



Investigation of Cavitation in Water Droplet Breakup from Shock Waves

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The deformation and breakup of water droplets impacted by a shock wave has been largely attributed to surface mechanisms. This study investigates the possibility of cavitation-induced droplet breakup. Shock waves of Mach 4 are used in this study to impact groups of droplets, both groups of degassed droplets and a group of non-degassed droplets. Distilled water droplets on the order of 1-3 mm in diameter are introduced into the shock tube. High speed images and deformation plots are used to explore the existence of cavitation in the droplets, as well as how they deform comparatively.

Nomenclature

fps = frames per second
 MS/s = Mega-Sample per second

I. Introduction

Droplet interaction with shock waves (SWs) is a well-documented and thoroughly studied phenomenon [1-4]. Prior experiments in this field investigated the mechanism of droplet breakup and how the droplet morphed as time passed beyond the impact. The breakup mechanism was determined to be surface tension-based effects, separated into regimes based on Weber number (We), the ratio between inertial and surface tension-based forces. In this regard, low

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We is associated with Rayleigh-Taylor Piercing and high We is associated with Shear-Induced Entrainment [5]. For some situations, surface instabilities may be the root cause of the droplet breakup [4]. In many instances, however, a different mechanism is likely a main driver and that is cavitation within the droplet. Recent experiments have captured cavitation events inside a 2D cylindrical “drop” [6], while another has observed a jet from a SW impacting a water droplet with an embedded vapor cavity. In both, the cavitation strongly influenced the droplet’s deformation morphology [7].

Experiments were performed using a shock tube to inject water droplets into the path of a supersonic SW. These experiments were preliminary in nature, designed to test the capability of the shock tube to perform these experiments as well as to determine the efficacy of the diagnostics being used. Additionally, a target Mach number was selected for all shocks in order to contribute to a gap in the literature. When performing a literature review, Mach numbers found tested for shock-droplet studies were mostly within the 1.1-3 range [1, 4, 7-17], with a few outliers of around 3.5 [18] and two papers with above Mach 10 [19, 20]. There seems to be a gap in the literature between Mach 3.5 and Mach 10 in terms of repeated tests at these elevated Mach numbers. This paper intends to provide data at approximately Mach 4.

II. Experimental setup

The experiments were run in the University of Central Florida (UCF) shock tube facility. The shock tube is a high-purity 14.17 cm diameter stainless steel ideal device which is divided into two sections: the driver and driven sides. The driver side of the shock tube is where the high-pressure gases are filled in order to burst a Lexan diaphragm sandwiched between the two sides. This high-pressure gas is typically nitrogen or helium; in the experiments described below, helium was used. The driven side of the shock tube houses the low-pressure gas which is typically the test gas. For the experiments described below, air was used. Additionally, the Lexan diaphragm which separates the two sections of the shock tube was 2.03 mm in thickness, scored to a slightly smaller thickness to allow bursting along directed lines, allowing for a high pressure ratio between the shock tube sections. Within the driven section of the shock tube is the testing and measurement region where the diagnostics and viewing windows are located. These windows are 3.81 cm x 16.51 cm and are in the same region as the droplet injection system.

