BETWEEN BOUNCING AND SPLASHING: WATER DROPS ON A SOLID SURFACE

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Abstract. A water drop falling on a super-hydrophobic surface can exhibit two qualitatively different types of behavior: bouncing (small Weber numbers) and splashing (large Weber numbers). In this paper, we examine the boundary between these two regions. The discussion is based on experimental observations.

1. Introduction

The impact of a liquid drop with a solid surface is a phenomenon that can be observed in many instances in everyday life, such as with rain falling and in a shower. The time scale of the process is of the order of a fraction of a second, so that the naked eye can hardly catch the dynamics of the interaction. A high speed camera reveals an interplay between several parameters, the most important being the surface tension, viscosity, and velocity of the drop at impact.[1]

Three types of behavior. In general, three different types of behaviors are observed: splashing, spreading and bouncing [1]. Splashing is observed on an automobile windshield in the rain, when the shock energy overcomes the cohesion of the surface tension, and the drop breaks into many droplets. Bouncing occurs most readily on hydrophobic surfaces (capillary forces on hydrophyllic surfaces may prevent the drop from leaving the surface), such as plant leaves and bird feathers, when the velocity of the drop at impact is not too high. Spreading is commonly observed with water drops in a bathtub or any other wetting surface, as well as with any viscous fluid, such as honey.

Overview of the process. The three kinds of energy in play are the kinetic energy, the surface energy of the drop, and the energy of internal motion of the fluid (actually, there are two different kinds of internal motion: macroscopic—turbulences, and microscopic—heat, produced by viscosity).[2] Surface energy gives rise to an an elastic force, while internal energy is produced by dissipative forces.

Prior to the impact, the drop only possesses kinetic energy. After it touches the surface, the drop is deformed so that a shock wave spreads radially outward near the surface, increasing the surface area of the drop, thus increasing its surface energy. A part of the initial energy is lost to internal energy (either as heat by

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[1] Another other physical quantity that can significantly affect the behavior of the drop during impact is the temperature of the surface,but we will only consider surfaces at room temperature.

[2] We neglect potential energy, which does not significantly contribute to the behavior during the time of contact.

viscosity or in turbulences), but for water, due to its low viscosity, dissipation will typically be low.

For moderate initial energies, the surface tension will be able to absorb the initial kinetic energy like a spring, and the restitution force will cause the drop (which is in pancake-like form at maximum elongation) to recoil. The motion is now radially inward, and when the drop shrinks and gains kinetic energy, a jet rises in the center (Worthington jet) which can lead to a lift off of the whole drop, and the drop bounces.

For higher energies, the surface tension is not sufficient to stop the outward motion as the drop spreads upon impact. As a rim is formed and the central part of the drop flattens, so-called fingers form along the edges. The outward velocity of the fluid in those fingers is such that they overcome the surface tension and break away from the surface, forming small droplets.

Dimensionless variables. The physical parameters are expressed in terms of several dimensionless variables. The Weber number is a measure of the ratio of the kinetic energy and surface tension, and is defined as

$$We = \frac{\rho v^2 d_0}{\sigma}\,, \tag{1}$$

where ρ is the fluid density, v is the velocity at impact, d_0 is the drop diameter before impact, and σ is the surface tension. Other dimensionless parameters, such as the Reynolds number and the capillary number, take into account the fluid viscosity, but as we use a low viscosity fluid (water), our considerations will be based mainly on the Weber number.

Super-hydrophobic surfaces. Materials that repel water on a molecular level are called hydrophobic. Water drops on surfaces made of such materials make large contact angles. An example of a hydrophobic material is wax, and both plants and birds use wax-like layers and secretions to repel water. However, both birds and plants use more than just the properties of the material to repel water efficiently: by using microscopically rough surfaces covered with a hydrophobic material, the contact angle is dramatically increased, and can be as high as 170° [2]. The roughness containes microscopic cavities, so that pockets of air are trapped between the surface and the drop [3]. Such surfaces are called super-hydrophobic.

Bouncing and splashing on super-hydrophobic surfaces. Bouncing and splashing are particularly easy to achieve on super-hydrophobic surfaces. The reason is obviously that there is little interaction with the surface, which might otherwise prevent the drop from leaving the surface (bouncing), or breaking apart (splashing). As noted above, bouncing is expected for lower impact velocities, and splashing for higher ones. It is natural to ask what lies in between these two limits, which are two qualitatively different types of behavior. Is there a sharp or gradual transition between bouncing and splashing? In either case, what does the behavior look like in that region? It is these questions that we set out to answer.

