Drop Fingering on Oblique Impact: Part 1—Experimental Data

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Abstract

Compared with other variations of drop impacts, the oblique impact has received comparatively little attention. Most experimental work detailed in the literature has focused on the perpendicular impact while subsequently varying other parameters. Indeed, it has been theorized that an oblique impact behaves much like a perpendicular impact except with the perpendicular component of the velocity being applicable to the behavior. But an oblique splashing drop preferentially splashes in the direction of travel (component parallel to the surface). Very little information exists to help describe how angled drop impacts differ from the perpendicular impacts. Motivation to better understand large-scale impacts has led to increased concern regarding these phenomena. Resources have been invested in experiments and modeling efforts to better describe the oblique splash problem.

Experiments spanned a range of conditions that involve between 0.2 and 10 cm diameter drops, velocities ranging from about 1 to 20 m/s, and impact angles from 90º to 45º (from horizontal). Data were recorded with high speed video for velocities of the spreading edge and splash at all locations around the circumference of the impact region. In addition, instability conditions were also evaluated. A significant database has been compiled that includes all relevant test parameters and measurements for each case. This work provides important new insight in which models can be developed for predicting impact, spreading and splash for angled impact.

Introduction

Large Weber number impacts are potentially encountered in transportation accidents, deliberate strikes like the attacks of September 11, 2001, and in some large industrial fluid applications. Because of the complexity, we strive to develop tools that can aid in the analysis of such events. A good literature review to this end is available in a recently completed document by Rein [1]. The perpendicular impact has been well studied while less attention is given to the oblique problem studied here. Indeed, in his recent review, Yarin [2] states in his conclusions that "the consequences of oblique impacts on dry surfaces are still insufficiently studied and understood." Since the review, there have been several studies that focus on small Weber number impacts without splashing [3-6]. But, in general agreement with this assessment for splashing drops, we have performed several series of tests aimed at discovering and quantifying the behavior of fluids impacting on surfaces at a large range of *We* where $We = \rho_f VD/\sigma$ with ρ_f being the fluid density and the velocity V is the perpendicular vector to the impact surface. The intent is to develop a reasonably accurate model for implementation in a spray code. Because the model must be capable of predicting millions to billions of drops, some empirical assumptions may be acceptable.

Because of complexity, data derived from impact studies are normally limited to that which can be extracted from photometric analysis. Size and form of the drop after impact is readily extractable from images. Splashing can generally be resolved. More energetic impacts will result in instabilities in the spreading drops, or fingers. These have been evaluated in the past by this research group for perpendicular impacts [7-8]. The previous work is extended by several test series focusing on oblique impacts. This report focuses on the fingering instabilities and the variations occasioned by the impact being oblique. In Part 2 of this paper series, a model is described that predicts the behavior of these data.

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Materials and Methods

Drop impact tests were done for a variety of liquids with impact angles from 90º to 45º (from horizontal). Three test facilities were utilized to accommodate drop sizes from 0.2 to 10 cm, different liquids, and ambient pressures ranging from 0.3 to 3 atm. In all cases, data were recorded with high speed Phantom digital cameras supplied by Vision Research. Frame rates varied form 4,000 fps to 17,000 fps. The number of fingers were counted at a radius of 2 to 3 drop diameters and verified by at least three observers from photometric images. The set-up for each test facility will be described separately below.

Small Droplet, Ambient Pressure

Drop impact measurements for small water and water–glycerin mixture droplets were conducted at the Photometric laboratory at Sandia National Labs. The droplets were created utilizing a dropper elevated above a smooth, 1 cm thick Plexiglas impact plate approximately 15 cm by 15 cm in size. The test series also included impacts onto roughed surfaces, but those results are not presented herein. The droplets were generally 4 mm in size and the impact velocity was controlled by varying the drop height above the impact plate. The cameras were placed below the impact plate where forward lighting was used to illuminate the droplet impact region. Ambient pressure at the lab facility for these experiments was approximately 0.85 atm due to an elevation of 1,700 m. Most tests were repeated between 4 and 10 times to generate an appropriate statistical sample.

Small Droplet, Pressure Vessel

Drop impact measurements as a function of pressure were conducted using an aluminum pressure chamber at the University of California Riverside Transport Phenomena Lab. This chamber was specifically designed and built to study the impact dynamics and heat transfer of liquid droplets under various pressure conditions, which cover the ranges of 20% below and 500% above atmospheric pressure. Two acrylic or quartz windows were mounted on both ends of the pressure chamber for imaging and illumination. Acrylic towers with different heights were used to obtain various droplet impact velocities ranging from 0.5 to 5.0 m/s. A commercial droplet generator (741 MD-SS, EFD Inc., East Providence, RI) was mounted on top of the acrylic tower to generate droplets of ~ 2 mm for water.

