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ABSTRACT
The dynamics of Newtonian nonelastic and viscoelastic droplets that impact an immiscible liquid surface were experimentally studied using high speed visualization techniques. The impact mechanisms of nonelastic droplets differed from those of viscoelastic droplets. The azimuthal instability seen along the rim bordering the nonelastic droplets was not observed during the impacting of viscoelastic droplets. The azimuthal instability is attributed to the Saffman–Taylor instability because of the viscosity discontinuity across the interface, and to the Rayleigh–Taylor and Richtmyer–Meshkov instabilities because of the density difference at the interface. The effects of the physical parameters, in terms of the Weber number, $W_e$, on the growth of the azimuthal instability were studied. The analysis revealed that the growth of the azimuthal instability increased the inertial force of the droplet upon impact. Moreover, surface tension-driven instability, known as the Plateau–Rayleigh instability, was also observed from impact of the nonelastic droplet, which was distinct from the viscoelastic droplets. The stabilizing role of the elasticity in the droplet impact was investigated using the elastocapillary number, $Ec$. For nonelastic droplets, the elastocapillary number is negligible, hence any disturbance could grow further and destabilize the liquid. However, for viscoelastic liquids, the $Ec$ is significant due to the presence of elasticity, which prevents the growth of any disturbances in the liquid.

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I. INTRODUCTION

Liquid droplets that impact both a solid, deep, liquid pool and thin liquid film surfaces have been extensively studied. The motivation of this subject is pertinent to a variety of applications, such as rapid spray cooling of hot surfaces (i.e., turbine blades, semiconductor chips, and electronic devices), ink-jet printing, spray painting, drug sprays in biotechnology, and atmospheric sciences. Most studies have focused on the dynamics of droplets that impact solids and miscible liquid surfaces. Droplet impacts onto a miscible liquid surface generally lead to coalescence, splashing, bouncing liquid off the surface, and the formation of Worthington jets with small fragmented droplets.

The impact of droplets on liquid surfaces depends on several factors, including the impact velocity, depth of the liquid pool, direction of the impact, and the physical properties of the droplet and liquid pool, including their miscibility. The droplet impact on an immiscible liquid has several industrial applications, such as metallic melt quenching, metallic liquid droplets on hot liquid pools, or droplet encapsulation due to immersion inside a liquid bath. Recently, the synthesis of nonspherical particles composed of polymers, gels, waxes, or biological materials through the impingement and deformation of liquid droplets on an immiscible liquid pool surface has been of extensive interest in dentistry, consumer products, food processing, and drug delivery systems. These nonspherical particles (e.g., paraffin wax droplets) exhibit non-Newtonian behaviors with viscoelastic characteristics. Despite the wide variety of industrial applications of Newtonian and viscoelastic droplet impacts on an immiscible liquid pool, there is a lack of attention on this subject in the literature.
Yakhshi-Tafti et al. studied the final shape of deionized water droplets after impacting an immiscible liquid (i.e., fluorocarbon liquid). They showed the formation of isolated spherical droplets above the immiscible liquid interface and concluded that immiscible liquid pools deform like an elastic membrane upon droplet impact, which leads to droplet bouncing and oscillations on the liquid pool surface. In their experimental study, they also found that spherical droplets may eventually deform into a “partially submerged lens-shaped” structure due to the presence of perturbations.

Lhuissier et al. studied water droplet fragmentation through perpendicular impacts onto a horizontal bath of silicone oils with different viscosities (0.65, 10, 50, and 200 mm²/s). In their experimental study, they focused primarily on the mechanism of droplet breakup into a collection of several noncoalescing daughter droplets after impacting an immiscible liquid pool and explained this phenomenon through the Plateau–Rayleigh mechanism. They proposed a mathematical model to explain the physical mechanism for the size distribution of daughter droplets after droplet fragmentation. They also obtained an empirical trend that revealed the dependency of the number of formed daughter droplets based on the impact velocity through a dimensionless parameter (Weber number), which compares the inertial force with the capillary force. They found that the number of daughter droplets linearly increases at higher Weber numbers. They also observed the presence of an azimuthal instability along the rim of the impacted droplet through the formation of a star-shaped structure.

Shaikh et al. experimentally studied the fragmentation of water droplets impacting millimetric oil films using high-speed visualization techniques. They found a critical impact parameter in terms of the Reynolds number and Weber number above which the number of daughter droplets may eventually deform into a “partially submerged lens-shaped” structure due to the presence of perturbations. In their experimental observations, they also reported the formation of isolated spherical droplets after impacting an immiscible liquid pool.

Here, we present a qualitative and quantitative experimental study that compares the impact mechanism of Newtonian nonelastic and elastic droplets on an immiscible liquid pool. We also reveal the significance of elasticity on the stability of viscoelastic droplets after impacting an immiscible liquid pool.