2. Methods

Setup. The experiments were conducted on a microscope slide treated with soot from a burning candle covered with eight light, evenly-sprayed applications of a brand shoe protectant.[3] The water-repellant in the shoe protectant was the hydrophobic material, while the role of the soot underneath was to provide a roughness to the surface, creating a super-hydrophobic surface. All trials were performed on the same microscope slide, which was positioned on two machine-planed wooden blocks sitting on a horizontal glass surface.

Drop administration was performed by rendering a 10ml pipette stationary a certain height from the slide. The experimental heights were recorded by measuring the distance between the tip of the pipette and the surface. All drops were taken from the same sealed water sample and administered by the same pipette with the same tip measuring 1.54mm O.D. The pipette was manipulated and most measurements were independently performed by both authors.

The impacts were captured by a Photron high-speed camera with a Nikon lens positioned such that the lens axis was aligned with the aloft slide at a lens-to-subject distance of 32cm. The lens was opened to f3.5 and each recording was performed at a frame rate of 1000 frames per second. Lighting was provided by two 1000W lamps stationed 98cm behind the subject with three diffusers.

Experiments were performed at each drop height a minimum of three times; more if the bounce behavior exhibited by drops at a specific release height appeared inconsistent. Various release heights were chosen to reflect the three encountered bounce behaviors, with more experiments performed closely around the hypothetical critical height between breaking and remaining whole.

Analysis. Measurements of drop sizes and contact angles were achieved by using an image analysis software capable of performing measurements.[4] The velocity of the drops was measured using a video analysis software capable of performing tracking[5] and exporting the results of the tracking to spreadsheets.[6] The velocities were measured for a sampling of release heights. The data was manipulated and stored in a spreadsheet. Curve-fitting and graphs were produced with the use of a numerical analysis program with curve-fit capabilities.[7]

3. Results

Contact angle. The contact angles were measured for eight different trials sufficiently long after the impact. The obtained value was $149.8° \pm 0.8°$.

Velocity at impact. Photron Motion tools provided a quite consistent tracking of the drop in time, which was used to calculate the velocity at impact. Figure 1 shows a distribution of the height from which the drop was released as a function of impact velocities, juxtaposed with a second degree polynomial fit. The fitted curve was used to estimate impact velocities for the remaining measurements.[8]

Contact time. The time from the moment when the drop touched the surface until the moment when it left the surface bouncing was measured for each experiment

[3] Kiwi Suede and Nubuck Protectant and Cleaner, Kiwi Brands Inc., Division of Sara Lee Corporation, Douglassville, Pennsylvania.

[4] Scion Imaging Software, Scion Corporation, Frederick, Maryland.

[5] Photron Imaging Software, Photron, San Diego, California.

[6] Microsoft Excel, Microsoft Corporation, Redmond, Washington.

[7] Matlab, The MathWorks, Inc., Natick, Massachusetts.

[8] Fitting was used rather than the free-fall formula $v = \sqrt{gh}$, because effects of air resistance were apparent in the measured velocities.

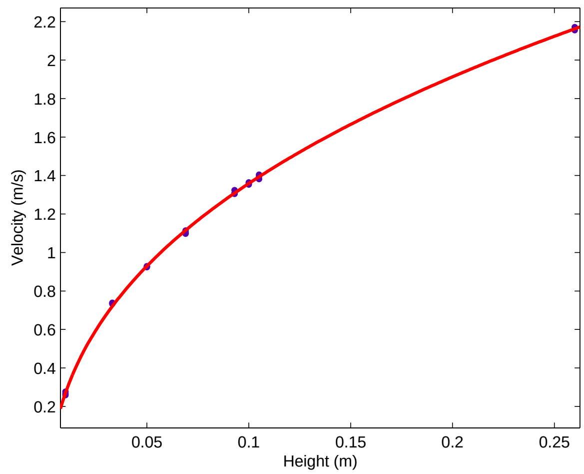

Figure 1: Height from which the drop was released as a function of the velocity at impact. The fit shown above is a quadratic fit, indicating that the height scales with the square root of the impact velocity of the drop. The shown fit is the inverted quadratic fit $h = 0.06002v^2 - 0.01509v + 0.01069$ with $R^2 = 0.9993$

