Oscillation and Recoil of Single and Consecutively Printed Droplets
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ABSTRACT: In this study, the recoil and oscillation of single and consecutively printed drops on substrates of different wettabilities are examined using a high-speed camera. The results show that, for a droplet impact on a dry surface at Weber number $\sim O\left(1\right)$, both inertia and capillary effects are important in the initial spreading regime before the droplet starts to oscillate. For a substrate of higher wettability, drop oscillation decays faster due to a stronger viscous dissipation over a longer oscillation path parallel to the substrate. It is also found that when a drop impacts on a sessile drop sitting on a hydrophobic substrate, the combined drop recoil twice resulted from the coalescence of the two drops, whereas no recoil is observed for the impact of a single drop on a dry surface under the same condition. Furthermore, a single-degree-of-freedom vibration model for the height oscillation of single and combined drops on a hydrophobic substrate is established. For the condition considered, the model predictions match well with the experiments. The results also show the extent to which the increase in the liquid viscosity facilitates oscillation damping and the quantitative extension of the oscillation time of a combined drop compared to a single drop.

1. INTRODUCTION

Drops impacting on a dry or a wet surface can result in different morphologies, from spreading and splashing to receding and rebounding, depending on the impact velocity, drop size, and properties of the liquid and substrate.1 Yarin2 carried out a detailed review of drop impacts on a solid substrate and on a shallow liquid film. The majority of studies focused on high-Weber-number drop impact that leads to a crown-shaped splash.3−6 However, for applications such as inkjet printing and spray deposition, low-Weber-number impact leading to drop spreading or “deposition” is a preferred process for material deposition. Drop spreading dynamics and the subsequent relaxation of low-Weber-number impact are important for a better control of the deposition morphology.

For the regime of “deposition” impact, the drop spreading dynamics can be separated into five consecutive phases: kinematic, spreading, relaxation, wetting, and equilibrium (see Figure 1).7 In the kinematic phase upon drop impact, the drop spreading radius increases with $t^{0.5}$ until it reaches the drop in-flight radius. In the following drop spreading phase, the contact line advances under the influence of surface tension, viscosity, and drop impact velocity. When the drop impact kinetics is either consumed by viscous dissipation, transferred into surface energy, or the combination of both, the drop reaches its minimum height and the drop spreading radius at the end of the spreading phase is often referred to as the primary spreading radius. With the drop transitioning into the relaxation phase, the air−water interface oscillates and pushes the liquid to flow both radially and vertically inside the drop. Drop recoil can occur during this phase and recoil becomes more significant with the decrease in substrate wettability8,9 and Ohnesorge number ($Oh = \mu/(D_0 \eta g)^{1/2}$) or with the increase of the Weber number ($We = \rho D_0 U^2/\sigma$).10 Here, $\rho$ is the liquid density, $D_0$ the drop in-flight diameter, $\mu$ the liquid viscosity, $U$ the impact velocity, and $\sigma$ the surface tension. Drop oscillation then gradually decays by viscous dissipation, and the drop reaches a spherical cap shape at the end of the relaxation phase. Additional spreading occurs in the wetting phase until the drop reaches its equilibrium contact angle. In the wetting phase, the drop spreading radius versus time for a nonevaporative

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drop on a very hydrophilic substrate follows the Tanner’s Law, \[ R \approx \frac{\theta}{\rho g} \], as a result of the competition between surface tension and viscosity.

For a single droplet impact onto a sessile drop of \( We \gg 1 \), drop spreading dynamics is expected to be similar to a single drop impact on a thin liquid film. In both cases, the condition of the substrate plays an important role. Fujimoto et al. and van Dam and Le Clerc using inkjet-printed micrometer-sized droplets, strong surface tension effects upon impact lead to different droplet spreading and oscillation damping behaviors than millimeter-sized drops of large \( Re \) and \( We \) numbers. In such a regime, the inertia is more dominant than the surface energy. For inkjet-printed micrometer-sized droplets, strong surface tension effects upon impact lead to different droplet spreading and oscillation damping behaviors than millimeter-sized drops of large \( Re \) and \( We \) numbers.

