defined as the ratio of relative speeds after and before an impact, taken along the line of the impact, according to the following equation:

$$e = \frac{\text{relative speed after collision}}{\text{relative speed before collision}} = \frac{v \text{ after}}{v \text{ before}}$$

When a tennis ball falls towards the ground, it accumulates a certain kinetic energy at impact due to its velocity (v before collision). When the collision occurs, there will be a loss of energy in form of heat; so the amount of the remained kinetic energy will decrease and the velocity is less than the impact time (v after collision) so that the ball goes up to the lower height. This occurs repeatedly and the ball bounces till the kinetic energy reaches zero. Now assume that there is a rubber ball instead. As can be expected, it bounces differently from the tennis ball and reaches different velocities after each collision. That is because of the difference between elasticity and coefficient of restitution for different types of materials, as shown in Figure 5.

We can describe the droplets as a kind of ball with a certain coefficient of restitution, which bounces after colliding to the same liquid surface with the same coefficient. It bounces hundreds of times in a short time period. To human eyes, what is observed is that the droplet stays on the surface and when it reaches zero kinetic energy, it submerges into water. This is why when the droplet fall on a harder surface like a piece of wood or a viscous liquid, like honey,

Figure 4: S (a) A large floating drop, as seen from the side. (b) The interference fringes of the air film as observed when the drop is lit from the top with white light. The black dot at the center is the reflection of the camera's lens. [2].

it deforms because the e coefficient is different for different surfaces, therefore the kinetic energy will be lost and used to deform the droplet (Figure 6).

So the velocity after collision and the e coefficient reaches zero as the result. (Figure 7) shows the elasticity of both liquid surfaces while collision.

The experimental set-up to use for investigating the physics of the problem is simply made of droppers, soapy water, a dish, a loudspeaker (without a frame) and a frequency app to induce different frequency to the water. The experimental setup, displayed in figure 8, consists of a speaker, a signal generator and an amplifier.

First soapy water was used to fill the dish. Next, the frame of the loud speaker was removed and placed the dish on top. After that, using the frequency app, different frequencies were induced to the dish. Results were recorded. Next, drops were placed with a dropper on the vibrating surface, as shown in figure 9. To determine the effect of different parameters, the experiments were performed using different droppers to produce drops with different diameters; different frequencies, amplitudes and different concentrations of soapy water.

Figure 6: Bouncing of a droplet after falling on the liquid due to the coefficient of restitution [3].

Results and Discussion

As mentioned before, various parameters affect the phenomena differently. Different experiments were done and the results were as follows.

Droplet diameter

The bouncing periodicity depends on the size of the droplet. For very small drops, it will continuously bounce. This is caused by the constant renewing of the air that separates the drop from the fluid below. The drops also become increasingly oblate as the drop sizes increase. By increasing the drop's diameter, the mass will increase and therefore the amount of after collision speed (V after) in constant kinetic energy will decrease. Consequently, the drop bounces less and the contact time between water and droplet goes up so the drop submerges faster. Briefly, the possibility of coalescence increases as the droplets become larger. Smaller droplets stay longer on the water surface, as shown in figure 10.

Figure 5: Bouncing ball.

Figure 7: Relative bounciness of various types of balls due to different e [4].

Liquid properties

Liquid properties such as density, viscosity and surface tension are very effective on the phenomena. In the very viscous fluid ($\mu\text{L} > 10^{-1} \text{ Pa}\cdot\text{s}$) investigated in previous works, each drop deforms into a small depression as it collides with the surface. It is obvious that the greater the surface tension, the greater the elasticity will be, and longer the droplets will last. Although adding soap to water will decrease the surface tension, the important point is the similarity of the two liquids and that the soapy water lubricates droplet impact and make their friction less and easier to move. This phenomenon is rarely seen in a pure water surface-pure water droplet interaction.

Figure 8:
Experimental Set-up.

Wave properties: Frequency and amplitude

Inducing frequency to the liquid surface will produce standing vertical waves, called Faraday waves, as seen in figure 11.

Stable droplet bouncing requires the vertical acceleration of the bath to be higher than a minimum threshold, where acceleration amplitudes which are comparable to gravity. Therefore, under a minimum amount of frequency, the droplets won't stay on the surface and the long contact time between two peaks of the wave will be enough for coalescence. By increasing the frequency for the optimum size of droplets, the stability time goes up and droplets bounce with higher frequency. As the frequency increases further, we see that the droplets begin to walk along the surface and move slowly. That is, the droplet do not simply bounce in a stationary position but instead wander in a straight line. Figure 12 shows two drops walking towards each other. Generally, they move in a straight line at constant speed; however, they can be diverted through interaction with boundaries or external forces.