Imaging of the droplet impact phenomena was performed using a high-speed Phantom camera set at 10,000 fps. Lighting was provided by high-intensity tungsten halogen lamps. In order to fully capture the impact dynamics, imaging was performed both laterally and vertically as shown in Figure 1. Only one camera was available for this test series, so the experiments were repeated for each camera position. Splashing phenomena were relatively consistent, so this did not present a problem. Because of the restrictions of the pressure chamber, vertical images from below the impact surface were obtained using a mirror at preset angles to obtain a perpendicular image as shown in Figure 2. Between 2 and 4 duplicate runs were performed for each setting to confirm repeatability.

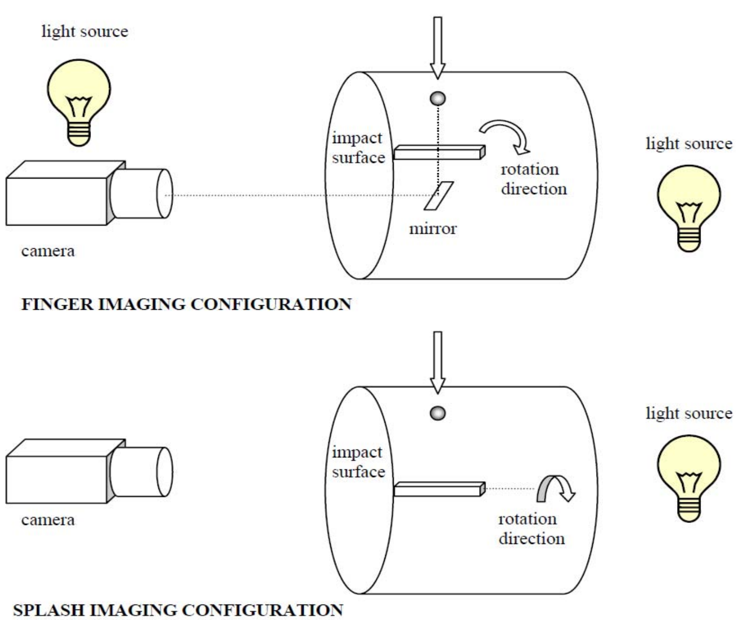

Figure 1. Camera and lighting configurations for splash (lateral) and finger (vertical) imaging.