Until now, most studies have been concerned with drop impact at large \( Re \) and \( We \) numbers (e.g., \( Re=\rho UD_l/\mu = 100–200 \) and \( We \gg 1) \). In such a regime, the inertia is more dominant than the surface energy. For inkjet-printed micrometer-sized droplets, strong surface tension effects upon impact lead to different droplet spreading and oscillation damping behaviors than millimeter-sized drops of large \( Re \) and \( We \) numbers.

Figure 2. Summary of the parameter space in a \( We–Oh \) plane for studies on inkjet-printed drops.

2. EXPERIMENTAL METHOD

In the experiments, picoliter drops were generated using a piezo-electric-driven ink jetting nozzle with a diameter of 60 \( \mu \)m (MicroFab MJ-AL-01). A Phantom v12.1 high-speed camera (Wayne, New Jersey) with a Navitar 12X Zoom lens (Rochester, New York) and a microscope excitation light source (X-Cite 120Q) were used to capture drop impact, spreading, and relaxation on a substrate with and without a predeposited sessile drop. Drop ejection and the camera system were synchronized with a delay generator (SRS DG645, Sunnyvale, California). Two drops with controlled temporal delay, created using a waveform generator (MicroFab Jethrive) and a delay generator, were printed consecutively on a substrate. Images were taken at 50,000 fps with pixel resolution of 256 \times 128 \( \mu \)m/pixel. To obtain better temporal resolution, the high speed camera is combined with the flash photography technique using different delay times between the camera exposure and drop ejection (e.g., 5, 10, and 15 \( \mu \)s), based on the high repeatability nature of the inkjet printing process.

Figure 1. Impact and spreading, has only been explored by Son et al. in inertia, capillary, and viscosity simultaneously. The substrate plays an important role. Fujimoto et al. and van Dam and Le Clerc using inkjet-printed water droplets on substrates with different wettabilities. The effects of surface tension and viscosity on drop oscillation and recoil, especially for consecutively printed drops, have not been investigated.

In this study, recoil and oscillation of inkjet-printed drops impact on a dry surface and on another sessile drop of the same liquid are examined using a high speed camera. Substrate wettability is systematically modified to reach 0–90° equilibrium contact angle while keeping surface roughness the same. Picoliter drops of water, water/glycerin mixture (W/G), and water/glycerin/isopropanol mixture (W/G/I) are used to independently examine the effects of surface tension and viscosity on drop relaxation. We focus on the low \( We \) number impact that results in drop deposition. Schematic illustration of droplet spreading radius as a function of time for drop impact on a hydrophilic substrate at low and high \( We \) numbers is shown in Figure 1. Due to different drop inertia, the kinematic, spreading, relaxation, and wetting phases for \( We \gg 1 \) and \( We \sim O (1) \) are expected to be different. Since the kinematic phase usually takes only \( \sim 10 \mu s \), at most one data point can be obtained within this time frame by changing the delay time between drop ejection and camera exposure. In addition, the initial drop impact becomes less important in the wetting phase. Much attention of this study is paid to the spreading and relaxation phases. The similarities and differences of drop impact on a dry surface and a sessile drop are presented. A single-degree-of-freedom vibration model is used to predict the height oscillation of single and combined drops on a hydrophobic substrate. The oscillation frequency and damping amplitude obtained from model predictions are in good agreement with our experimental results of drop oscillation on a hydrophobic substrate with and without a predeposited sessile drop.
assumed to be a spherical cap and the gravitational effect was neglected due to a very small Bond number ($Bo = \rho g D_0^2 / \sigma < 0.005$, where $g$ the gravitational acceleration).