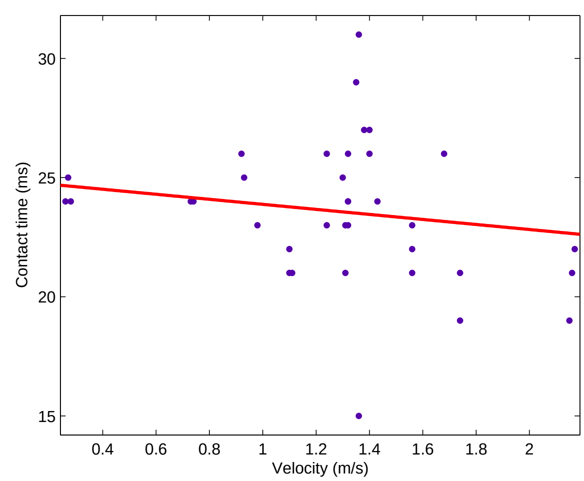

Figure 2: Contact time as a function of impact velocity. The fit shown is a linear relationship whose slope is nearly zero. This indicates an independant relationship between contact time and impact velocity. Fit shown is $t_{\text{contact}} = -0.001267v + 24.97$ with $R^2 = 0.1164$.

and the plot against the impact velocity is shown in Figure 2. The measurements of contact time were performed by counting the frames in the video in which the drop is in contact with the surface. The accuracy of the measurements is limited by the shortness of the contact time ($\sim$ 24ms) in terms of the temporal resolution of the camera (1ms).

Drop deformation. The maximum diameter—the size of the drop at its most flattened form, at the point where it stopped expanding and is about to start contracting—was measured in each experiment, and a plot of the results versus the impact velocity is shown in Figure 3. The size of the drop was normalized with respect to the diameter of the drop prior to impact.

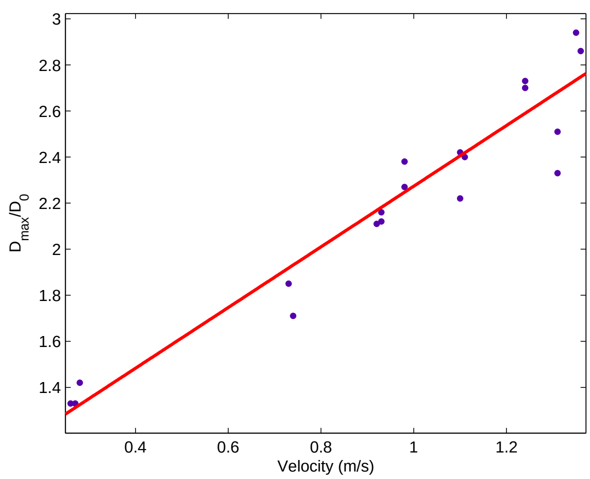

Figure 3: Normalized maximum deformation as a function of impact velocity. The fit shown is a linear relationship. This indicates that the maximum deformation scales linearly with impact velocity, and by extension, with $\sqrt{We}$. Fit shown is $D_0/D_{\max} = 1.317v + 0.956$ with $R^2 = 0.9116$

Qualitative behavior. The observed behaviors are summarized in Table 1. We classify the behaviors into two groups, *bouncing* and *splashing* according to *how the drop splits*: if droplets are separated as a result of radial motion along the surface, we call that *splashing*; otherwise the drop is *bouncing*, in which a smaller drop may be separated on the top of the jet-like shape as a result of vertical motion. Note that even in what is here defined as splashing, there is typically a part of the drop that remains in the center and bounces.

Since all other parameters in (1) are constant for all trials, we use the relative Weber number $We_{\text{rel}} = v^2 d_0$.

Table 1: Behaviors observed for various impact velocities and drop sizes. The "Split parts" column combines the splitting of the drop after bouncing the first time and the estimate of droplets created after splashing (0 = the drop stayed together, 1 = drop split into two parts, few < several < many < myriad). The "Bounce height" column measures the maximum rebound height of the bottom part of the largest drop after the first bounce.