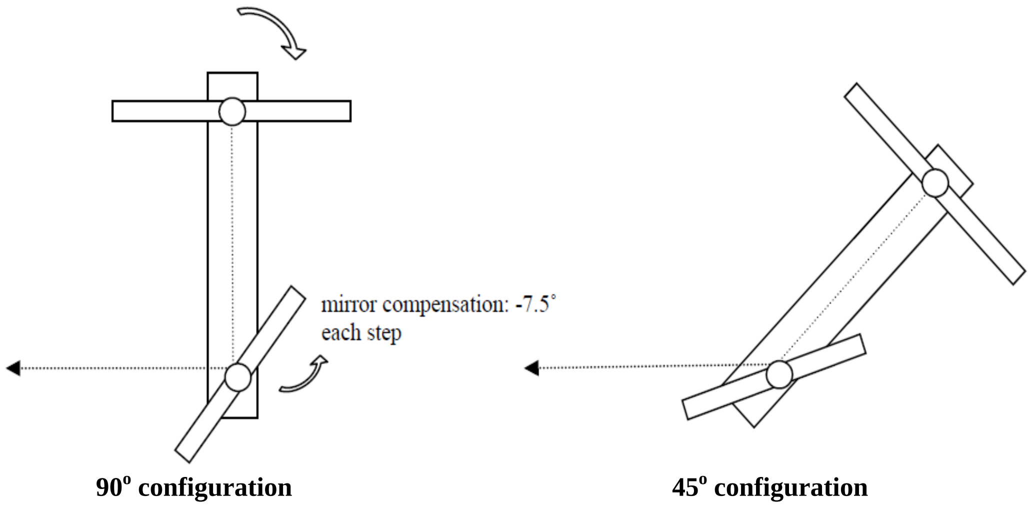

Figure 2. Impact surface and mirror configurations for finger imaging**.**

Large Diameter, High We Tests

The large diameter drop impact tests were conducted at the outdoor Sandia Drop Tower facility. The liquid was delivered to the impact plate in a spherical latex container (i.e. water balloon) in order to keep the liquid intact prior to impact. Immediately prior to impact, the latex was removed via sharp blade at the center of impact. For these, three different puncturing blades configured at 75, 60 and 45 degrees from horizontal were used on the angled drop test series. The blades were mounted on to the center of a 2.5 cm thick by 1.25 m long by 1.25 m wide smooth Lucite table top positioned approximately 25 cm below the diffuser plate. Since the table top was rotated and setup at different angles the spike angle configuration compensated for the angle of the table. The diffuser plate containing the oval shape hole in the center of the plate was position directly above the spike. The Lucite table top and diffuser plate were supported in place by a steel angle iron frames mounted on to a set of adjustable tri-pod stands placed on top the drop tower steel target; see Figure 3(a). Cameras were located underneath and to the side of the impact target table. The side camera was for an overall view and to verify that the latex was punctured and removed prior to the spherical liquid slug impacting the table. The ambient pressure for these tests was approximately 0.85 atm because of the higher elevation of the test facility (1,700 m).

A 10 cm internal diameter by 20 cm long PVC tube was attached to the bottom of the tower trolley beam shown in Figure 3(b). The purposed of the PVC tube was to hold and guide the latex container during the release. The balloons were placed inside the PVC tube and held in place by a thin sheet of aluminum foil that was taped to the bottom of the tube. The aluminum foil was cut with a small incision approximately 2 cm by 2 cm long cross-shape located in the center of the PVC tube. The incision on the foil provided minimum resistance to the latex container during the release, therefore minimizing the container distortion and rotation.

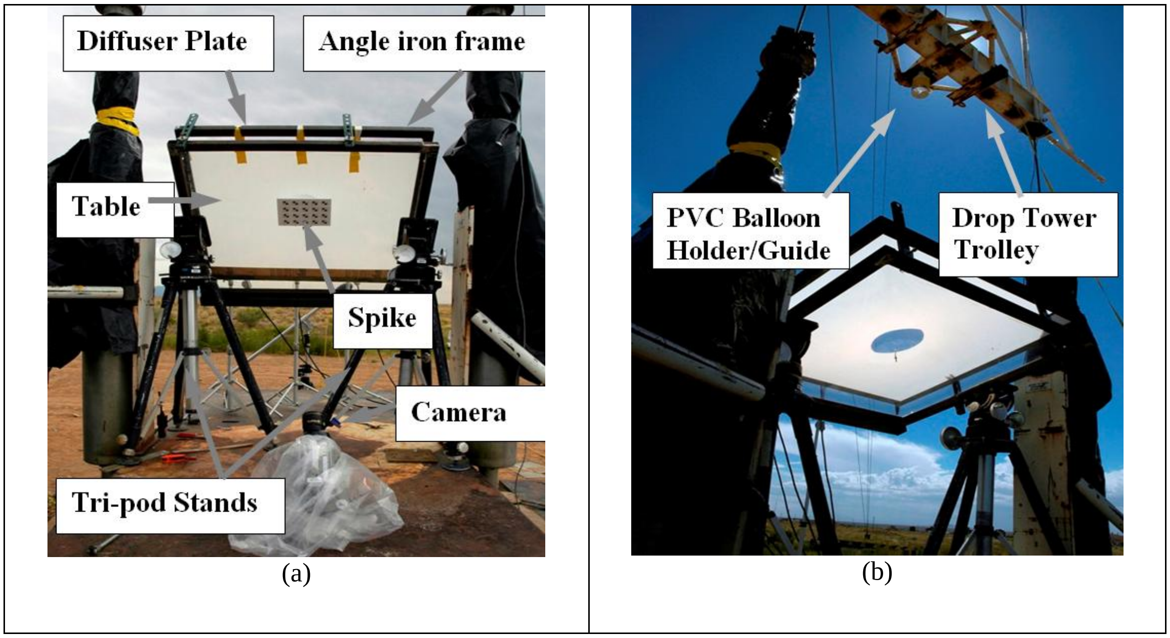

Figure 3. Experimental setup for large scale impact testing.

