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ABSTRACT
We investigate the dynamics of a drop containing a single solid particle impacting on a solid surface. The particle rebounds through the drop during impact and can separate from the deposited liquid above an impact velocity threshold. We show that this threshold can be predicted by a simple energy balance. Moreover, we discover a new type of liquid jetting ejected above the particle faster than the impact velocity. We demonstrate that this jetting is due to the focusing effect of the liquid on the solid substrate below the rebounding particle. Although the wetting properties of the particle have a minor effect on the separation threshold, they play a key role in the liquid jetting by affecting the immersion depth of the particle at the time of impact.

The impact of a liquid drop on a solid surface has received a large amount of attention due to its wide range of applications, from combustion to spray coatings or forensic science. In many industrial processes, such as inkjet printing or additive manufacturing of ceramics and cements, the impacting liquid drop contains solid particles. For these applications, it is important to understand how the presence of the particles can affect the deposition dynamics, as well as how to prevent the splashing of the particles during the impact.

Recent studies have focused on the impact of drops containing a large number of particles. For small particles compared to the size of the drop, the dynamics of the liquid in the drop can be understood as a homogeneous liquid phase. As the particles’ sizes increase, they can affect the spreading of the drop and form clusters in the final splat. If the particles are located at the interface of the drop, they form a liquid marble that can rebound from the solid surface or break up during impact. Individual particles can be ejected at higher impact velocities and modify the splashing dynamics. The separation of the particles can be observed when the inertia of individual particles overcomes the surface tension energy barrier and the viscous dissipation of the liquid.

In this letter, we propose to investigate the fundamental problem of the particle separation from the impacting drop by placing a single particle on the surface of the impacting drop. The particle is suspended below the drop by surface tension, before it is released to fall onto the solid surface. We focus on the separation threshold of the particle and the jetting produced above the separation threshold. We demonstrate for the first time a new jetting mechanism produced vertically above the impacting drop, where the liquid
can be ejected ahead of the particle even faster than the impact velocity. This jetting is strongly affected by the wetting properties of the particle.

**Experimental setup.** A small pendant drop of Milli-Q water is first produced below a nozzle with an outer diameter of 1.25 mm, connected to a syringe pump by a tube. A solid particle is inserted below the pendant water drop where it stays attached by surface tension \(^{33–35}\) [Fig. 1(a)]. The formed compound drop is then released by injecting more water through the nozzle in a quasisteady way until it falls by gravity.

We record the impact on a microscope glass slide from the side with a high-speed camera (Photron SA-Z) connected to a macro lens (Leica Z16 APO) at a frame rate of 20 000 frames/s [Fig. 1(b)]. The light is provided by a cold light source (Sumita LS-M352A) reflected by a diffuser (tracing paper) on top of a mirror to improve the transparency of the drop. Both the glass slides and the particles were cleaned before the experiments in two successive ultrasonic baths with isopropanol and ethanol. The resulting contact angle between water and the slides \(\theta_0\) was about 30°, while the contact angle between water and the solid particle \(\theta_p\) varied with the material of the particle, as reported in Table I. The impact velocity \(V\) is varied by adjusting the falling height \(V = 0.4–3.0\) m/s. The nondimensional time \(t^*\) is defined as \(t^* = t/\tau\), where \(\tau = D_p/V\) with \(D_p\) being the diameter of the impinging drop and \(t^* = 0\) is the time when the particle first touches the solid surface.

**Particle separation.** The particle first impacts on the solid substrate, from which it rebounds vertically (Fig. 2). The liquid then impacts on the glass slide along a circle around the particle, entrapping a bubble behind the rising particle. While the liquid spreads on the solid surface, the particle travels vertically through the drop, followed by the entrapped bubble, and eventually emerges vertically from its apex. At low impact velocity, the particle cannot separate from the drop [Fig. 2(a) (multimedia view)]. It rises above the spreading drop but is then pulled back by the liquid bridge connecting it to the deposited liquid. Above a threshold velocity, the liquid bridge pinches off, leading to the separation of the particle from the main drop [Fig. 2(c) (multimedia view)]. In contrast, a water drop produced with the same nozzle but without the particle never deforms vertically during the spreading phase as observed in the cases with the particle [Figs. 2(b), 2(d), and 2(f)].