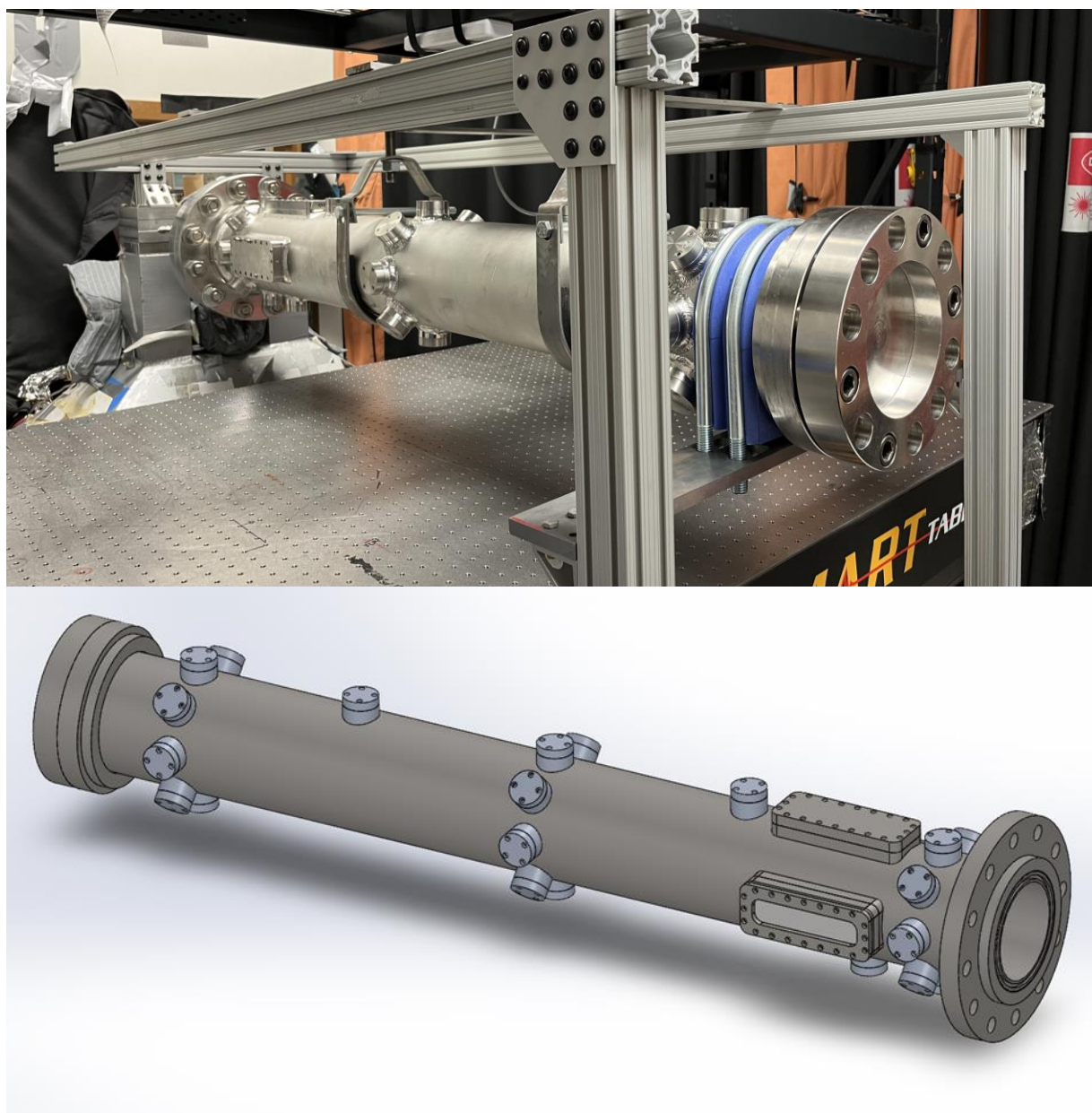


Figure 1: UCF Shock Tube extension and CAD.

The experiment begins when the pressure differential becomes significant enough for the Lexan diaphragm to burst. Using previous experimental data, an educated guess can be made as to what driver pressure will burst the diaphragm. Knowing this value, a continuous stream of droplets can be injected at a pressure lower than the estimated breaking pressure. Once it reaches breaking pressure, the diaphragm will burst and a SW will form and travel down the length of the driven section of the shock tube. When it crosses a specified PCB, the diagnostics will trigger to capture the impact of the droplet(s) from the SW. The droplet injector is a custom designed injector system which connects via solenoid to a small reservoir filled with water. A pressure differential is applied to the reservoir, using a syringe pump, which pushes the water through the piping and the solenoid into the shock tube in the form of a grouping of droplets. The water used in these experiments was distilled and two of the three were degassed for a period of more than 12 hours to ensure that no dissolved gases remained present in the liquid. Additionally, for comparison, one experiment is included where the water was not degassed.

