Laser diagnostics for characterization of sprays formed by a collapsing non-equilibrium bubble

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Abstract. In this paper, we investigate the use of laser diagnostic tools for in-plane imaging of bubble induced spray using a laser sheet and Mie scattering technique. A perspex plate of thickness 10 mm with a hole of diameter 1 mm in the center is placed in the middle of a glass tank filled with water such that the top surface of the plate coincides with the water surface. A bubble is created just below the hole using a low-voltage spark circuit such that it expands against the hole. This leads to the formation of two jets which impact leading to a spray and break-up into droplets. The spray evolution is observed using a laser sheet directed in a plane through the center of the hole. The illuminated plane is imaged using a high-speed camera based on the Mie scattering from glass beads suspended in the liquid. Results show that Mie scattering technique has potential in studying bubble-induced sprays with applications such as in fuel sprays, drug-delivery etc, and also for validation of numerical codes. We present results from our ongoing experiments in this paper.

1. Introduction

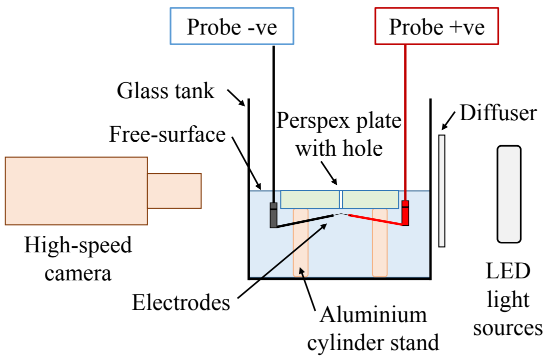
An oscillating non-equilibrium bubble in the presence of a non-uniform pressure field can lead to the formation of a high-speed jet in the bubble during its collapse. This can occur in the presence of a free surface [1-2], a rigid boundary [3-6] or due to the interaction of the bubble with a shock-wave [7-9]. The jet while thought of as a mechanism for cavitation damage, can also be used to actuate flows at small scales. For example, the jet in a collapsing bubble has been shown to lead to pumping in both water [10], and viscous fluids [11] when there is a hole in the boundary at the location of jet impact. Recent work [12-14] has further shown that if the bubble expands nearly hemi-spherically against the hole in a plate positioned on the surface of a liquid, it can lead to the formation of two jets - an initial slow jet during the bubble expansion, and a faster second jet during the collapse of the bubble towards the wall. The interaction of the two jets can lead to the formation of fine sprays and droplets [12-13] and also high-speed jets at the micrometer length scale with potential application in needle-free drug delivery [14].

Study of the formation of fine spray is particularly relevant for studies on fuel atomization for better combustion and mixing. The spray characteristics such as droplet size distribution and jet/spray velocity give particularly useful information. One approach for such characterization is the Mie scattering technique where laser is used to illuminate a plane and the phenomena occurring in the plane are visualized using glass-beads (that scatter light) and collected by a camera through a narrow band-pass filter. In bubble related studies, the scattering of light by bubbles itself can give information on the bubble size [15-16]. The technique has also been used to study the droplet size in aerated sprays [17] and for collapse of a sonoluminescing bubble [18].

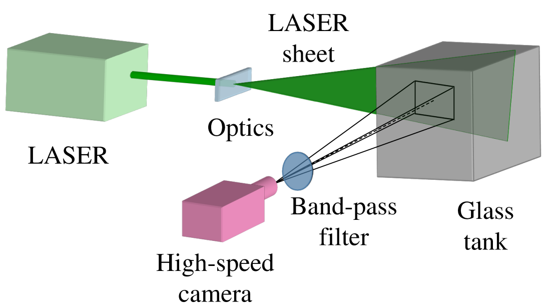
In this paper, we explore the possibility of using Mie scatter technique to characterize the spray formed due to bubble-induced jets. To create the spray, we use a similar experimental set-up as Karri et al. [12], but with an improved circuit for creating the spark bubble as presented by Goh et al. [19] which gives repeatable bubble sizes. A planar sheet of light using a laser is used to illuminate the plane of the hole. Micro-metric glass bead particles dispersed in the water scatter the incident radiation and these are then imaged using a high-speed camera. Preliminary results show that this technique can be applied to characterize the spray and thus give further insight into the potential of bubble-induced sprays in various applications.