The drop in-flight diameter and impact velocity were kept at 60 $\mu$m and 0.77 m/s, respectively. The ambient temperature maintained at 22 °C and the relative humidity was around 50% for all experiments. For a drop impacting on a dry surface, the starting time ($t = 0$) is defined as the bottom of the drop touches the substrate. Similarly, $t = 0$ for the case of a drop impacting on a predeposited sessile drop is when the second drop contacts the top of the first drop.

3. RESULTS AND DISCUSSION

3.1. Spreading and Oscillation of a Single Drop. 

a. Effect of Substrate Wettability. Figure 3 shows snapshots of a single DI-water droplet impact on substrates with equilibrium contact angle $\theta_{eq}$ of 0°, 45°, and 90°. Upon impact, the drop deforms under inertia until it becomes a disc like shape around $t = 25$ $\mu$s, where the drop reaches its minimum height. At this time, the drop kinetic energy is partly converted into surface energy due to increased surface area and partly consumed by viscous dissipation. It has been reported that, at a high Weber number ($We \gg 1$), inertia dominates the drop impact and during the initial spreading regime (the kinematic and spreading phases shown in Figure 1) the drop spreading kinetics, i.e., drop radius versus time, is independent of the substrate wettability. However, for low-Weber-number drop impact (e.g., $We = 0.49$ for DI-water droplets in this study), both inertia and capillary effects are important in the initial spreading regime. As shown in the drop spreading radius versus time plot of Figure 4a, in the initial fast spreading regime (from drop impact up to 18−33 $\mu$s, depending on the substrate wettability), the spreading radius $R$ versus time plot shows three different slopes for wetting angles of 0°, 45°, and 90°. The uncertainties of drop radius and height measurements are ±0.83 $\mu$m.

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substrate wettability is a result of the capillary effect in the initial spreading regime.

At the end of the initial spreading regime, drop reaches its minimum height (e.g., \(t \approx 25 \mu\text{s}\)) where the kinetic energy reduces to zero. However, at this stage, the shape of the drop is far from equilibrium. Due to inertia, a large amount of liquid in the drop is squeezed to the contact line region leading to a large curvature at the air–water interface near the contact line, which locally increases the liquid pressure. A pressure gradient is hence induced between the center and the periphery of the drop pushing the liquid to flow inward to the drop center until the drop reaches a maximum height (\(t \approx 45 \mu\text{s}\) in Figure 3) with a large local curvature at the center of the drop surface. A reversed liquid pressure gradient is then set up and causes an outward liquid flow until a large local curvature builds up again at the contact line region to stop the liquid motion. Under the effect of the surface tension and inertia, the liquid inside the drop oscillates back and forth between the contact line and the center of the drop in the relaxation phase until the oscillation is completely damped down by viscous dissipation and the drop shape reaches a spherical cap. It is important to note that, in contrast to the cases with \(\text{We} \gg 1\) where the contact line is often pinned during the drop relaxation phase of pico-liter drops, \(\text{for drops with We} \sim O(1)\), capillary spreading takes place during drop oscillation in this study. As shown in Figure 4a for the cases of \(\theta_{eq}^W \sim 0^\circ\) and \(\theta_{eq}^W = 45^\circ\), during the relaxation phase (from the end of initial spreading to about \(t = 100 \mu\text{s}\)), the drop spreading radius increases while the height of the drop oscillates, as shown in Figure 4b.

Figure 4b also shows that, upon drop impact, it takes a longer time \((\sim 270 \mu\text{s})\) for the viscous stress to dissipate the height oscillation of a drop impact on a hydrophobic substrate \((\theta_{eq}^W = 90^\circ)\). In contrast, for a hydrophilic substrate \((\theta_{eq}^W \approx 0^\circ\) or \(45^\circ)\), the stronger capillary spreading prior to the relaxation phase leads to a larger drop contact area on the substrate, which in turn increases the viscous dissipation and results in an relaxation phase of less than 100 \(\mu\text{s}\). This can also be clearly observed in Figure 3, where the drop shape changes between \(t = 145\) and \(165 \mu\text{s}\) on the substrate of \(\theta_{eq}^W = 90^\circ\) but not on the other two cases with \(\theta_{eq}^W \sim 0^\circ\) and \(\theta_{eq}^W = 45^\circ\).