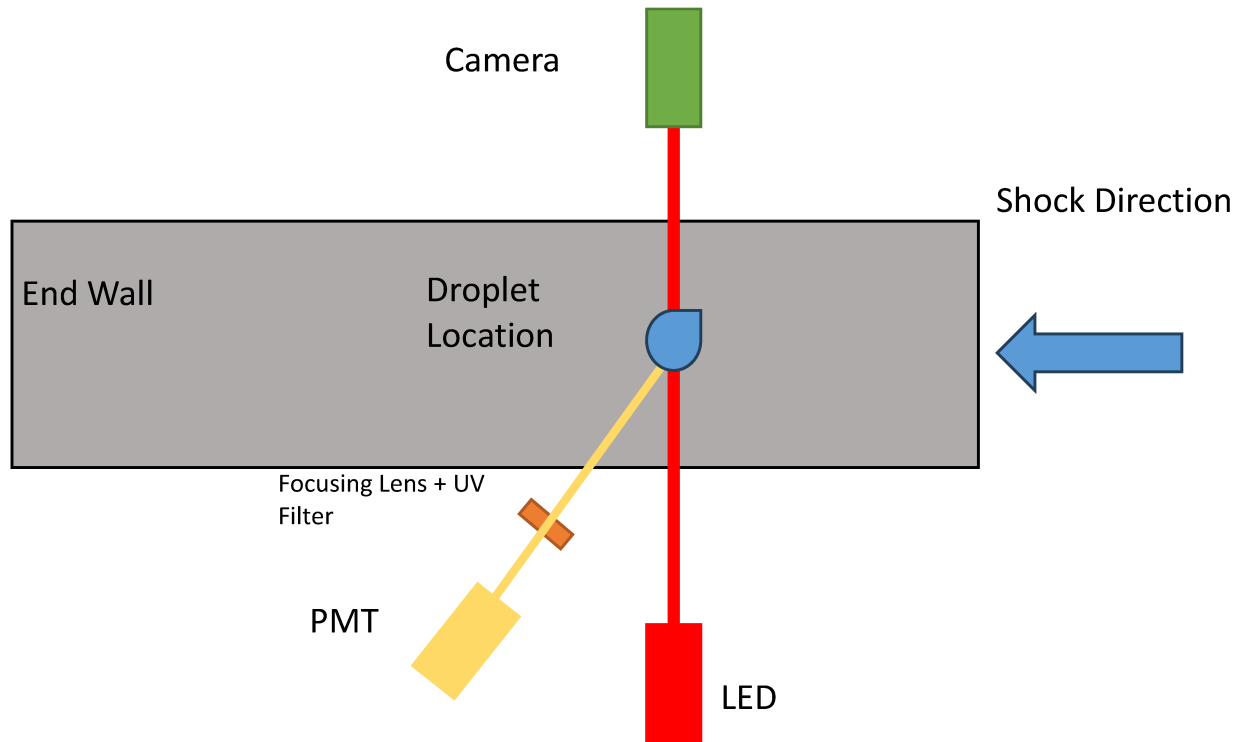


Figure 2: Schematic of diagnostic locations.

The impact is recorded using a Photron FASTCAM SA-Z. The recording was done at 80,000 and 210,000 fps with a resolution of 384x160 and a shutter speed of 3.15 μ s. Background subtraction was applied to the images in order to pull solely moving particles from the frames. As a result of this, some artifacts appear in the frames where the shock wave is passing. This allows for the rounded edge of the light source to be seen in the images. Data acquisition was done through an NI PCI-6133-unit sampling at 2.5 MS/s. All triggering and data collection was done through an in-house LabVIEW program.

In an attempt to capture cavitation, a Thorlabs PMTSS photomultiplier tube (PMT) was used to detect the light emissions coming from cavitation. This PMT was coupled with a 310 nm narrow bandpass filter intended to block broadband lighting coming from extraneous sources and to focus in on the desired wavelength. It can be noted in the literature that cavitation emits light around the 310 nm wavelength due to the presence of OH^* [21, 22]. The light coming from the vapor cavity collapse was also intended to be collected and focused using a focusing lens with a focal length of 60.

III. Results

The impact between a SW and a group of water droplets is shown below, where the shock wave is moving at about Mach 4 and the droplets are anywhere between 1-3 mm in diameter. Experiments of this nature are preliminary for upcoming work, and only camera data was obtained to compare.