**TABLE I.** Properties of the cleaned particles without surface treatment. The restitution coefficient \(\beta\) was calculated by high-speed imaging experiments of dry particle impacts, with dispersion less than 6%. The size of the separated liquid around the particle \(aD_p\) was measured by three repetitions just above the separation threshold, and the dispersion of \(a\) is within 4.5%. \(\theta_p\) is the contact angle between the particle and water, measured from the images before impact.

| Material      | \(\rho_p\) (kg/m\(^3\)) | \(D_p\) (mm) | \(\beta\) | \(\alpha\) | \(\theta_p\) (deg) |
|---------------|--------------------------|--------------|-----------|-----------|------------------|
| Cellulose acetate | 1299                     | 1            | 0.770     | 1.79      | 86               |
| Glass         | 2300                     | 1            | 0.881     | 1.41      | 73               |
| Silicon nitride | 3500                     | 1            | 0.868     | 1.38      | 36               |
| Zirconia      | 6500                     | 1            | 0.862     | 1.35      | 67               |
| Steel         | 7800                     | 0.15–1       | 0.826     | 1.40      | 69–98            |

This suggests that the particle can separate only if the kinetic energy of the particle can overcome the additional surface energy produced by its separation. If we neglect the viscous dissipation and added mass around the particle moving in the drop liquid, the particle velocity before separation can be estimated as the velocity after rebound, captured by its restitution coefficient \(\beta = V_r/V_i\), the ratio between the rebound velocity of the particle \(V_r\) and its impact velocity \(V_i\). After pinch-off, some liquid and an air bubble separate together with the particle, leading to a total size \(aD_p\) separating from the drop, with \(D_p\) being the particle diameter. The values of \(\beta\) and \(\alpha\) are reported in Table I. The energy balance at the critical velocity can thus be written as

\[ \frac{1}{2} m_p (V_r)^2 = \pi (aD_p)^2 \sigma, \]

where \(m_p\) is the mass of the particle and \(\sigma\) is the water surface tension. The critical velocity is therefore

\[ V_i = \frac{\alpha}{\beta} \sqrt{\frac{12 \sigma}{D_p \rho_p}}. \]  

In the nondimensional form, this corresponds to a critical particle Weber number,

\[ We_p = 12 \left( \frac{\alpha}{\beta} \right)^2, \]

where \(\rho_p\) is the density of the particle. A critical \(We_p\) was also previously demonstrated to characterize the splashing onset produced by the separation of the particles from an impacting drop containing many particles.\(^{20}\)

We can verify systematically this threshold by varying the particle size and density, using different materials as listed in Table I. We observe that the critical impact velocity decreases when the size and density of the particle increase [Figs. 3(a) and 3(b)]. The transition is very well captured by Eq. (1), without any adjustable parameter, except for the lowest density particles (cellulose acetate). In that case, the impact velocity required for the particle separation increases up to \(V \approx 1.5\) m/s where the morphology of the particle separation changes. The liquid emerging together with the particle from the apex of the drop is already affected by the liquid jetting, increasing the volume separating with the particle. The values of \(\alpha\) measured experimentally therefore do not reflect the energy necessary for

![FIG. 1.](image-url)
particle separation, but rather some energy coming from the liquid jetting. The particle also starts shifting off-center before impact at that impact velocity. Using the same typical value of $\alpha$ observed for other particle densities very well predicts the separation threshold (blue line).

In contrast, the drop diameter and the wetting properties of the particle play a weaker role on the threshold [Figs. 3(c) and 3(d)] and are absent in Eq. (1). The threshold was slightly larger for particles with a larger contact angle. In that case, the measured $\alpha$ increased only by less than 3% for the hydrophobic particles, which could not