After drop oscillation, the capillary effect dominates further spreading of the drop in the wetting phase until it reaches equilibrium. As shown in Figure 4a, for a hydrophilic substrate of \(\theta_{eq}^W \sim 0^\circ\), the contact line advances faster in the wetting phase due to a stronger capillary driving force, \(\theta^3 - \theta_{eq}^3\). For a hydrophobic substrate of \(\theta_{eq}^W = 90^\circ\), however, the drop already reaches its equilibrium contact angle at the end of initial spreading and hence no further spreading is observed in the wetting phase.

b. Effect of Surface Tension and Viscosity. The effects of surface tension and viscosity on drop spreading and oscillation are then investigated based on a hydrophobic substrate \((\theta_{eq}^W = 90^\circ)\). The drops of water \((W)\), water/glycerin mixture \((W/G)\), and water/glycerin/isopropanol mixture \((W/G/I)\) are used. As...
shown in the drop spreading radius versus time plot of Figure 5a, at the end of the initial spreading regime where the drop reaches the minimum height, the water drop spreads the least extent due to its high surface tension ($\sigma_w = 72 \text{ mN/m}$). For the W/G/I drop of the same viscosity as that of W/G ($\mu_{W/G} = 5 \times 10^{-5} \text{ Pa}\cdot\text{s}$), its lower surface tension ($\sigma_{W/G/I} = 38 \text{ mN/m}$) leads to farthest spreading among three drops.

Similar to water, the W/G and W/G/I drops also oscillate after impacting on a hydrophobic substrate. As shown in Figure 5b, it takes about 250 $\mu$s for the height oscillation of a water drop ($\mu_w = 0.96 \text{ mPa}\cdot\text{s}$) to damp down, while the oscillation of the W/G and W/G/I drops last less than 100 $\mu$s due to stronger viscous dissipation resulted from a higher liquid viscosity. The results also show that, by comparing the damping time of the W/G and W/G/I drops, surface tension does not play a significant role in oscillation damping for a single drop impacting on a hydrophobic substrate at a low Weber number.

3.2. Coalescence, Recoil, and Oscillation of Two Consecutively Printed Drops. a. Effect of Substrate Wettability. Now consider the scenario when a drop impacts on a sessile drop consisting of the same liquid. Figure 6 shows snapshots of a water drop of 30 $\mu$m in-flight radius impact on another evaporating water drop sitting on substrates of $\theta_{eq} \sim 0^\circ$, 45$^\circ$, and 90$^\circ$, respectively. Here, $t = 0$ is when two drops first touch each other and the impact velocity is at 0.77 m/s. As shown in Figure 6, upon impact of the second drop on top of the first drop (e.g., $t = 4 \mu$s), the local mean curvature of the air–water interface at the neck region between two drops is very large. The unbalanced surface tension and pressure in the neck region results in a fast expansion of the neck width,23 pumping liquid from both drops into the neck region. The contact angle of the first drop on substrates is hence decreased. For the substrate of $\theta_{eq} = 90^\circ$, the contact angle of the first drop decreases below its static receding contact angle and drop recoil is observed at $t = 20–30 \mu$s, as shown in Figure 6 at $t = 24 \mu$s. However, recoil is not observed on hydrophilic substrates of $\theta_{eq} \sim 0^\circ$ and 45$^\circ$. For such cases, the dynamic contact angle of the first drop is still larger than the static receding contact angle. This can be explained by the increase of contact angle hysteresis with substrate hydrophilicity.24