Results and Discussion

Measurements were taken to determine the total number of fingers (N_f), number of fingers in the up hill ($N_{f\text{-}HU}$) and down hill hemispheres ($N_{f\text{-}HD}$), and the number of fingers in each quadrant as shown in Figure 4. This was done for water over a wide range of *We* from 10^2 to 10^6 and at varying ambient pressure. Figure 5 shows results for the number of fingers as a function of *We* for angles from 90 to 45 degrees from horizontal. The experimental uncertainty for the data in Figure 5 is dependent on the *We*. At the higher *We* (>100), the uncertainty is 25% and at small *We* (<100), the uncertainty approaches 100% at the threshold of where instability formation occurs.

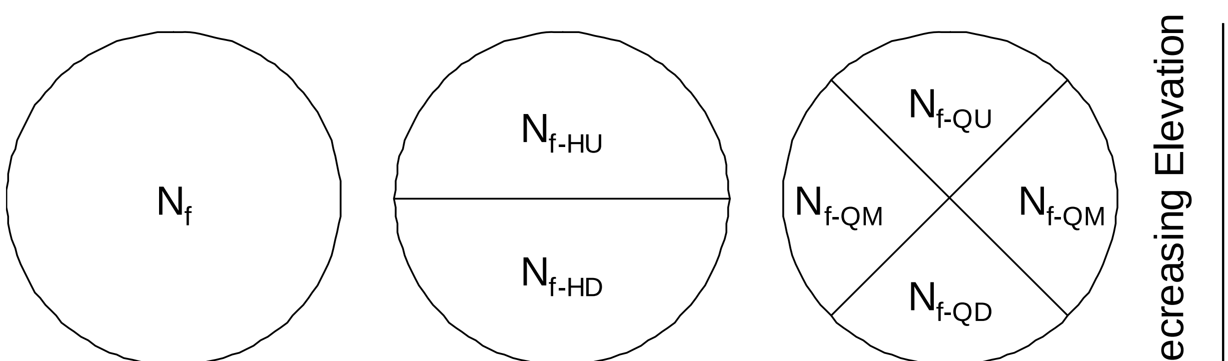

Figure 4. Schematic for measuring the number of fingers at varying impact angles.