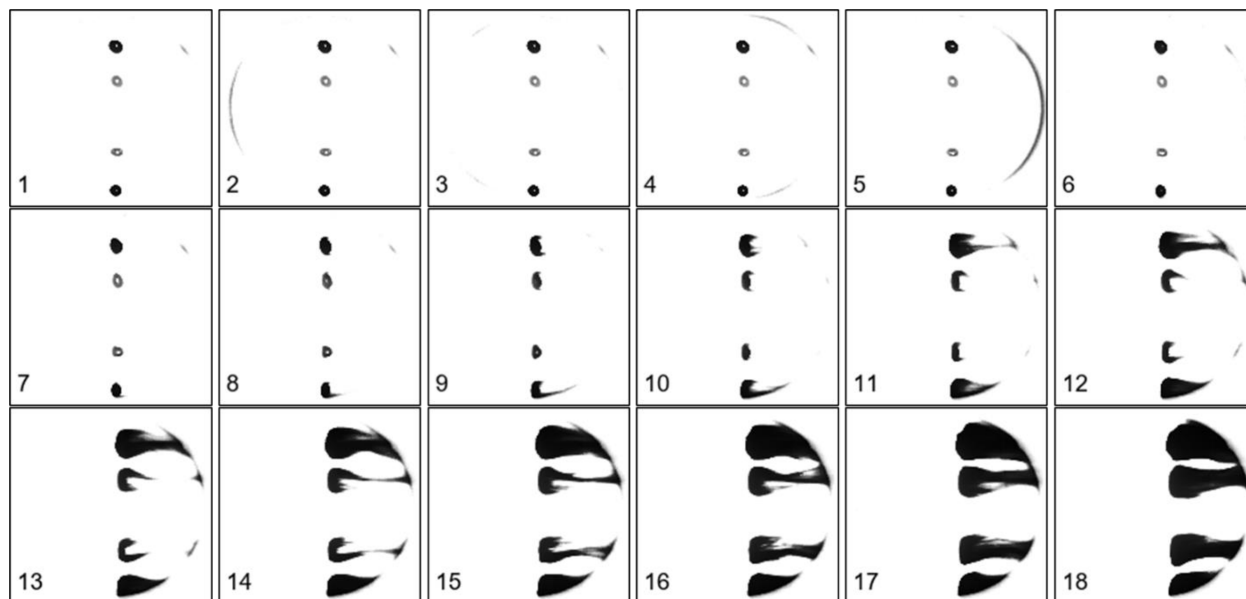


Figure 3: Group of droplets being impacted by a Mach 3.9 SW.

The first experiment shown is a group of droplets ranging from 1-1.65 mm in diameter being impacted by a SW moving at Mach 3.9. It is important to note with these experiments that there is a visual distortion present in the images. From frame 9 onward, the trailing droplet wake consisting of vapor and daughter drops is distorted and elongated. For the purpose of determining the impact of cavitation on droplet breakup, distortion in the aft end of the droplets is not of concern, however it is present. In terms of droplet breakup, it can be seen in frames 9-12 how the two central droplets undergo flattening and stripping from the upper and lower points of the bulk of the droplet mass. The droplets in these experiments are all three-dimensional, so this stripping fluid is occurring radially around the droplet mass.

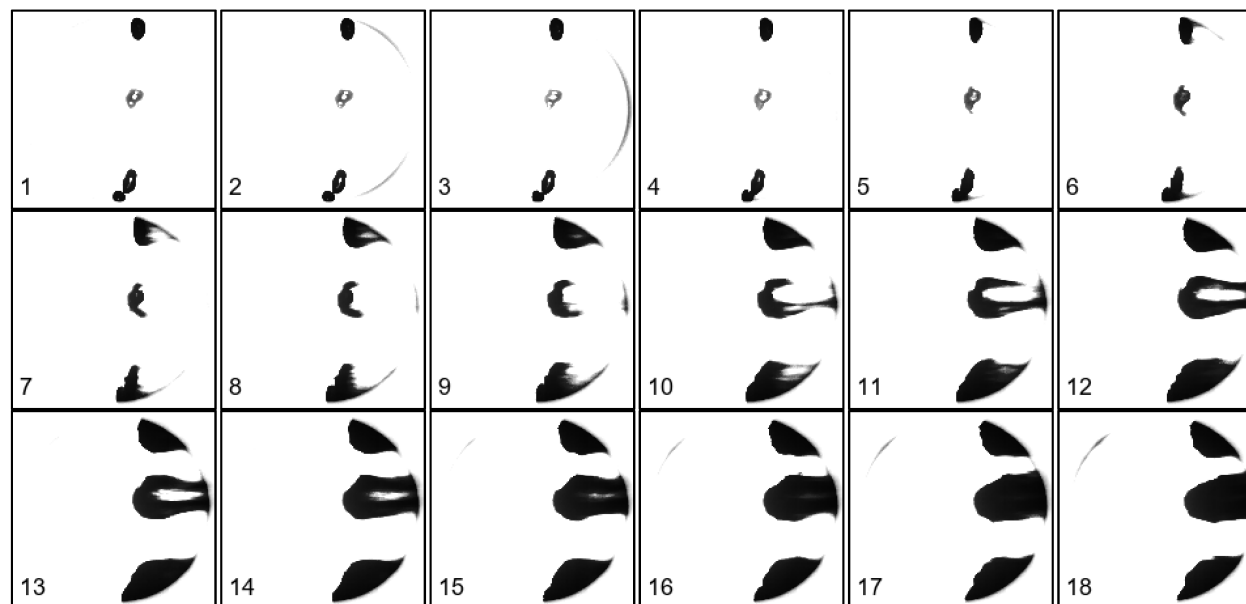


Figure 4: Group of droplets being impacted by a Mach 3.92 SW.