It is also observed that, at $t = 24 \mu$s in Figure 6, a tip appears at the center of the drop surface for substrates of $\theta_{eq} = 45^\circ$ and...
90°. Note that, for $\theta_{\text{eq}}^\mu \sim 0^\circ$, similar phenomenon is also observed at around $t = 30 \mu s$. Because the drastic capillary driven expansion of the neck region is faster than the downward motion of the second drop, the liquid in the center top region of the second drop consequently lags behind. This tip at the drop top surface results in a pressure gradient to accelerate the liquid to flow downward, and gives rise to an inertia pressure overshoot which in turn pushes the liquid radially toward the edge of the drop.\(^{23}\) This pressure overshoot leads to a crater like depression of the combined drop on a hydrophilic substrate of $\theta_{\text{eq}}^\mu \sim 0^\circ$ at $t = 64-84 \mu s$, as shown in Figure 6. On a hydrophobic substrate, however, the overshoot increases impact inertia causing the combined drop to spread more than the equilibrium spreading radius during initial spreading. As a result, the surface tension drives the liquid from the periphery back to the center of the combined drop, causing the contact angle to be smaller than the static receding contact angle where a second recoil is observed at $t = 64-84 \mu s$.

Similar to the effect of substrate wettability on drop oscillation time for a single drop, it takes a shorter time for the oscillation of a combined drop to be dissipated on a hydrophobic substrate compared to a hydrophilic one, i.e., the oscillation lasts 144 $\mu s$ on a substrate of $\theta_{\text{eq}}^\mu \sim 0^\circ$ versus more than 204 $\mu s$ on a substrate of $\theta_{\text{eq}}^\mu = 90^\circ$ as shown in Figure 6 for a combined water drop.

b. Effect of Viscosity and Surface Tension. Figure 7 shows snapshots of W/G and W/G/I drops impact on a sessile drop of the same liquid on a hydrophobic surface of $\theta_{\text{eq}}^\mu = 90^\circ$. The corresponding drop spreading radius versus time and drop height versus time for W, W/G, and W/G/I drops are compared in Figure 8. In contrast to the water drop, no recoil and tip are observed for W/G and W/G/I drops at $t = -3 \sim 37 \mu s$. Higher viscosity of both W/G and W/G/I drops slows down droplet coalescence (i.e., neck region expansion),\(^{23}\) giving enough time for the second drop to provide the liquid needed for neck expansion. In addition, no second recoil is observed as a result of higher viscous dissipation and the lack of pressure overshoot leads to the absence of more than equilibrium spreading radius. The two recoils for water drop and the lack of recoil in W/G and W/G/I drops can be clearly observed in the spreading radius versus time plot of Figure 8a. Figure 7 also shows that, due to stronger viscous dissipation, the oscillations of the combined W/G and W/G/I drops are both damped down in $\sim 217 \mu s$ much less than that of $500 \mu s$ for water drop as shown in the drop height versus time plot in Figure 8b. Similar oscillation decays for W/G and W/G/I also indicate that the effect of surface tension does not play a significant role in oscillation damping.

3.3. Comparison between Drop Impact on a Dry Surface and on a Predeposited Sessile Drop. a. Recoil in Drop Impact on a Sessile Drop. When two water drops consecutively impact on a dry substrate, due to drop coalescence, the spreading and oscillation of the combined drop differ from that of a single drop. Since the jetting delay between two drops is 0.02 s, much longer than the oscillation and spreading time for the single drop, the first drop has already equilibrated into a spherical cap before the impact of the second drop. Moreover, the jetting delay is only about 0.6% of the time for a single water drop to evaporate. The effect of evaporation of a water drop is hence neglected in this study.