II. MATERIALS AND METHODS

A. Experimental setup

The experimental setup used in this study is illustrated in Fig. 1. The droplets were dispensed using a syringe pump (Modern Nexus 6000 Chemyx, Inc.) at flow rate of 16.7 μl/s. The pump was stopped once a droplet that formed at the needle tip was at a reproducible size of \( D_w = 2.77 \pm 0.22 \text{ mm} \) and \( D_V = 2.78 \pm 0.21 \text{ mm} \), where \( D_w \) and \( D_V \) are the diameters of distilled water (i.e., nonelastic) and viscoelastic droplets, respectively. After the droplet gets detached from the needle, it fell freely onto a horizontal pool of oil from various heights (6.5, 11.5, 16.5, 21.5, 31.5, 41.5, 51.5, and 61.5 cm). The container used to hold the oil was a cubic transparent plastic material with dimensions of \( 98 \times 98 \times 98 \text{ mm}^3 \). The liquid pool was approximately 1560 times larger than the droplet size. Therefore, the wall effect was not considered in our study.

All experiments were conducted under ambient conditions. The dynamics of the droplet impacts were recorded using a Photron Fastcam Ultima APX high-speed video camera with a Micro Nikkor 105 mm lens (Nikon) at 2000 frames/s to follow the crater evolution, the size and number of immersed fragmented droplets, and the growth dynamics of the crater on the oil surface via visualizations from both top and side views. This suggests that the moment of impact was captured within 500 μs. The camera recordings for the top and side views were manually triggered. The camera for the “top view” images was tilted by approximately 30° from normal to the horizontal surface of the liquid pool. The effective pixel resolution was approximately 18.5 μm/pixel. The primary source of the experimental error was from the difficulty in measuring the number of pixels for the physical parameters, such as the droplet diameter. This pixel reading error in the images was approximately 3 pixels. This experimental error was considered in the measured droplet diameter, droplet impact velocity, maximum height of the formed crater, and the calculation of the dimensionless parameters used in this study. The entire process of the droplet impact was illuminated using a photographic 500 W spotlight (see Fig. 1). The velocity of the droplet during impact was measured explicitly for each experiment by tracking the location of its upper or lower part 0.5 ms prior to impact using image-processing software. This software was also

![FIG. 1. Schematic diagram of the experimental setup.](image-url)
used to threshold the droplet from the background, and the droplet diameter was measured from the side to view its sphericity. The experiments were conducted several times for each case to validate the reproducibility of the experimental findings.

B. Materials

1. Viscoelastic liquid

An aqueous solution of 0.025% by mass of polyethylene oxide (PEO) with a molecular weight of $8 \times 10^6$ g/mol was used as the viscoelastic liquid. A small amount of food grade red #40 color dye was added to the solution. The surface tension was measured using the Wilhelmy plate method in a digital tensiometer K10ST (Krüss). The shear viscosity, $\mu$, was measured using a Brookfield Viscometer model DV-II+ with a concentric cylindrical geometry (Taylor-Couette geometry). It is important to note that the dye did not influence the viscosity of the solution. However, it may have slight effects on the surface tension. The viscoelastic solution exhibited slight shear thinning characteristics, as shown in Fig. 2(a). The density was measured with a volumetric flask and a laboratory balance. The PEO contribution to shear viscosity, $\mu_0$, is defined as the difference between the viscoelastic solution and the solvent viscosities, i.e., $\mu_0 \equiv \mu - \mu_s$.

The apparent extensional viscosity of the solutions was probed using a Capillary Break-up Extensional Rheometer (CaBER, Thermo Scientific\textsuperscript{TM}), which forms a liquid bridge between two cylindrical fixtures. Applying an axial step-strain to the liquid bridge led to the formation of an elongated filament. The CaBER uses a laser micrometer to measure the evolution of the midpoint filament diameter with time for each viscoelastic liquid. A small amount of food grade red #40 color dye was added to the solution. The surface tension was measured using the Wilhelmy plate method in a digital tensiometer K10ST (Krüss).

To overcome this issue, the diameter data were fit using the following empirical formula:

$$D(t) = D_0 \left(1 + \frac{k_1}{t + t_1}\right) \exp\left(-\frac{t}{t_2}\right) - V_2 (t - t_2),$$