2. Experimental set-up and procedure

The experimental set-up used is shown in Figure 1 (a). It comprises of a glass tank (250 mm × 250 mm × 250 mm) which is filled with water to nearly 75% volume. A perspex plate (80 mm × 80 mm × 10 mm) with a through-hole of 1 mm diameter in the center of the plate is positioned such that the top of the plate coincides with the free-surface. A low-voltage spark circuit [19] is replicated here and used to generate a bubble just below the hole. The circuit uses the principle of charging capacitors to a voltage of 60 V through a DC power supply, and then allowing them to be sparked through a pair of electrodes which are placed in the water. The charging, discharging and sparking circuits are connected to relays and a MOSFET, and the different parts of the circuit are controlled using an NI-DAQ (model USB-6008) through a LAB-view program. The bubble expansion and collapse below the plate leads to two separate jets which are then visualized using Mie scattering technique.



(a) Line-of-sight imaging



(b) High-speed Mie scatter imaging

Figure 1. Experimental set-up.

We first tested the repeatability of the bubble sizes obtained using the circuit before studying the bubble under the hole. For these experiments, the sparking electrodes were placed in the tank such that they are at least 10 diameter lengths away from the nearest wall. The electrode length used were L = 10 mm. The capacitors were short-circuited through the electrodes to create a bubble and the bubble growth and collapse was recorded using the high-speed camera with diffused back-lit illumination. For the experiments involving the bubble near a holed plate, we used planar imaging using a laser. Here a continuous laser beam (532 nm wavelength) is projected through a cylindrical lens (f = -15 mm) to form a sheet of 1 mm thickness which passes through the central plane of the hole in the plate. The sheet is in a direction perpendicular to the camera as shown in the Figure 1 (b). Micro-metric glass beads (TSI, 8-12 μm diameter) are dispersed in the water as seeding particles to generate the Mie scatter. As the fluid is actuated

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due to the bubble growth and collapse through the hole, the glass beads also move along with the water (in the jets) and reflect the laser radiation. The Mie scatter light is captured by the camera through a narrow band-pass filter (wavelength: 532 nm ± 10 nm) to indicate the movement of the jet. Image processing (inversion) is then done on the images using MATLAB to get details of the flow.

3. Results and Discussion

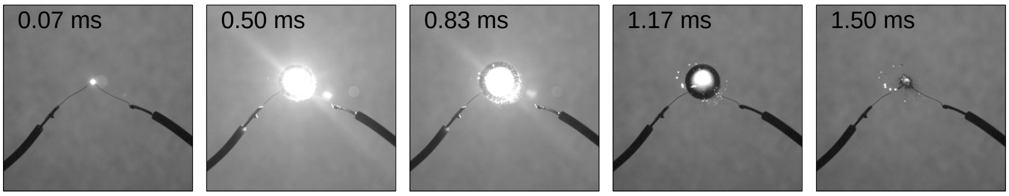

Figure 2. Evolution of a typical bubble using the spark circuit.

Figures 2 and 3 shows details about the bubble created by the spark-circuit. Figure 2 shows the evolution of a free-field bubble with time. The electrodes are short-circuited at t = 0.00 ms (when the spark begins), and the spark is shown here at t = 0.07 ms. The bubble grows, reaching a maximum size (around 8 mm diameter) around t = 0.83 ms, and collapses by about t = 1.50 ms. As shown in Figure 3, the maximum size obtained is slightly smaller than those by Goh et al.[19] possibly due to differences in the electrode material and wires used. The consistency of bubble sizes is necessary to get useful information from the Mie scatter technique in characterizing the spray.

