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The interaction of falling and sessile drops on a hydrophobic surface

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The dynamic behavior of drops impacting surfaces, liquid films or pools, and moving drops has been previously investigated; however, the behavior of falling drops impacting a sessile drop at rest has been explored to a lesser degree. In this work the coalescence, spreading, and recoil following the concentric impact between a falling water drop and a sessile water drop is studied on a Teflon substrate (hydrophobic). The influence of the Weber number, *We*, on drop spreading is the primary focus. For experiments at $We \sim 200$, the impacts results in drops that spread a maximum diameter and then recoil to a final equilibrium diameter. At lower Weber numbers the drops spread to a maximum diameter, then recoil, and then undergo a second spreading event to the final equilibrium diameter. These observations suggest that at higher Weber numbers more energy is dissipated in the deformation of the liquid volume that occurs via crown formation, contact line movement, and spreading. Experimental observations are compared with analytical predictions based on conservation of energy with two treatments of energy dissipation. Analytical predictions for the maximum spread diameter are within 10% of measurement and indicate that approximately one half of the kinetic energy of the impacting drop is dissipated in the approach to maximum spreading diameter.

1. Introduction

The dynamic behaviors of drops undergoing impact with surfaces, liquid films, or other drops are important in many processes; for example, ink jet printing, sprinkler systems, spray injection in combustion engines, spray cooling of electronics, and erosion due to rain, among others. Due to its importance in applications and long standing status as a fluid mechanics problem of experimental, theoretical, and numerical research, drop impact has been the subject of numerous investigations starting with Worthington's original experiments on drop impact with flat plates [1] and liquid pools [2]. Investigations have expanded to include further studies on interactions between drops and surfaces, head-on or angled drop-drop collisions, and drop impacts with a liquid films or pools; see the reviews of Rein [3], Orme [4], Yarin [5], and Josserand and Thoroddsen [6].

Water drops have been the primary focus of the literature but studies have also been performed for a number of other fluids with diverse properties: hydrocarbon fuels [7], alcohols and glycerin [8], molten metal [9], nanofluids [10], and others. In studies of impacts between drops and surfaces, various substrate materials have been considered including smooth and rough glass, polyvinyl chloride (PVC) and wax [8] and stainless steel [11], among others. The fluid and surface material are important as their interaction govern drop geometry through surface chemistry, roughness, and other interaction factors. Parametric studies investigating the influence of contact angle, surface characteristics, impact velocity, and fluid viscosity on the spreading and rebound of a single drop impacting a substrate have been reported by several authors [12–18].

In the present study, the concentric impact of a falling water drop with a sessile water drop on a flat substrate is experimentally investigated. These experiments are performed on a hydrophobic Teflon substrate which provides a nearly hemispherical sessile drop. Previous experiments have been reported for drop-drop impacts on a glass surface by Fujimoto et al. [19] and on glass and aluminum surfaces by Nikolopoulos et al. [20]; however, in both of these cases the chosen surfaces (more hydrophilic) provide a high degree of wettability such that the interaction between the falling drop and the sessile drop is similar to that between a falling drop and a thin liquid film. Here, we study the interaction of a falling drop with a nearly hemispherical sessile drop, which to our knowledge has not been previously reported. The most closely related study is that of Liang et al. [21] who studied the impact of a falling liquid drop with a hemispherical drop on top of a spherical steel surface, a significantly different geometry than the present study.

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The modeling of drop impacts on surfaces has been approached both theoretically and numerically in the literature. Of note, Chandra and Avedisian [11], Mao et al. [13], Roisman et al. [22], Okumura et al. [23] have developed analytical models based on conservation of energy. In the present study, the Chandra and Avedisian model is extended to the drop-drop impact on a surface, as experimentally investigated here, and is evaluated for its prediction of maximum spreading diameter. In addition to these prior analytical modeling approaches, numerical methods have also been applied to describe the behavior of single drops impacting a surface, many using the volume of fluid method. For examples of numerical prediction of drop-surface interactions see: Pasandideh-Fard et al. [12], Gunjal et al. [24], and Wildeman et al. [25].

In the present work we investigate the behavior of a falling drop concentrically impacting a hemispherical sessile drop, a phenomenon important in spray applications that take place in close proximity to non-wetting surfaces that produce well-defined sessile drops rather than liquid films. *We* experimentally observed using high-speed image acquisition, determine the influence of Weber number (*We*) on, and extend analytical conservation of energy methods to model the spreading behavior of post-impact drops.