We_{rel} ($10^{-3}\text{m}^3\text{s}^{-2}$)	h (mm)	Bounce or Splash	Split parts	Bounce height (mm)
0.27	10	bounce	0	2
0.27	10	bounce	0	3
0.30	10	bounce	0	2
2.07	33	bounce	1	5
2.13	33	bounce	1	5
3.31	50	bounce	1	4
3.31	50	bounce	1	4
3.34	50	bounce	2	5
3.70	60	bounce	1	7
3.70	60	bounce	2	6
3.77	60	bounce	2	7
4.67	69	bounce	2	5
4.86	69	bounce	0	6
4.93	69	bounce	0	6
6.04	85	bounce	1	4
6.09	85	bounce	2	7
6.26	85	bounce	1	5
6.32	100	splash	2	4
6.41	93	bounce	0	4
6.64	93	bounce	1	5
6.72	93	splash	4	2
6.88	93	splash	1	3
6.91	93	bounce	0	3
6.91	93	splash	2	3
7.01	93	splash	2	2
7.36	100	bounce	0	2
7.49	100	bounce	0	2
7.56	105	splash	few	2
7.59	105	splash	4	3
7.74	105	splash	2	2
8.17	105	splash	4	2
9.67	120	splash	several	4
9.75	120	splash	many	5
9.95	120	splash	several	3
11.86	145	splash	many	4
12.30	145	splash	many	3
20.44	260	splash	myriad	6

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We_{rel} $(10^{-3}\mathrm{m}^3\mathrm{s}^{-2})$	h (mm)	Bounce or Splash	Split parts	Bounce height (mm)
20.48	260	splash	myriad	4
20.63	260	splash	myriad	5

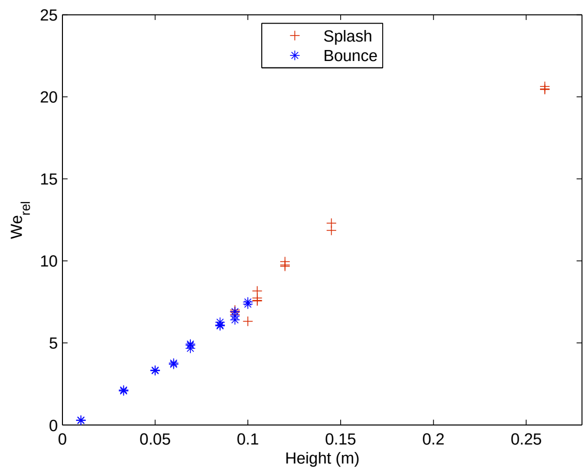


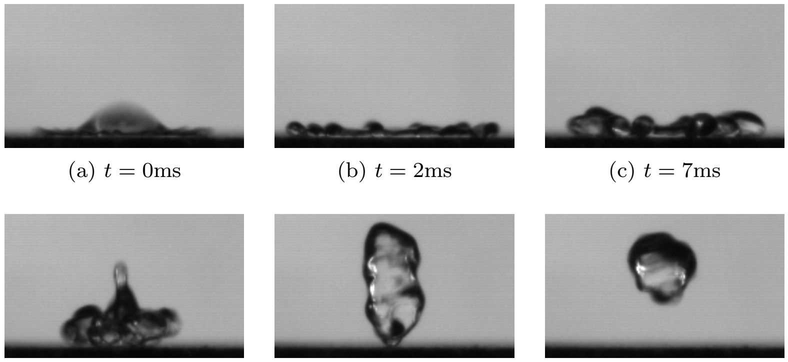
Figure 4: Types of behaviors in terms of the height and the Weber number. The drops observed to splash are represented as data points with plus signs and the drops observed to bounce are represented as data points with asterisks. The drops bounce for smaller relative Weber numbers and splash for larger relative Weber numbers. For heights 10cm $\pm$ 0.7cm both splashing and bouncing were observed. (The data plotted is contained in the first three columns of Table 1.)

4. Discussion

Contact time. Within the range of velocities measured (~ 0.2–2m/s), the contact time is independent from impact velocity (Figure 2) within the accuracy of the measurements (see the remark on contact time measurement precision on page 5). This coincides with the results obtained by Richard et al. [4], who used the same range of velocities.

Maximum diameter. As seen in the results section, the normalized maximum diameter of a drop's deformation upon impact was linearly related to the impact velocity (Figure 3).[9] This verifies the findings of Okumura et al. [5].