In addition to the frequency, the amplitude of standing waves is also effective. Higher amplitudes place the droplet in a higher position each time a peak passes its location. Thus, in the bouncing process, it takes longer for the droplet to reach its peak point and turn down again. This will cause in an increase in contact time, and also deviates the droplet from a straight vertical line path and makes it hover along the surface. An important point is that the Faraday

Figure 9: Smaller drops stay (bounce) on the water surface.

Figure 10: Smaller drops stay (bounce) more and longer on the water surface.

Figure 11: Faraday waves.

waves are supported slightly below the super-critical threshold. By increasing the frequency, from a certain amount the interface destabilizes, no bouncing or walking will occur and the water splashes out of the dish. This amount is called Faraday threshold ($f > 550$ Hz) and is displayed in figure 13.

As shown in table 1, by adding more soap to the water, and by making different densities, the lifetime of the droplets will increase.

As shown in table 2, by increasing the frequency, the droplet lifetime will increase, but after 140 Hz, that is the threshold, the droplet lifetime will decrease.

Surface tension

In this part, the method involved slowly lifting a ring, often made of platinum, from the surface of a liquid. The force, F , required to raise the ring from the liquid's surface is measured and related to the liquid surface tension γ as shown in figure 14:

γ : Surface tension

F : Force measured by Newton meter

w : Ring's weight

r : Ring's radius

As shown in chart 1, by adding soap to the water, surface tension will decrease. By decreasing the surface tension of the water, the lifetime of the droplets will increase, as shown in chart 2.

Additional Observations

Throughout experiments, droplets with a rotation around their center were observed, which tended to form clusters (Figure 15), and coalesce with each other to make larger ones.

By adding potassium permanganate, we could see droplet clusters better, as shown in figure 16.

We also did this experiment with Mercury droplets, as shown in figure 17.

Figure 12: Walking droplets.

Figure 13: Faraday Threshold Condition.

Table 1: Droplet lifetime with different Densities
at Frequency: 280 (Hz).

DENSITY	LIFETIME ± 1 (s)
15 ml water + 5 ml soap	7
15 ml water + 10 ml soap	14
15 ml water + 15 ml soap	22

Table 2:

Droplet lifetime at different frequencies.

OSCILLATION FREQUENCY (Hz)	LIFETIME ± 1 (s)
90	3
100	4
120	12
140	Minutes
160	44

Figure 14:

Surface Tension is measured using the ring method. [5].

Figure 16:

Droplet clusters with potassium permanganate and water.

Figure 18: Regular and super hydrophobic materials' performance against water [6].

Conclusion

In this study, it was found that the parameters which influenced the droplet's life time included:

1-Surface Tension: by adding soap to the water, surface tension will decrease. By decreasing the surface tension of the water, the lifetime of the droplets will increase.

2-Vibration Frequency: by increasing the frequency, the droplet lifetime will increase, but after 140 Hz, that is the threshold, the droplet lifetime will decrease.

3-Drop size

4-Dropping height

Figure 15: Droplet clusters bouncing on the surface due to nonlinear standing waves.

Figure 17:

Mercury droplets in water.

Recently, scientist found an ultra-hydrophobic thing named super hydrophobic. Ultra-Ever Dry is a super hydrophobic (water) and oleo phobic (hydrocarbons) coating that will completely repel almost any liquid. Ultra-Ever Dry uses proprietary nanotechnology to coat an object and create a barrier of air on its surface. This barrier repels water, oil and other liquids unlike any coating seen before. In addition, it is being used for painting on the wall against with a super hydrophobic coating. This stops any liquid from sticking to or being absorbed by the wall, but also bounces it back in the direction it came with more force, as shown in Figure 18. This has applications for smartphones, which get smudged and covered with finger-grease. Not only would a super-hydrophobic screen self-clean its way out of this problem, it could reduce glare by scattering incoming light rays in all directions.

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Chart 1: Soap concentration and surface tension.

Chart 2: Drops' lifetime as a function of surface tension at Oscillation Frequency: 140 Hz.

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REVIEW

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This paper studies the behaviour of a droplet of liquid, placed on a vibratin bath of the same liquid. It has been observed in the past that such droplet has a significant life time of its own before being observed by the bath. The authors proceeds in an extensive experiment of the influence of different parameters on the lifetime of the droplet. The characteristics of all the liquid, the droplet and the vibration itself are being studied and are all found to influence the lifetime.

This paper is very well and logically written, the experimental part is clear and well carried through and is extensive. There are two remarks that I would like to make: first, the author mentions the importance of this phenomena in the chemical micro fluidic applications; it would have been great, to either supply a reference to such applications or say a few more words on how exactly is this phenomena used. Second, it is not very clear which parts of the work described by the author were cited and which innovated. Typically this separation is achieved by having a previous work section in the beginning where all previous work would go (see last paragraph of the conclusion), and explicitly stating the innovation in the introduction.