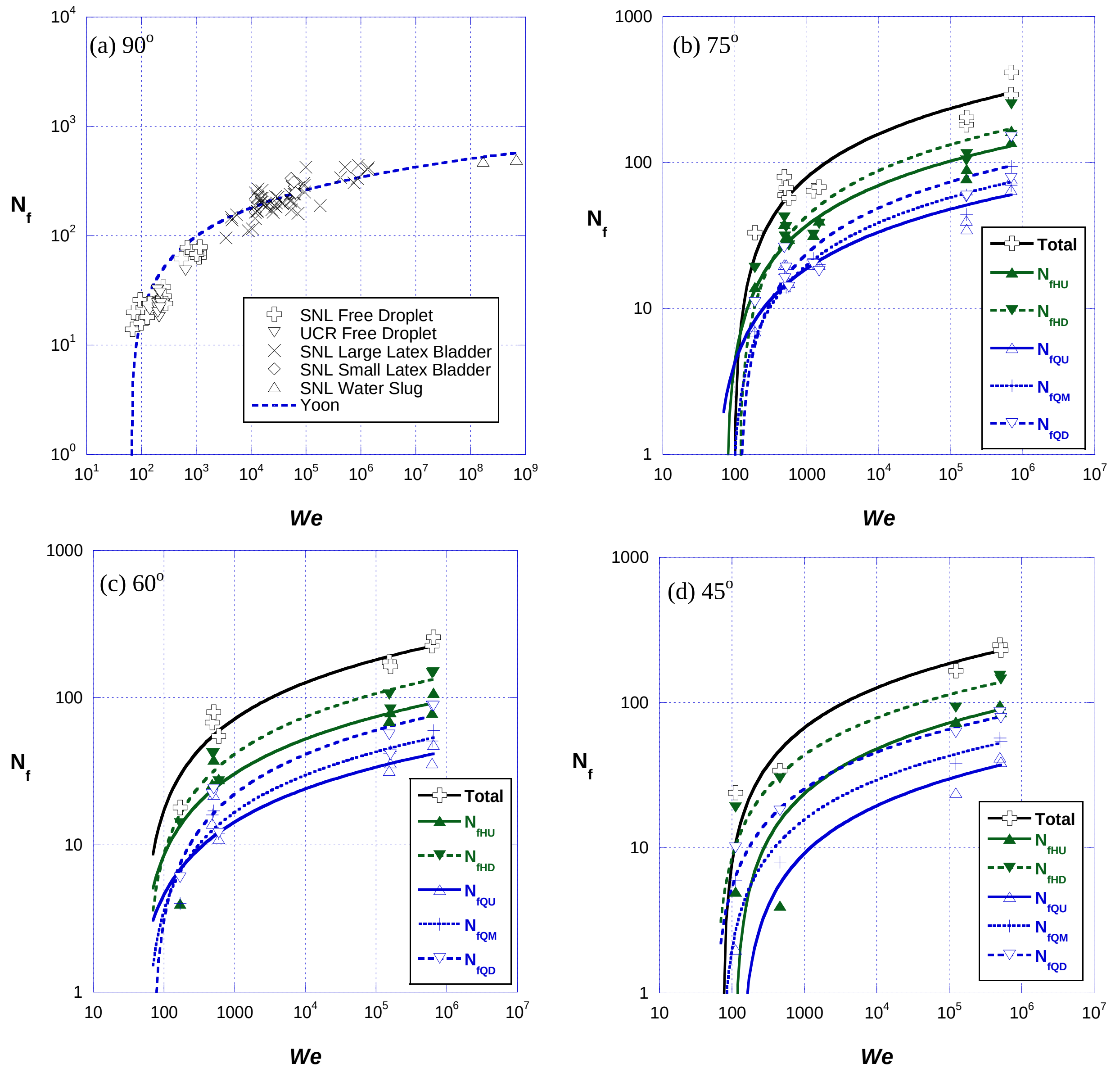

Figure 5. Number of fingers (N_f) vs. *We* at (a) 90°, (b) 75°, (c) 60°, and (d) 45° impact angles for water impacts. Results are from the Sandia small droplet tests, UCR pressure vessel tests at 1 atm, and the Sandia drop tower tests.

The results from Figure 5 demonstrate that 1) the number of fingers follow the relationship as described by Yoon et. al. (2007) regardless of the experimental method for creating the impact event, 2) the total number of fingers decreases as impact angle goes from 90 to 45 degrees, and 3) the number of fingers in the downward direction are consistently higher than the number spreading in the uphill direction. This effect becomes more pronounced as the impact angle goes from 90 degrees to 45 degrees. In fact the number of fingers in the downward direction are almost a factor of two higher when compared to the uphill direction when the impact angle is 45° (Figure 5d).

In addition, measurements were taken for small drop impacts at angles from 90 to 45 degrees with varying air pressure. Results of these tests are in Table 1. As observed in the test results from Figure 5, the total number of fingers decreases as impact angle goes from 90 to 45 degrees. Ratios of the hemispherical number counts are presented, with the 90 degree results being suggestive of the uncertainty for these tests (i.e., those ratios should all be '1'). With the added variable of pressure it was observed that the number of fingers may increase with pressure and this effect appears most pronounced at the 45 degree impact angles. Pressure also appears to affect the ratio of fingers formed in the uphill over the downhill direction. In general, the ratio is decreased as a function of decreasing pressure. This significance is not unexpected based on the work in Jepsen et. al. (2006) where it was shown that air and increased air pressure can create splashing and affect fingering phenomena.

Table 1. Number fingers at various pressures and *We* for the UCR pressure vessel tests. The drop heights and impact velocities are the same for a) and b) but the effective *We* changes due to impact angle.

a) 18 cm drop height	90° (We~175)		75° (We~160)		60° (We~150)		45° (We~125)	
P (atm)	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f
.3	1.02	49	.67	20	.27	19	.25	10
1	.97	59	.74	33	NA	NA	.37	13
3	1.04	49	.84	35	.83	22	.42	16

b) 80 cm drop height	90° (We~600)		75° (We~560)		60° (We~520)		45° (We~425)	
P (atm)	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f	N_{f-HU}/N_{f-HD}	N_f
.3	1.07	63	.83	66	.57	38	.14	25
1	.87	51	.95	59	.81	56	.57	35
3	.90	52	.89	51	.94	42	.63	39

Conclusions

During droplet impact events, there are many cases where the impact angle is something other than perpendicular. Understanding how impact angle affects fingering instabilities and splash is of vital importance when developing models to predict such events. The oblique impact of water droplets was studied experimentally as a function of *We* and ambient pressure. Impact angles ranged from perpendicular to 45 degrees. Drop diameters of 0.2 to 10 cm and impact velocities from 1 to 20 m/s were studied. The results of this testing demonstrates that impact angle affects the total number of fingers as well as the number of fingers spreading uphill, downhill or sideways from the impact point. The testing done at various pressures also demonstrates angle and pressure both affect the fingering formation. The data base from this testing should allow for significant advances in model development for impact and dispersion of liquid droplets.

Acknowledgements

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