in which $D_1$, $t_1$, $k_1$, $V_2$, and $t_2$ are the fitting parameters. The fitting function is shown as a continuous curve in Fig. 2(b). This fitting function [Eq. (2)] is theoretically motivated from different capillary-driven filament necking regimes and is capable of completely describing these three capillary thinning stages, which are generally observed during midpoint diameter measurements: (I) fast initial necking of the liquid filament as it reaches the region of balance between elastic and capillary forces; (II) exponential thinning stage (i.e., middle section of the transient filament diameter curve); and (III) final stage related to approaching the finite molecular extensibility and self-similar drainage stage, described by the linear term in Eq. (2) in which $V_2$ is defined as capillary velocity for the final stage and to be scaled by $\frac{\sigma_0}{\mu}$. The fit analytical function that describes the variations in the filament diameter with time was differentiated to calculate the extensional viscosity. The physical properties, including the extensional viscosity at high strains, for the viscoelastic solution used in this study are presented in Table I. The interfacial tension between the viscoelastic liquid and oil, $\sigma\left(D_0\right)$, was measured to be 24.6 mN/m using the du Noüy ring method with a digital tensiometer K10ST (Krüss).
After the crater reaches its maximum depth, it begins to cover the water droplet, causing it to immerse at the bottom of the crater. After the crater reaches its maximum depth at \( \sim 4 \text{ ms} \) [Figs. 3(a) and 3(b)]. During this time, the droplet hemispherical cap structure separates from the crater due to the circulatory motion of the vortex ring and elongates as a cylindrical shape before forming a pendant droplet. The formed pendant droplet separates from the surface and immerses, which subsequently breaks up into a large droplet and several smaller droplets that are connected together through a thin filament that is composed of tiny droplets [Fig. 3(c)]. A small droplet is fragmented from the large droplet and attaches underneath [Fig. 3(c)]. The longitudinal fragmentation of the thin filament from the distilled water inside the oil and the subsequent formation of a “beads-on-a-string” structure [Fig. 3(c)] is attributed to Plateau–Rayleigh instability. The Plateau–Rayleigh instability is a capillary-driven effect that reduces the surface energy of the thin filament due to the effects of gravity. Lhuissier et al. showed a similar mechanism of water impacting silicone oil, except for the configuration of the large droplet with small droplets connected through thin filaments shown in the presented experiments. For Weber numbers less than 420, there was no observed instability in the azimuthal direction of the droplet. The formation of the “thin filament” as well as the “beads-on-a-string” structure leads to the formation of the bubble entrapment phenomenon as was observed in this study [Fig. 3(c)].

### III. RESULTS AND DISCUSSION

#### A. Water droplet impact on the oil surface

The water droplets impact perpendicularly into a pool of oil at eight different heights ranging from 6.5 to 61.5 cm, which corresponds to Weber numbers, \( W_e \), from 112.5 \( \pm \) 25.2 to 1222.1 \( \pm \) 63.2. The Weber number compares the kinetic energy with the surface energy of the droplets, \( W_e = \rho W U_W^2 D_W / \sigma_{WO} \), in which \( \rho W \) is the water density, \( U_W \) is the impact velocity, \( D_W \) is the water droplet diameter, and \( \sigma_{WO} \) is the interfacial tension between the water droplet and the oil. A series of images are shown to illustrate the dynamics of water droplets impacting the oil surface from heights that correspond to \( W_e \) of 112.5 \( \pm \) 25.2 [Fig. 3], 469.9 \( \pm \) 53.0 [Fig. 4], 777.8 \( \pm \) 84.9 [Fig. 5], and 1222.1 \( \pm \) 63.2 [Fig. 6].

For small Weber numbers (\( W_e = 112.5 \pm 25.2 \) and 262.0 \( \pm \) 39.0), the droplets deform into a lens-shaped structure after the impact (Fig. 3). A crater then forms on the oil surface with a hemispherical cap at its bottom in the shape of a reversed “mushroom” structure due to the formation of a vortex ring initiated by the droplet impact at \( \sim 4 \text{ ms} \) [Figs. 3(a) and 3(b)]. The droplet impact also initiates a transverse sinusoidal motion on the oil surface that propagates outwards as a circular-hydraulic jump with the same surface capillary wave. The crater expands until eventually reaching its maximum depth at \( \sim 9.5 \text{ ms} \). Meanwhile, the water droplets flatten and spread at the bottom of the crater. After the crater reaches its maximum depth, it begins to cover the water droplet, causing it to immerse in the oil and sink. During the crater expansion, the droplet flattens and spreads at the bottom of the crater to form a hemispherical cap (i.e., vortex ring). After the crater reaches its maximum depth, the droplet starts to retract with a perfect circular shape at its edge [Fig. 3(b)]. During this time, the droplet hemispherical cap structure separates from the crater due to the circulatory motion of the vortex ring and elongates as a cylindrical shape before forming a pendant droplet.

#### 2. Newtonian nonelastic liquids

Distilled water with red food grade dye was prepared in this study as the nonelastic Newtonian liquid. Mineral oil, purchased from Sigma-Aldrich, was used as an immiscible liquid bath on which the droplets were impacted. The physical properties of the Newtonian liquids were measured in the same way as the viscoelastic fluid. Table II shows the physical properties of the Newtonian liquids, where the interfacial tension between the distilled water and oil, \( \sigma_{WO} \), was measured as 26.9 mN/m.