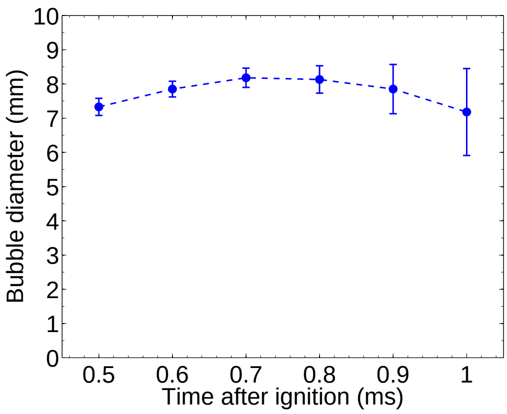

Figure 3. The variation of the bubble radius with time as obtained from five different experiments on a free-field bubble. The error bars show ± standard deviation indicating good repeatability of the bubble-sizes particularly at its maximum size.

Figure 4 shows the images obtained by the Mie scatter technique of the bubble expanding and collapsing below the hole in the perspex plate. The times after ignition (in milliseconds) are shown on top of each image. The position of the plate and the hole is shown in all the 6 images by two rectangles with a narrow gap(hole) in the middle. The bubble can be seen expanding at t = 0.24 ms. At t = 1.22 ms, the bubble has nearly collapsed and a faint first jet can be visualized on top of the plate. The next snapshot at t = 2.07 ms shows the situation after the second jet due to bubble collapse has impacted on the first jet. The evolution of the jet and its break-up into sprays (from the sides of the jet) can be seen from t= 2.44 ms to 3.66 ms. The images in this sequence were taken at 41,000 fps with an exposure time of 23 μs. The last two frames show 2 consecutive images of the spray at t = 3.63 ms and 3.66 ms respectively which can be processed further using a Particle Image Velocimetry (PIV) software, say to obtain the velocity information. This forms part of our ongoing study.

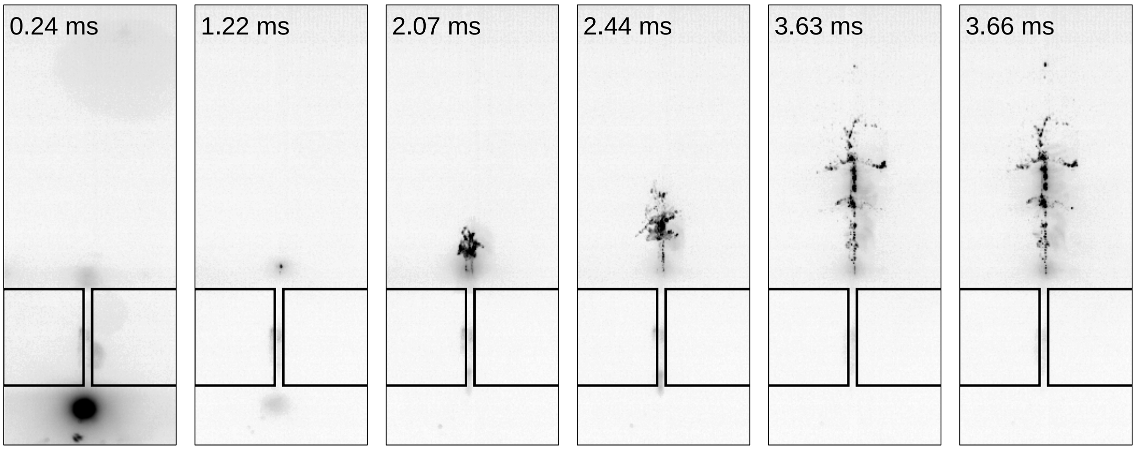

Figure 4. Mie scatter images of spray evolution formed by a collapsing non-equilibrium bubble. Images are normalized to the peak signal within the image sets.

4. Conclusions

An experimental set-up to use Mie scatter technique to visualize the sprays formed by bubble induced jets has been developed. The jets were produced by the collapse of a non-equilibrium oscillating bubble below a holed plate positioned on the surface of water, which leads to spray formation. A laser-based Mie scatter technique to visualize the sprays in the plane is demonstrated in this paper and will be expanded further to measure the flow-field data from the sprays.

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