The second experiment shown is a group of droplets in the range of 1.5-2.5 mm in diameter being impacted by a Mach 3.92 SW. Again, for this experiment, the visual distortion of the droplet wakes is present. Additionally, the SW is passing during frames 2 and 3, which is represented by the visibility of the edges of the light source on the right side of both frames. In this particular droplet breakup sequence, the droplet present in the middle of the frames shows a

strange breakup pattern comparatively to the others and to literature, which will be referred to later as the “odd drop”. This droplet is also oddly shaped and seems to be multiple droplets stuck together, which is likely the cause of the deformation forming a strange shape as time progresses. Between Figure 3 and Figure 4, some differences can be noted in the droplet deformation. In Figure 3, the droplets have a more standard spherical shape which led to a smoother droplet face in the windward direction. This is in opposition to the droplets in Figure 4, where the oddly shaped front faces of the droplets as they were falling created a more rippled windward surface.

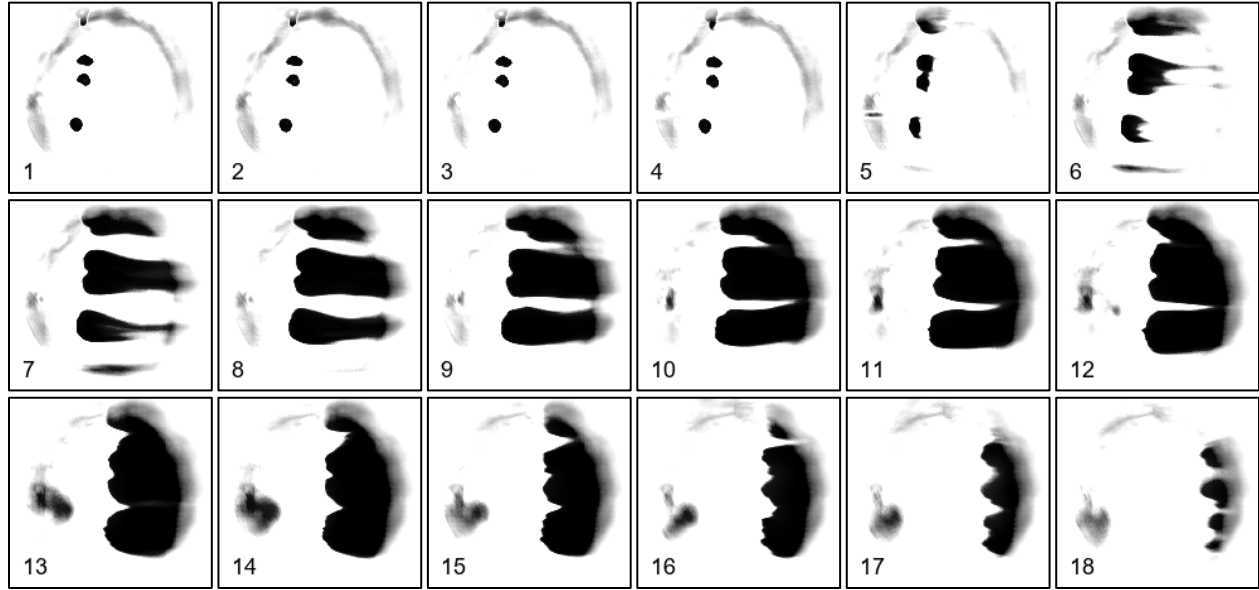


Figure 5: Group of non-degassed droplets being impacted by a Mach 3.87 SW.