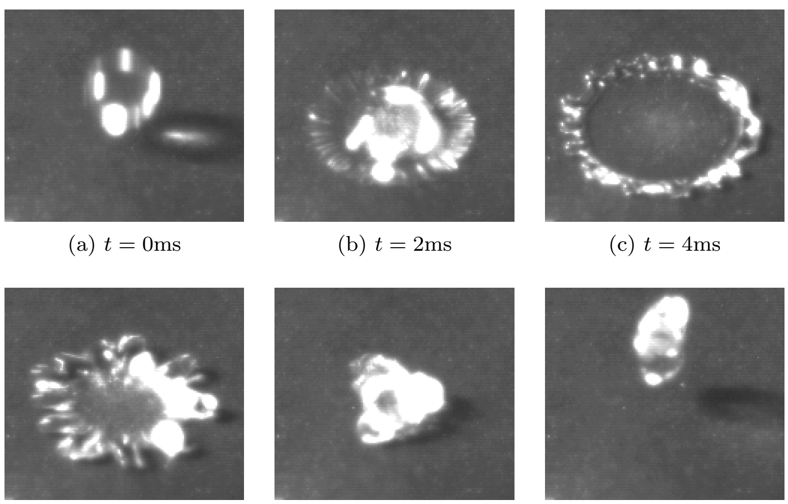
[9] Only trials without splashing were used.



(a) $t = 0$ms (b) $t = 2$ms (c) $t = 7$ms

(d) $t = 12$ms (e) $t = 24$ms (f) $t = 32$ms

Figure 5: Impact of a water drop released from the threshold height of 100mm. The fingers in 5b are distinctive, but they do not separate. The drop pulls back together and bounces up, remaining in one piece at all times. Picture 5f shows maximum rebound height.



(a) $t = 0$ms (b) $t = 2$ms (c) $t = 4$ms

(d) $t = 7$ms (e) $t = 11$ms (f) $t = 14$ms

Figure 6: Impact of a water drop released from the threshold height of 100mm, viewed from above.

Qualitative behavior. As predicted, the drop bounces for smaller Weber numbers and splashes for larger ones. In a certain interval of Weber numbers though, both behaviors are observed. The degree of oscillation of the drop prior to impact is a parameter that we were unable to control, and which we have not measured, and it may have contributed to a drop with a somewhat smaller Weber number splashing, while one with a larger Weber number did not. For values of the relative Weber number around 7 in Table 1, the drops in some trials exhibited a peculiar behavior: fingers were forming along the edge of the rim, but they did not have enough kinetic energy to break away from the drop. Instead, as they were pulled back by the surface tension, they were lifted above the surface and broke towards the center. This behavior is shown in Figures 5 and 6. The drop remained in one piece at all times, and the bounce height was the lowest recorded — in fact it was of the same order as for the lowest incoming velocities, in which the drop was released from a height that is 10 times lower. This suggests that roughly 90% of the incoming kinetic energy is dissipated into internal turbulent motion.

This threshold is quite distinctive both by its qualitative behavior and by this high dissipation of energy into internal turbulent motion. For smaller Weber numbers, despite the smaller incoming kinetic energy, the drop rebounds higher, and usually splits in the air, whereby the breakaway fraction typically rebounds much higher than the remaining drop. For larger Weber numbers, splashing occurs, where breakaway droplets leave taking some kinetic energy with them, but still the central drop rebounds higher than at the threshold. It was noted that the remaining part of the drop after splashing oscillates more vigorously after the rebound than when no splashing occurs,[10] which leaves even less available energy for internal turbulent motion.

Since the drop bounces so little at this threshold (the height of the rebound is of the order of the drop's diameter), it could be said that this is the boundary behavior between bouncing and splashing.

Suggestions for further experiments. An important limitation of our experimental setup was the lack of control over drop production. The pipette was manipulated by hand, and oscillations were imparted onto the drops as they left the pipette tip. These oscillations are very much undesired, since they break the symmetry of the system, and the irregularity of the drop's motion is dramatically amplified after bouncing. This means that a significant portion of the energy after bouncing is converted to oscillation energy, which is difficult to measure.

If these oscillations were not present, it would be interesting to measure the restitution coefficient as the impact velocity increases from smaller values towards the critical splashing value. What could be inferred from the discussion above is that the restitution coefficient should decrease as the splashing threshold is approached (despite larger kinetic energies), since increasingly more energy is dissipated in internal motion.

References

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[10] This is intuitive due to the perturbations caused by the break off of droplets.