FIG. 2. Impact of a water drop containing a steel particle with diameter $D_p = 1$ mm, $D_d = 3.19$ mm, $\theta_p = 141^\circ$, and $\theta_s = 30^\circ$. [(a), black filled square] The particle stays in the deposited liquid: $V = 0.74$ m/s, $W_e = 59$, at $t^* = 0, 0.37, 1.58, 2.37, 3.35$, and 5.36. [(c), red filled up-pointing triangle] Particle jetting: $V = 0.79$ m/s, $W_e = 66$, $t^* = 0, 0.36, 1.57, 2.35, 3.37$, and 3.86. [(e), blue filled circle] Liquid jetting: $V = 2.36$ m/s, $W_e = 603$, $t^* = 0, 0.19, 0.69, 1.17, 1.67$, and 1.95. [(b), (d), and (f)] Impact of a water drop produced from the same nozzle without the particle, at the same impact velocities and times as the above cases with particles. The resulting drop size is slightly larger than the drop produced with a particle attached: $D_d = 3.34$ mm. The scale bar is the same for all panels: 1 mm. Multimedia views: (a) https://doi.org/10.1063/1.5139534.1; (c) https://doi.org/10.1063/1.5139534.2; (e) https://doi.org/10.1063/1.5139534.3

FIG. 3. Separation threshold of the particle. The transition (green filled diamond) corresponds to cases for which the separation is not repeatable, $\theta_s = 30^\circ$. (a) Effect of the particle size on separation, $\rho_p = 7800$ kg/m$^3$, $\theta_p = 98^\circ$. The blue line is the theoretical separation velocity from Eq. (1). (b) Effect of the particle density on separation, $D_p = 1$ mm, $\theta_p = 36^\circ$–$98^\circ$ (see Table I). The same theoretical separation velocity as in (a) is added for comparison ($\alpha = 1.4, \beta = 0.826$). (c) Effect of the drop size for $D_p = 1$ mm, $\rho_p = 7800$ kg/m$^3$, $\theta_p = 98^\circ$. (d) Effect of the particle contact angle for $D_p = 1$ mm, $\rho_p = 7800$ kg/m$^3$. Error bars from the dispersion on $\alpha$ and $\beta$ are indicated as dashed lines in (a) and (b).
be the reason for this higher threshold. It could be explained by the additional traveling distance of the particle through the drop, the larger added mass effect due to the presence of a larger bubble behind the particle, or the higher energy needed for a hydrophobic particle to enter the liquid after impact.36

Jetting. Just above the separation threshold, the attached liquid and air bubble stay around the separated particle, which we call particle jetting [Fig. 2(c) (multimedia view)]. As the impact velocity increases further in Fig. 2(c) (multimedia view), the bubble bursts after the particle emerges above the drop and more violent jetting can be observed. The liquid is ejected ahead of the particle, with a maximum liquid jetting velocity \( V_j^* \approx 1.4 \) times larger than the impact velocity \( V \) [Figs. 2(e) and 4(a)].

We can quantitatively characterize the transition between particle jetting and liquid jetting by comparing the height of the liquid jet to the position of the particle at \( t^* = 2 \): if the liquid is more than one particle diameter above the particle, it is defined as liquid jetting; otherwise, it is particle jetting. We also systematically measured the maximum jetting velocity \( V_j \) for four different particle densities over a range of impact velocities [Fig. 4(b)]. The nondimensional maximum jet velocity increases with the impact velocity, before decreasing. The liquid is ejected above an impact velocity \( V \approx 1.5 \) m/s and is consistent with a maximum jet velocity larger than one. The decrease observed at higher impact velocities corresponds to unavoidable horizontal shifting of the particle below the drop due to the air drag [Fig. 4(c) (multimedia view)].

The exit dynamics of a solid sphere from a water-air interface has been studied experimentally by Truscott, Epps, and Munns.37 However, they did not observe the same type of liquid jetting as we did. They did not observe similar phenomena, and their maximum measured impact velocity \( V \approx 1.4 \) times larger than the impact velocity \( V \) in their experiments [Fig. 2(f)].

To identify the mechanism responsible for the liquid jetting, we can follow in more detail the dynamics of the liquid impact on the solid surface in Fig. 6. As the particle rises through the drop, the liquid separates from the solid particle to impact on the solid surface around a circle of similar size as the particle \( r^* = 0.22 \). At the time of the liquid-solid surface contact, the solid has already traveled some distance upward, thus entrapping an air cavity behind. The liquid impacting vertically on the solid surface can thus produce a horizontal lamella both outward, as observed classically for liquid drop impacts, and inward, due to the available space created by the air cavity. The lamella converging inward on the solid surface eventually focuses to the center of the drop, where it forms a jet emerging vertically behind the particle as observed in the third frame at \( t^* = 0.30 \). The liquid jetting is therefore due to the inertial focusing of the liquid at the center of the drop, shooting upward behind the particle when it reaches the center. The jet then travels around the sphere, and the jet velocity observed above the particle is strongly reduced compared to its initial velocity [Fig. 6(b)].