Figure 9 shows the comparison between drop impact on a dry surface and on a sessile drop. In contrast to a single drop that continuously spreads on a hydrophobic substrate until it reaches an equilibrium contact angle, two stages of drop recoil as discussed in section 3.2a are observed for the combined drop as a result of drop coalescence as shown in Figure 9a. It has been reported that on a hydrophobic substrate, no recoil is observed for low-Weber-number drop impact on a dry surface, whereas increasing the Weber number can result in the emergence of drop recoil.\(^{26}\) It can hence be concluded that drop impact on another sessile drop is capable of decreasing the threshold Weber number for drop recoil.

b. Single-Degree-of-Freedom Vibration Model of Drop Height Oscillation on a Hydrophobic Substrate. When a drop impacts on a surface or on a sessile drop, the single or combined drop deforms and spreads under the effects of inertia and surface tension, causing the drop to oscillate between minimum and maximum drop heights. During oscillation, energy is dissipated by viscous stress, which eventually brings the drop to rest. Treating drop oscillation on a hydrophobic substrate as a single-degree-of-freedom vibration system consisting of mass, spring, and damper, the inertia force resulted from drop impact is given by

$$F_{\text{inert}} \sim \rho R_n^3 H$$

where $R_n$ is the drop nominal radius and $R_n = (3V/(4\pi))^{1/3}$, $V$ is the volume of the single or combined drop, and $H$ is the drop height. When the drop shape deviates from a spherical cap, the surface tension force works to retain a spherical cap shape and it is scaled as

$$F_{\text{sur}} \sim \sigma(H - H_{\text{eq}})$$
During the drop oscillation phase, the viscous drag force for oscillation damping is scaled as

\[ F_{vis} \sim \mu R_n H \]  

(3)

Therefore, the height oscillation of both single and combined drops governed by inertia, surface tension and viscous drag forces can be balanced by

\[ H + C_1 \frac{\mu}{\rho R_n^2} H + C_2 \frac{\sigma}{\rho R_n^3} (H - H_{eq}) = 0 \]  

(4)

where the coefficient \( C_i \) is related to oscillation amplitude, \( C_i \) is related to frequency, and the oscillation damping amplitude, \( H(t) \), is given by

\[ H(t) = H_0 e^{-C_1 \mu / \rho R_n^2 (t-t_0)} \]  

(5)

where \( H_0 \) is the initial amplitude of the oscillation when the drop first reaches its minimum height at \( t_0 \). During oscillation, liquid inside the drop flows both radially and vertically. On a hydrophilic substrate, the drop spreading radius is larger than that on a hydrophobic substrate, thus the stronger radical motion of the liquid plays a more important role in oscillation damping. However, the single-degree-of-freedom model considered here is only appropriate for the drops oscillating on a hydrophobic substrate where the vertical flow is more dominant during oscillation.

c. Height Oscillation. It is found that for \( C_1 = 6.28 \), the damping of the oscillation amplitude calculated by eq 5 best fits to the experimental data of the height oscillation of a single drop on a hydrophilic substrate shown in Figure 9b. With the same value for \( C_1 \), the evolution of the oscillation amplitude for the combined drops are calculated by using eq 5. Note that the effect of evaporation is neglected in the amplitude calculation. As shown in Figures 8b and 9b, the results of the single-degree-of-freedom vibration model is in good agreement with the experimentally observed drop oscillation dynamics on hydrophilic substrates for both single and combined water, W/G, and W/G/I drops. The single-degree-of-freedom vibration model, can be used to explain the effect of viscosity to mass ratio on oscillation damping, as shown in the exponent of eq 5. The model can also predict the slower oscillation damping of a combined water drop as compared with a single drop as shown in Figure 9b: the volume of the combined drop is twice as that of the single drop and a larger value of \( R_n \) leads to a larger oscillation amplitude in eq 5, thereby a longer damping time. Similarly, as shown in Figure 8b, faster oscillation damping of W/G and W/G/I drops compared with the water drop can also be predicted with a larger viscosity value in eq 5. Moreover, the absence of surface tension term in eq 5 indicates that the surface tension does not play an important role in oscillation damping. This can be observed in Figure 5b and 8b for both single and combined W/G and W/G/I drops.