### Table II. The physical properties of the Newtonian liquids.

| Solution       | \( \rho \) (kg/m\(^3\)) | \( \sigma \) (mN/m) | \( \mu \) (mPa s) |
|----------------|-------------------------|------------------|------------------|
| Distilled water| 1002                    | 66.2             | 1.1              |
| Mineral oil    | 857                     | 30.9             | 23               |

For larger Weber numbers (\( W_e = 650.4 \pm 77.0 \) and 777.8 \( \pm \) 85.0), similar mechanisms occur after impact, but with additional three events [Figs. 5(a)–5(c)]. The first event is that during the droplet retraction at the bottom of the crater, its shape becomes irregular [Fig. 5(a)] for \( t = 14 \) and 15 ms], revealing an instability.
FIG. 3. (a) Side and (b) top views of a water droplet impacting ($W_e = 112.5 \pm 25.2$) on oil bath. (c) Thin filament consisting of fragmented minidroplets that connect the large and small droplets to the oil surface.

at the bottom of the droplet that causes further fragmentation. The second event is that the structure of the Worthington jet is disturbed and it forms a wavy-shape structure during its upward motion [Fig. 5(d)]. The third event is that in addition to the longitudinal instability of the droplet with its fragmentation [Fig. 5(c)], the droplet edge becomes distorted and unstable during the droplet flattening and retraction along the azimuthal direction. This forms a noncircular shape (i.e., "star-shaped" structure) during penetration into the oil below the crater [Fig. 5(b) at $t = 11, 13, 14, and 15$ ms]. The azimuthal instability along the rim of the flattened droplet is attributed to several instability mechanisms, including the Rayleigh–Taylor, Richtmyer–Meshkov, Kelvin–Helmholtz, and Saffman–Taylor instabilities, which are discussed in Refs. 33 and 37–42.

The Kelvin–Helmholtz instability is along the interface between two parallel immiscible liquids with different tangential velocities and densities in which the heavier liquid is at the bottom. The azimuthal instability along the rim of the flattened droplet cannot be related to the Kelvin–Helmholtz instability since the lighter liquid (oil) is at the bottom of the interface. The Saffman–Taylor instability is known as viscous fingering and occurs along the interface of two immiscible liquids when a lower viscosity liquid displaces a higher viscosity liquid. The interface between the two immiscible liquids remains stable and no distinct patterns are formed. Since distilled water has a lower viscosity than oil, the azimuthal instability along the rim of the flattened droplet because of the viscosity difference is similar to the Rayleigh–Taylor and Richtmyer–Meshkov instabilities, wherein the interface of the two immiscible liquids with different densities is subjected to an impulsive velocity difference. The distilled water droplets have different densities relative
to oil, and the water droplet impacts the oil as an example of impulsive acceleration. Therefore, the azimuthal instability of the droplet rim is attributed to both Rayleigh–Taylor and Richtmyer–Meshkov instabilities.

Rayleigh-Taylor instability can be described by destabilizing the rim through fluid rearrangement driven by the capillary force, which is a similar physical mechanism to that of Plateau-Rayleigh instability. The associated characteristic time scale over which this physical instability happens can be determined based on the physical properties of the droplet,

$$
\tau_c \sim \sqrt{\frac{\rho D^3}{\sigma}},
$$

in which $\rho$ is the density of the droplet, $D$ is the droplet diameter, and $\sigma$ is the surface tension of the droplet. For nonelastic (water) droplet impact on the oil surface, the characteristic time scale associated with this capillarity-driven instability along the rim is \(\sim 17.9 \text{ ms}\).

For larger Weber numbers ($We = 1044.4 \pm 57.9$ and $1222.1 \pm 63.2$), a mechanism similar to the previous case occurs after impact with one more additional events appearing (Fig. 6). Droplet fragmentation along its edge is initialized due to the strong azimuthal instability during droplet retraction [Figs. 6(d) and 6(e)]. Furthermore, the droplet retraction leads to the formation of a very extreme “star-shaped” structure and more vertices [Fig. 6(e)]. After the formation of the “star-shaped” structure on the rim with several vertices (i.e., legs of the “star-shaped” structure of the rim bordering the flattened droplet), they continue thinning until some begin breaking off from the flattened droplet and form smaller daughter droplets [Fig. 6(b) at $t = 17 \text{ ms}$]. At the same time, a Worthington jet forms and rises in the oil. Meanwhile, the Worthington jet tip becomes
unstable and forms a wavy-shaped structure that then fragments into smaller droplets that continue jumping upward into the air [Fig. 6(d)]. The Worthington jet then retracts and falls with the mini droplets on the oil surface and floats. Some of the fragmented droplets sink into oil, whereas a few of them (relatively tiny ones) stay on the oil surface. It is important to note that in all cases, the crater reaches its maximum height at \( \sim 9.5 \) ms.