2. Experimental method

The experimental setup for observing drop-drop impacts on a horizontal surface is depicted in Fig. 1. Water drops were generated using a NE-300 New Era syringe pump. The syringe pump forced deionized water (Evoqua deionizer) through a Hamilton Gastight syringe (model 1001, 1 mL) with a blunt tip removable needle (point style 3, 22 gauge, 2 in). The syringe pump was set to a flow rate of 0.2 mL/min. A sessile drop was first placed on the substrate by lowering the syringe pump to a location slightly above the substrate and allowing the drop to detach via gravity from the needle tip directly onto the substrate. The procedure provides a sessile drop whose shape is governed by surface-liquid interactions, minimizing any spreading of the sessile drop. After depositing the sessile drop on the substrate, the syringe pump is elevated to a previously determined height. At this height, the syringe pump operates at 0.2 mL/min forming a drop at the end of the needle which subsequently detaches due to gravity, falls, and concentrically impacts the stationary sessile drop below.

The high-speed camera (MotionPro X3 with 1280 × 1024 resolution and AF-S Micro Nikkor 40 mm lens) captures the impact and spreading/recoil dynamics of the liquid volumes on the substrate. The frame rate of the camera was 2500 fps with an exposure time of 2.6 μs. A function generator was used to trigger the high-speed camera for each trial. The camera and lens assembly provided a field of view of approximately 2.2 cm × 1.8 cm. A halogen light source and diffuser were used to provide back-lit illumination.

The substrate on which drop impact occurs was Teflon. The Teflon substrate sat on a lab jack, allowing it to be raised and lowered to bring the test location into the camera field of view, and was cleaned prior to experiments using a triple rinse each of acetone, isopropanol, methanol, and deionized water.

Experiments were completed for two sets of drop volumes: (1) collisions of drops of the same volume (13 ± 0.3 μL) described as “equal” and (2) collisions where the sessile drop (26 ± 0.6 μL) was twice the volume of the falling drop (13 ± 0.3 μL) described as “double”. Drop volume was determined via image analysis; full-zoom images were acquired and edge finding routines were used to determine drop volumes for the given syringe and flow rate. Experiments for each volume pair were carried out for the release of the impacting drop from different heights, yielding different impact velocities and Weber numbers. Following acquisition, images for each trial were processed to create a binary image from which the location of the liquid interface(s) could be defined and the dynamic geometry of the drops determined. A calibration image was used to convert from camera pixels to millimeters.

Experimentally achieving concentric impact was more difficult for higher Weber numbers; hence, multiple experiments were performed and only experiments in which the impacting drop centerlines were offset by no more than 5% of the base drop diameter (D_b) were considered. Within this degree of impact eccentricity, the results exhibited minimal deviation in spreading behavior as illustrated by the scatter in Fig. 7 shown below in Section 4.

3. Results

A schematic of the drop pair prior to impact and the coalesced liquid volume at the maximum spreading diameter is shown in

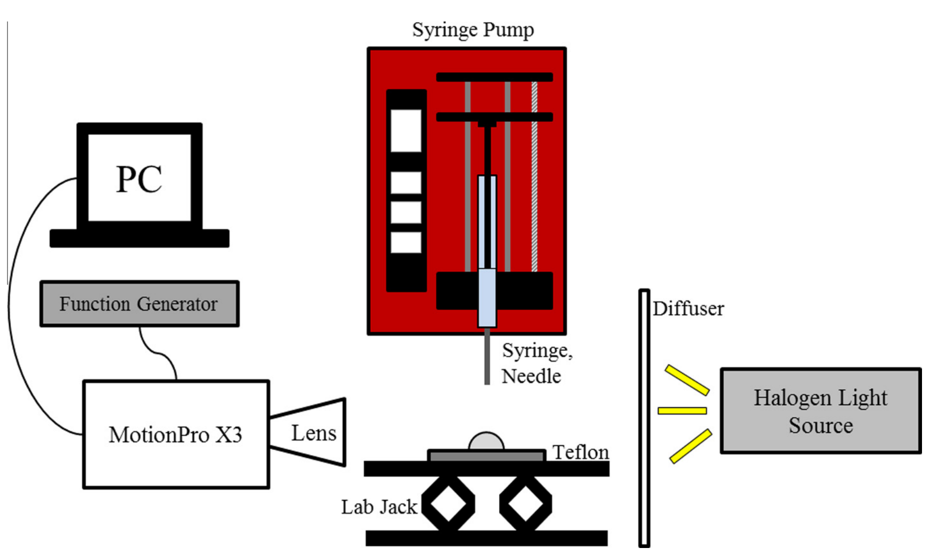

Fig. 1. Experimental apparatus: syringe pump and blunt syringe, Teflon substrate where the sessile drop is placed for concentric impact with the falling drop, MotionPro X3 high-speed camera and lens providing a side-view of the drop-drop impact, and light source and diffuser to provide back lighting.