In addition, the period of height oscillation can be rewritten as

\[ T = \frac{1}{f} = \sqrt{\frac{C_2 \rho R_n^3}{\sigma}} \]  

(6)

which can also be obtained directly from dimensional analysis of the Euler equation of a drop as in Okumura et al.\(^27\) Equation 6 can be scaled with the oscillation period of a combined water drop \( T_{W} = (C_2 \rho R_n^3/\sigma W)^{1/2} \) as

\[ T = \frac{T_{W}}{\sqrt{\frac{\rho R_n^3}{\rho W R_W^3}}} \]  

(7)

Equation 7 indicates that, the mass and surface tension rather than viscosity are the major factors influencing the drop oscillation period. The scaled oscillation periods of the single and combined water and W/G drops are shown in Figure 10, based on measurements from Figures 8b and 9b. It is found that the scaled periods of the single water drop, combined water drop of 0.02 s jetting delay, combined water drop of 0.5 s jetting delay, and combined W/G drop of 0.02 s jetting delay all fit fairly well with the calculated curve for a water drop \( (\sigma = \sigma_w) \) for the condition considered. As shown in Figure 10, although the viscosity of W/G is 5 times larger than that of water, its surface tension 94% of water leads to an oscillation period close to the water curve calculated from eq 7. The error bars in Figure 10 are standard deviations of several repeating experiments.

By neglecting the evaporation of the first W/G/I drop, the scaled period of the height oscillation, \( T/T_{W} \), based on eq 7 is 1.37. However, the experimentally measured scaled period is 1.07. The volatile isopropanol owning to a 5.7% volume decrease during the 0.02 s jetting delay causes the drop density between W/G and W/G/I and the viscosity identical to W/G. Thus, the damping rate, which is related to density, viscosity and drop volume, is not significantly affected by evaporation. However, the time-dependent concentration of the isopropanol significantly affects the surface tension of the combined drop, thereby affecting the oscillation period. Using eq 7 to estimate the oscillation period of a combined W/G/I drop without considering the effect of evaporation becomes inappropriate.

4. CONCLUSION

In this paper, the recoil and oscillation of single and two consecutively printed drops on substrates of different wettabilities are examined by side-view images using a high speed camera. The results show that, for a single droplet impact on a dry surface at \( We \sim 0 \) (1), both inertia and capillary effects play important roles in the initial spreading regime leading to substrate wettability dependent spreading kinetics before the droplet starts to oscillate. This observation is very different from the inertia-dominated drop impact at \( We \gg 1 \), where variations in drop spreading kinetics with substrate wettability are negligible.
On a substrate of higher wettability, drop oscillation decays faster due to its stronger viscous dissipation resulted from a longer liquid oscillation path parallel to the substrate. Drops with a high viscosity (W/G and W/G/I) oscillate shorter in time than low viscous drops (water). Similar results on the effect of wettability and viscosity on drop oscillation time are found for the combined drop after a drop impacts on a sessile drop of the same liquid.

It is found that, when a drop impacts on an evaporating sessile drop sitting on a hydrophobic substrate, as two drops coalesce and the combined drop subsequently spreads on the substrate, drop recoil twice due to the coalescence of the two drops. This stands in contrast to the absence of recoil for a single drop impact on a dry surface under the same condition, indicating that the threshold value for drop recoil is lowered in the presence of another sessile drop.

Furthermore, a single-degree-of-freedom vibration model for the height oscillation of the single and combined drops on a hydrophobic substrate is established. The model predictions are in good agreement with the experimental results of the drop relaxation phase. The results also show that, as the liquid viscosity increases or the drop mass decreases, oscillation damping is accelerated. The drop spreading and oscillation dynamics revealed here are important for inkjet printing, spray deposition, and other solution-based additive fabrication techniques.

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Notes

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