As the droplet impact velocity increases, the azimuthal instability becomes stronger and causes longer and sharper dentations (i.e., legs of the “star-shaped” geometry) along the droplet edge. This leads to droplet fragmentation at the vertices of the flattened, unstable, droplet edge (Fig. 7). The azimuthal instability begins at \( \text{We} > 469.9 \pm 53.0 \) with the onset of droplet fragmentation at \( \text{We} = 1044.4 \pm 57.9 \). For \( \text{We} \geq 650.4 \pm 77.0 \), the number of vertices that form along the “star-shaped” structure of the unstable flattened droplet increases as the Weber number increases (Fig. 8). Figure 9 summarizes the mechanism of the impact of nonelastic Newtonian droplets on an immiscible liquid surface.

B. Viscoelastic droplet impacting oil surface

The dynamics of the viscoelastic droplet impacting an immiscible liquid surface was experimentally studied. Newtonian elastic (0.025 wt. % PEO solution) droplets fell perpendicularly on the surface of a deep pool of oil. The droplets were dropped from the same heights as before, which correspond to Weber numbers, \( \text{We} \), ranging from 109.8 \( \pm 23.7 \) to 1044.5 \( \pm 79.0 \). \( \text{We} = \rho_{\text{V}} U_{\text{V}}^2 D_{\text{V}} / \sigma_{\text{VO}} \), where \( \rho_{\text{V}} \) is the viscoelastic droplet density, \( U_{\text{V}} \) is the impact velocity, \( D_{\text{V}} \) is the
FIG. 6. (a) Side and (b) top views of the water droplet impacting \((\text{We} = 1222.1 \pm 63.2)\) the oil bath. (c) Finger instabilities along the edge of the flattened droplet. [(d) and (e)] Wavy like structure from a Worthington jet and the formation of small droplets.
is the viscoelastic droplet diameter, and $\sigma_{VO}$ is the interfacial tension between the viscoelastic droplet and the oil. A series of images are shown to illustrate the impact dynamics of a viscoelastic droplet on an oil surface from three heights with $We$ of 109.8 ± 23.7 (Fig. 10), 472.7 ± 50.7 (Fig. 11), and 1044.5 ± 79.0 (Fig. 12).

Figure 10 shows the viscoelastic droplet impact from 6.5 cm ($We = 109.8 \pm 23.7$). The droplet forms a lens-shaped structure [Fig. 10(b) at $t = 5$ ms], and a relatively tiny droplet forms at its bottom [Fig. 10(a) at $t = 5$ ms]. A crater forms and expands in the shape of an upside down “mushroom” with a hemispherical cap at its bottom through the formation of a vortex ring due to the impact [Fig. 10(a) at $t = 5$ ms]. Concurrently, the droplet forms a crown structure inside the crater, and the droplet simultaneously falls into the crater and begins to retract inside before immersing into the oil [Fig. 10(b)]. After the crater reaches a maximum height, it retracts, moves upwards, and becomes distorted [Fig. 10(a) at $t = 10$ ms]. Meanwhile, the droplet, which is located underneath the crater, starts to separate from the retracting crater. The droplet then forms an elongated cylindrical structure and converts into a pendant droplet that separates from the oil surface [Fig. 10(a) at $t = 20$ and 32.5 ms]. Once the droplet detaches from the oil surface, it falls while still in contact with the oil surface through a thin filament, which is connected to the droplet and oil surfaces [Fig. 10(a) at $t = 37.5$ ms]. The filament thins even further while stretching due to the downward motion of the droplet. The filament then becomes unstable due to the interfacial tension and forms a very thin thread consisting of several much smaller droplets (i.e., beads-on-a-string structure) based on the Plateau–Rayleigh instability.

Figure 7. Edge of the flattened droplet during its retraction for:
(a) $We = 112.5 \pm 25.2$, (b) $We = 469.9 \pm 53.0$, (c) $We = 650.4 \pm 77.0$, (d) $We = 777.8 \pm 85.0$, (e) $We = 1044.4 \pm 57.9$, and (f) $We = 1222.1 \pm 63.2$.

Figure 8. (a) Number of vertices, $N_v$, formed along the unstable flattened droplet (star-shaped structure) vs the Weber number, $We$, for water droplets impacting the oil surface. (b) Schematic of the fingering instability along the rim of the flattened droplet to create the vertices (fingers).
Meanwhile, an instability is present on the oil surface with a transverse sinusoidal vibrational motion (i.e., transverse wave-propagation). This event is caused by the impulsive transfer of kinetic energy from the droplet to oil surface through the impact. Consequently, the momentum created on the oil surface is transferred to the sinking droplet through the thin filament. This causes the sinking droplet to bounce back upwards inside the oil. Then, the droplet falls and the unstable filament stretches, which causes the beads-on-a-string structure to tear apart. During this event, tiny droplets, which form at the bottom of the sinking droplet as caused by its fragmentation, remain attached underneath.