Finally, the third experiment displays a group of droplets ranging from 1.5-2 mm in diameter (excluding the top droplet which appears as two droplets merged in the imaging) being impacted by a Mach 3.87 SW. Once again, visual distortion is present in these images, as well as an increased concentration of liquid water on the windows which is causing the additional dark spots in the frames. These droplets experience typical droplet breakup at this increased Mach number region, which includes the stripping from the equators of the droplets as well as a gradually flattening and radially expanding droplet mass. An important note for this particular droplet breakup sequence is that the frame rate here is significantly smaller than the previous two experiments shown. In this experiment, the frame rate is 80,000 fps compared to the previous experiments which were recorded at 210,000 fps. This leads to a difference in time between the frames (12.5 μ s for this experiment versus 4.76 μ s for the prior two experiments), which can change the way the breakup is perceived. In this case, we can see that the droplets appear to have traveled through the frame faster than the others, which is not the true case. However, of note in these images is a sawtooth like shape on the leading edges of the droplets breaking up in Figure 5 frames 15-17. This is similar to the morphology seen in [23]. The droplet sequence from Figure 3 also experiences this sawtooth morphology towards the end of its breakup, which was not included in the frames presented. Also visible in this droplet breakup sequence is a jetting present on the windward face of the bottom droplet in frame 12 and 13. This jet eventually transforms into the sawtooth shape previously discussed. Additionally, this grouping of droplets in Figure 5 was not subjected to the degassing procedure that the other experiments were. The presence of cavitation should change the breakup of the droplets, and the lack of degassing in this experiment should have allowed for dissolved gases to be present in the water.

Figure 6 shows a selection of three droplets, one from each of the experiments displayed above, and the nondimensional deformation and time from these experiments. Non-dimensionalizing was done to remove dependence on camera frame rate and changing diameters and velocities of the droplets. Deformation was non-dimensionalized using droplet initial diameter, where deformation is simply the expansion in the vertical direction as the droplet breaks up. Time is non-dimensionalized using a critical time defined in [23], which takes into consideration the densities of the drop and the surrounding gases, the velocity of the flow around the drop, and the diameter of the drop prior to being impacted by the high-speed flow. From this graph, there is very little noticeable difference between the degassed and non-degassed droplets. The orange line representing the “odd drop” shows a difference in breakup at the beginning due to the strange shape of the droplet and it being merged with another smaller droplet. The sharp

expansion and shrinking of this drop is due to the way this droplet sheds the outer bits of droplet mass before stabilizing into relatively normal deformation.

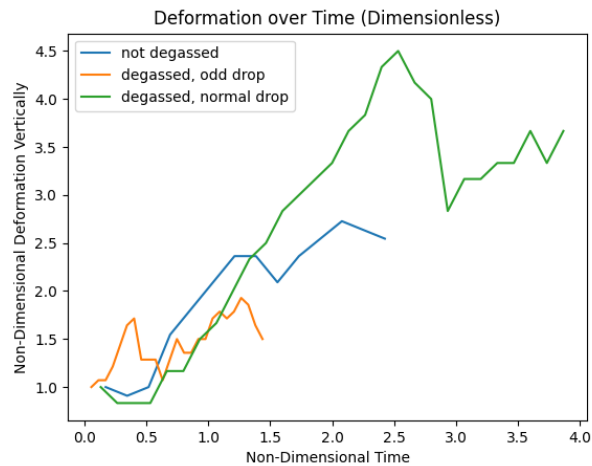


Figure 6: Dimensionless deformation in the vertical direction over dimensionless time from one droplet from each of the experiments displayed above.

When it comes to the usage of the PMT, no verifiable data was gathered beyond noise from the diagnostic itself. This is due to a few reasons, mainly being that the PMT was found to be misaligned with the droplet location. Additionally, with multiple droplet locations from the grouping of droplets, as well as the fact that they are moving in the frame, it is rather difficult to align the PMT properly in a way that will capture emissions in every experiment. This will be rectified in future experiments by utilizing tools to keep the droplets steady, as well as to only inject single droplets at a time versus these experiments where there were multiple droplets in each frame.

IV. Conclusion

This study investigates the possibility of cavitation being an impactful force on droplet-shock breakups. The literature shows the possibility of this and there are initial signs from the breakup of these droplets that may indicate cavitation in the droplets. More work needs to be completed utilizing the PMT to obtain more conclusive evidence, as well as a more rigorous testing of individual droplets rather than groups of droplets which can interfere with one another. Additionally, a higher frame rate camera will be used to obtain more detailed images of the droplets, as well as an acoustic levitator which will allow for individual droplets to be maintained in one place and directly impacted with SW without external interferences.

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