According to this liquid jetting mechanism, the contact angle \( \theta_i \) of the liquid on the impacted surface should not have any effect on the jetting dynamics. Although the dynamic contact angle can affect the splashing of the outward lamella,38,39 it does not influence its velocity and should therefore not affect the inertial focusing at the center. To verify this hypothesis, we have modified the substrate wettability from hydrophilic \( (\theta_i = 30^\circ) \) to hydrophobic \( (\theta_i = 106^\circ) \) and repeated the experiments of Figs. 5(a) and 5(b), as presented in Figs. 5(c) and 5(f). No significant difference could be identified on both the jetting velocity and the separation threshold.

### Figure 4

Jetting of the drop containing a particle, \( \theta_i = 30^\circ \). (a) Typical time evolution of top liquid and particle velocity, corresponding to Fig. 2(e) \( V^* = V/V \). (b) Maximum jet velocity \( V_j^* = V_j/V \) and type of jetting, for \( D_3 = 1 \) mm and four different particle densities \( \rho_p \) (kg/m³): 2300 (yellow), 3500 (empty), 6050 (green), and 7800 (full), \( \theta_i = 36^\circ–98^\circ \) (see Table I). (c) Impact dynamics with an off-center particle corresponding to the circled triangle in (b). \( D_3 = 1 \) mm, \( \rho_p = 2300 \) kg/m³, \( V = 2.45 \) m/s, \( t^* = 0, 0.19, 0.4, 0.48, 1.03, 1.35, \) and 1.76. Scale bar: 1 mm. Multimedia view: (c) https://doi.org/10.1063/1.5139534.4
The liquid jetting mechanism discovered here can be compared with other types of jets previously observed in the literature. A vertical liquid jet, with maximum jet speed larger than the impact velocity, was also observed by Bartolo, Josserand, and Bonn following the impact of a drop on a hydrophobic surface. In their experiments however, the jetting was produced during the retraction of the drop on the surface, while the jet we observe here is formed at a much earlier time during the spreading of the liquid. It is also well known that...
that the bursting of a bubble at a pool surface can also produce a fast vertical jet.\textsuperscript{41,44} The liquid jetting observed in our experiments could seem similar at first sight, as it emerges from the apex of the drop together with a bursting bubble. However, the images in Fig. 6 clearly demonstrate that the liquid jet is formed within the cavity behind the rising particle even before the bursting of the bubble and is therefore due to a different mechanism. In our experiments, the jet is formed after the impact of the liquid lamella focusing radially, closer to the high-speed jet formed after the impact of a disk\textsuperscript{5} rather than the collapse of a cavity from its bottom.\textsuperscript{9}

It would be interesting to compare the maximum jet velocity produced by this focusing of the liquid on the solid surface in our experiments with jets previously observed in the literature. However, it is produced inside the air cavity within the drop, where it is very challenging to measure due to the curved liquid interfaces. We can still estimate the jet velocity behind the particle by measuring the jet position when it reaches the center of the drop, where the interface is nearly vertical. In Fig. 6, this jet velocity is about 4.2 times the impact velocity, while the jet emerges from the drop apex above the separating particle at a distance of 1.6. The maximum jet velocity\textsuperscript{41} we have characterized earlier is therefore not representative of the maximum jet velocity produced within the drop, due to the losses for the jet to overcome the solid particle.

Conclusions. We have characterized in this letter the conditions for which a particle in an impacting drop will be ejected away from the deposited liquid and demonstrated a new jetting mechanism where the liquid is ejected faster than the particle. We have derived a theoretical expression for the separation threshold and explained the mechanism behind the jetting observed. This fundamental study still needs to be expanded to the case where the particle is completely covered by the drop liquid and to the more general case of having multiple particles in the drop to bridge the gap toward the understanding of general impact of drops containing particles. Beyond the vertical dynamics observed in this letter, it would also be interesting to investigate how the horizontal splashing of a drop on a solid surface at high impact velocities would be affected by the presence of the particle.

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