Figure 11 shows the viscoelastic droplet impacting from a height of 21.5 cm ($We = 472.7 \pm 50.7$). After the impact, the droplet continues to descend below the oil surface and creates a crater that grows in both depth and diameter. Meanwhile, the droplet changes its shape from a spherical cap into a pancake shape (flattened structure). The submerged droplet, which is not a perfect spherical shape, elongates along the downward direction [Fig. 11(a)]. The azimuthal rim bordering the flattened droplet remains stable in a perfect circular shape and does not fragment while in contact with the oil surface [Fig. 11(b)]. This is attributed to the stabilizing effect of the elastic stress present within the droplet due to extensional thickening of the high molecular weight polymer solution. This shows that the extensional thickening (i.e., elasticity) of the liquid dampens its instability. The center of the flattened droplet initially indents downwards before retracting, forming a Worthington jet at its center. The Worthington jet rises, and the droplet shape converts to a vertically elongated, pendant-shaped, immersed droplet. Next, the droplet shape becomes spherical while still being attached to the oil surface before eventually separating from the oil and sinking. A
FIG. 10. (a) Side and (b) top views of the viscoelastic droplet impacting ($We = 109.8 \pm 23.7$) the oil bath.

A similar mechanism occurs for droplet impact for heights ranging from 6.5 to 41.5 cm ($109.8 \pm 23.7 \leq We \leq 603.7 \pm 41.2$).

For droplets falling from greater heights ($h > 41.5$ cm) corresponding to $We > 603.7 \pm 41.2$, a similar mechanism occurs with two additional events [Figs. 12(a) and 12(b)]. First, the circular-shaped rim bordering the droplet becomes distorted and forms a wavy-shaped structure [Fig. 12(b)]. However, this instability recovers quickly due to the large stabilizing effect of the extensional viscosity within the droplet. Second, the droplet is rapidly covered by the crater and begins to sink.

Unlike the water droplet impact, there is no droplet fragmentation along the rim that borders the flattened viscoelastic droplet, which signifies azimuthal stability of the rim after impacting the oil surface. This reveals a large stabilizing effect due to the
FIG. 11. (a) Side and (b) top views of a viscoelastic droplet impacting \( \text{We} = 472.7 \pm 50.8 \) the oil bath.
FIG. 12. (a) Side and (b) top views of a viscoelastic droplet impacting ($We = 1044.5 \pm 79.0$) the oil bath.
extensional viscosity from the long-chain high-molecular-weight PEO molecules in the viscoelastic droplet. Moreover, there is no droplet fragmentation along the vertical axis of the droplet symmetry and only a tiny droplet fragments off, which stays connected underneath the main immersed droplet inside the oil. The same mechanism was seen for all considered Weber numbers ($109.8 \pm 23.7 \leq We \leq 1044.5 \pm 79.0$).

A series of schematics are illustrated in Fig. 13 to summarize the mechanisms of Newtonian viscoelastic droplets impacting an immiscible liquid surface, and the dependency on the physical properties of both the droplet and the immiscible liquid pool. The Worthington jet is much smaller for viscoelastic droplet impacts compared to nonelastic droplets. The Plateau–Rayleigh instability only occurred at the lowest impact velocity [Fig. 13(a)] for the viscoelastic droplet. For viscoelastic droplet impact on the oil surface, the characteristic time scale associated with this capillarity-driven instability along the rim (i.e., Rayleigh-Taylor and Plateau-Rayleigh mechanisms) is $\sim 20.3$ ms, which was damped by the elastic stress presented in the viscoelastic droplet.

The “beads-on-a-string” structure of the immersed thin filament from the formation of satellite droplets and the wavy-shaped structure of the risen Worthington jet were both present for nonelastic droplet impacts but did not occur for the viscoelastic droplets. This is attributed to the stabilizing effect of the extensional viscosity in the viscoelastic droplet. The wavy-shaped structure of the Worthington jet is caused by surface tension-driven deformations (i.e., capillary stress) as well as the disturbance growth through inertial forces. However, the “beads-on-a-string” structure of the thin filament from the formation of satellite droplets and the wavy-shaped structure of the risen Worthington jet were both present for nonelastic droplet impacts but did not occur for the viscoelastic droplets. This is attributed to the stabilizing effect of the extensional viscosity in the viscoelastic droplet. The wavy-shaped structure of the Worthington jet is caused by surface tension-driven deformations (i.e., capillary stress) as well as the disturbance growth through inertial forces. However, the “beads-on-a-string” structure of the thin filament from the formation of satellite droplets and the wavy-shaped structure of the risen Worthington jet were both present for nonelastic droplet impacts but did not occur for the viscoelastic droplets. This is attributed to the stabilizing effect of the extensional viscosity in the viscoelastic droplet. The wavy-shaped structure of the Worthington jet is caused by surface tension-driven deformations (i.e., capillary stress) as well as the disturbance growth through inertial forces. However, the “beads-on-a-string” structure of the thin filament from the formation of satellite droplets and the wavy-shaped structure of the risen Worthington jet were both present for nonelastic droplet impacts but did not occur for the viscoelastic droplets. This is attributed to the stabilizing effect of the extensional viscosity in the viscoelastic droplet. The wavy-shaped structure of the Worthington jet is caused by surface tension-driven deformations (i.e., capillary stress) as well as the disturbance growth through inertial forces. However, the “beads-on-a-string” structure of the thin filament from the formation of satellite droplets and the wavy-shaped structure of the risen Worthington jet were both present for nonelastic droplet impacts but did not occur for the viscoelastic droplets. This is attributed to the stabilizing effect of the extensional viscosity in the viscoelastic droplet. The wavy-shaped structure of the Worthington jet is caused by surface tension-driven deformations (i.e., capillary stress) as well as the disturbance growth through inertial forces.
The extensional stress caused by the presence of high-molecular weight polymer in the viscoelastic liquid could stabilize the thin filament and prevent its breakup through damping the initial disturbance that is caused by the surface tension gradient. Moreover, the extensional viscosity (elasticity) in the viscoelastic thin filament could also dampen the inertial forces by converting kinetic energy into elastic energy storage from stretchable PEO molecules. To show the strength of the elasticity for the viscoelastic liquid compared with the other physical properties, a dimensionless parameter called the “elastocapillary” number, $Ec$, was studied, which measures the combined significance of the elastic stress and capillary stress compared to the viscous stresses. The elastocapillary number is defined in terms of the Weissenberg number and capillary number as

$$Ec = \frac{\text{Wi}}{\text{Ca}} = \frac{\lambda \sigma}{\mu l}$$  

(4)

The Weissenberg number, $Wi = \frac{V}{Vc}$, is interpreted as a ratio of the polymeric time scale, $\lambda$, to the convective time scale, $t_{\text{conv}} = \frac{l}{V}$, where, $\lambda$ is the relaxation time (polymeric time scale) of the elastic liquid, $V$ is the characteristic velocity, and $l$ is the characteristic length scale for the flow geometry. The capillary number, $Ca = \frac{\mu l}{\sigma}$, defines the ratio between the viscous stress and the capillary stress (i.e., surface tension stress). Here, $\mu$ is the dynamic viscosity and $\sigma$ is the surface tension.

In this study, the characteristic length scale, $l$, and characteristic velocity, $V$, are defined by the droplet diameter (i.e., $D_D$ and $D_W$) and impact velocity (i.e., $U_V$ and $U_W$) of the droplet, respectively. The interfacial tension at the droplet/liquid pool interface (i.e., $\sigma_{VO}$) is used in the capillary number. As the relaxation time scale for nonelastic liquids (i.e., water) is negligible, the Weissenberg number and the elastocapillary number are relatively small (i.e., $Wi \ll 1$ and $Ec \ll 1$). This signifies the fact that the stabilizing effect of the elastic stress is negligible compared with the destabilizing effects caused by the inertial and surface tension-driven forces. Therefore, any disturbance caused on the thin nonelastic filament or the nonelastic Worthington jet could grow further to destabilize the structure of the liquid, as seen in the case of the water droplet impacting the oil surface.

However, the impact of the viscoelastic droplets had a nonzero relaxation time that is comparable with the convective time scale defined by the impact velocity and diameter of the viscoelastic droplet. Consequently, the elastocapillary number is a significant parameter that defines the stability of the thin filament and Worthington jet that form from the viscoelastic droplet. The formation of the Worthington jet in the viscoelastic droplet had an elastocapillary number of 69.84 ± 6.33 by considering the surface tension of the viscoelastic-air interface, $\sigma_{V} = 52.2$ mN/m from Eq. (4). The viscoelastic thin filament immersed in the oil had an elastocapillary number of 32.91 ± 2.98 based on the interfacial tension ($\sigma_{VO} = 24.6$ mN/m) at the viscoelastic-oil interface in Eq. (4).

**C. Maximum height of the crater formed during impact**

As explained in previous sections, a crater structure forms after the droplets impact the oil surface. The crater expands in the azimuthal direction, which increases its diameter, and along its axis of symmetry, which increases its depth. The crater expands up to a certain depth before retracting, which further leads to its immersion in the oil. The maximum depth of the crater, $H$, was measured for each experiment. Figure 14 shows the dimensionless maximum depth of the craters (H/D) as a function of the Weber number for water and viscoelastic droplets impacting an oil surface. As the Weber number increases at higher impact velocities, the crater deepens further into the oil. This observed trend for water and viscoelastic droplet impacts follows a power law rule with different coefficients for the two cases. The water droplet impact follows the power law of ($\frac{D}{H} \sim We^n$, $n_w = 0.16 \pm 0.02$) compared to the viscoelastic droplet impact of ($\frac{D}{H} \sim We^n$, $n_v = 0.36 \pm 0.03$). It is important to note that the shape of the crater to be formed (i.e., hemispherical or cylindrical) plays an important role in the empirical relation. Here in this study, the hemispherical shape is considered for the analysis.

**IV. CONCLUSIONS**

The impact dynamics of the viscoelastic and water droplets on an oil surface were experimentally studied using a high-speed camera recording at 2000 frames/s. The effects of the physical parameters, including the density, shear viscosity, extensional viscosity, and surface and interfacial tensions, were considered to study the dynamics of droplet impacts through two dimensionless parameters: the Weber number, $We$, and the elastocapillary number, $Ec$. The impact velocity of the water droplets impacting oil was varied from 1.0 ± 0.2 m/s to 3.3 ± 0.1 m/s, which corresponds to impact Weber numbers ranging from 112.5 ± 25.2 to 1222.1 ± 63.2. The impact velocity for viscoelastic droplets impacting oil ranged from 1.0 ± 0.2 m/s to 3.2 ± 0.2 m/s, corresponding to impact Weber...
numbers between 109.8 ± 23.7 and 1044.5 ± 79.0. The mechanism of water droplet impacts was different from that of viscoelastic droplets.

The formation of the "thin filament" and "beads-on-a-string" structure led to the formation of bubble entrapment as observed for nonelastic droplet impacts on the oil surface. However, for the case of viscoelastic droplet impact on the oil surface, the mechanisms of "thin filament," "beads-on-a-string" structure, and bubble entrapment only occurred for the lowest impact velocity. Previous studies showed the role of surface tension, shear viscosity, as well as impact velocity in the occurrence of bubble entrapment after droplet impact on a liquid pool and relating this phenomenon to the collapse of the impact crater through local weakening of the capillary wave that is responsible for bubble pinching. Since nonelastic and viscoelastic droplets have similar viscosities as well as interfacial tension, and the experiments were conducted in a similar velocity range for both nonelastic and viscoelastic droplets, the main physical parameter, which distinguishes the impact dynamics behavior of these droplets is the elasticity effect. This may be attributed to the stabilizing effect of extensional viscosity of the viscoelastic droplet due to the presence of high-molecular weight polymers.

During the impact of water droplets on the oil surface, the rim that borders the flattened nonelastic droplet (i.e., azimuthal rim) becomes unstable, which leads to instability along the azimuthal direction at large Weber numbers (We > 469.9 ± 53.0) and forms a star-shaped structure. As the Weber number (i.e., impact velocity) increases, the azimuthal rim of the water droplet becomes increasingly unstable, leading to an increased number of vertices along its star-shaped structure. This analysis reveals a growth in the azimuthal instability at higher inertial forces of the droplet upon impact. The azimuthal instability is attributed to the Saffman–Taylor instability (viscosity discontinuity across the water-oil interface) and Rayleigh–Taylor and Richtmyer–Meshkov instabilities (density differences at the interface). The impacted droplets also become unstable along the droplet axis of symmetry during its immersion in oil, which initiates droplet fragmentation. The number of droplet fragments intensifies as the Weber number increases. Moreover, a surface tension-driven instability, also known as a Plateau–Rayleigh instability, was observed along the immersed thin filament through its breakup and along the risen Worthington jet. This formed a wavy-shaped structure after the nonelastic (water) droplet impacted the oil surface. It is important to note that the Worthington jet generally forms after crater reaches its maximum depth (i.e., during the crater retraction stage), in which crater pulls back to its initial form. This phenomenon has been observed in previous studies.

For the viscoelastic droplet impacting the oil surface, the azimuthal instability along the rim bordering the droplet, the surface tension-driven instability along the immersed thin filament, and the risen Worthington jet were not observed. This reveals a strong stabilizing effect of the extensional viscosity (elasticity) of the viscoelastic droplet, which is related to the presence of long-chain high-molecular weight PEO molecules in the viscoelastic droplet.

The stabilizing role of elasticity in the droplet impact was investigated using the elastocapillary number, \( Ec \). For nonelastic droplets, the elastocapillary number was negligible (i.e., \( Ec \ll 1 \)); hence, any disturbance could grow further and destabilize the immersed thin filament and the risen Worthington jet after droplet impact. However, for viscoelastic liquids, the elastocapillary number was significant (\( Ec \approx 70 \) for the risen Worthington jet and \( Ec \approx 33 \) for the immersed thin filament) due to the elasticity of the droplet, which could prevent the growth of any disturbance in the droplet after impact.

The maximum height of the crater that formed while the droplet was immersed in the oil was measured for both water and viscoelastic droplets at the considered Weber numbers. The maximum height of the droplet increases with the impact Weber number for both water and viscoelastic droplets. The plots follow a power law with different exponents for water and viscoelastic droplets.

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