JET FORMATION FROM BUBBLE COLLAPSE AT A FREE SURFACE

Krishnan Sangeeth[*], Baburaj A. Puthenveettil[*a)] & Emil J. Hopfinger [**]
[*] *Department of Applied Mechanics, IIT Madras, Chennai, 600036, India*
[**]*LEGI-CNRS, Grenoble, France*

Summary We present results of experiments conducted to study bursting of air bubbles at a free surface, for the range of bubble radius 0.42 mm < R < 2.7 mm, in water and glycerol-water solutions. We show that the jet velocity increases with decrease in radius as 1/R till R= 1 mm for glycerine- water, below which the velocity has an opposite dependence on R. The stages leading to jet formation are presented from high speed imaging of the process.

Introduction

Bursting of bubbles at the free surface of a liquid results in the formation of fast moving liquid jets. Duchemin et al (2002), performed simulations of this phenomena for a wide range of bubbles and found that the velocity varied as $R^{-1/2}$ for R > 0.5 mm, where R is the undeformed bubble radius. Boulton Stone and Blake (1993) however found a R^{-1} variation of jet velocity for the same range of R, using boundary integral simulation. These contradicting results are yet to be verified experimentally in fluids of different viscosity. The physical mechanism behind these scaling of jet velocity is still not clear, since various theories predict differing exponents of R in the relation for jet velocity (Longuet- Higgins, 1995, Katz, 1999). It is also important to explore the similarities of a cavity collapse at the free surface to other physical singularities in nature such as collapse of standing waves (Zeff et al, 2000).

Experimental setup and measurements

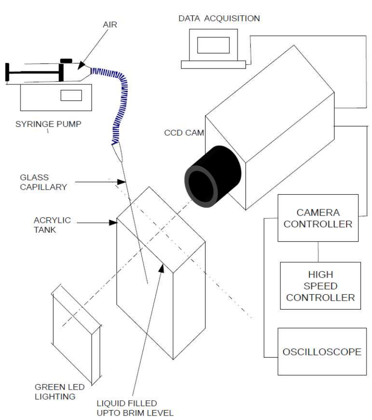

Fig 1: The schematic of experimental set- up

We study the collapse of a bubble at a free surface, and the subsequent jet formation, using the setup shown in figure 1 in water and glycerol-water mixture (68.3% of glycerol). The liquid was taken in a transparent acrylic tank of 3.5x5 cm^2 cross sectional area and filled up to the brim level for avoiding meniscus. Capillary tubes of different sizes were used for producing bubbles of sizes 0.42 mm < R < 2.7 mm inside the liquid. Air was fed into the capillary by operating a syringe pump running at constant discharge. The discharge was selected in such a way to avoid crowding of bubbles at the free surface, thereby eliminating the possibility of bubbles merging. The bubble released from the capillary stays at the free surface for a short time and then bursts. This bursting process was captured by a high speed CCD camera with high intensity LED back lighting and at frame rates < 19000 Hz. The following measurements from the images were conducted. 1. undeformed bubble radius R, obtained from the image of the rising bubble in the liquid, 2. static parameters of the bubble and 3. the sequence of bubble bursting.

Results

The variations of the static parameters of the bubble at the free surface in figure 2(a) with respect to R were studied. Equating buoyancy force to surface tension force at the rim section, $R_r /R \approx 0.81\ R/R_c$, where $R_c = (\sigma/\rho g)^{1/2}$ is the capillary length, as obtained by Boulton-Stone matches our measurements (figure 3(b)).. The height of the bubble above the free surface h_c in glycerol- water matches the prediction of Allan et al (1961). Princen's (1965) prediction of the height of spherical cap η matches with present experimentation (figure 3(c)). Deformation of the bubble from a spherical shape can be understood by studying the variations of R_m and Z_c with R/R_c. Due to the compression of the bubble in the vertical direction due to buoyancy, and the subsequent elongation in the horizontal direction to conserve volume R_m/R increases while Z_c/R decreases with increase in R/R_c.

Fig 2 shows the stages of bubble bursting, along with the time gap between those stages. The bursting starts when a hole develops in the spherical thin film part of the bubble. The hole in the stretched film becomes larger and reaches the rim in short time (~1/3000 sec) creating a cavity in the free surface. The retracting film also produces very thin ligaments along the periphery of the rim, as shown in figure 2(b), which ligaments give rise to tiny droplets. The exposed rim (figure 2(c)) cause generation of high Laplace pressure inside the rim thereby pushing the fluid downwards with very high speed, the cavity

a) Corresponding author. Email: apbraj@iitm.ac.in.

also collapses due to surface tension reducing the free surface area. The stages of cavity collapse can be seen from figure 2(d) to 2(f). Since the cavity collapse occurs in about of 10^{-4} sec, it is highly possible that the collapsing phenomena to follow an impact time scale rather than convective time scale. Figure 2(f) and 2(g) show the final stages of axisymmetric flow convergence to produce a jet.

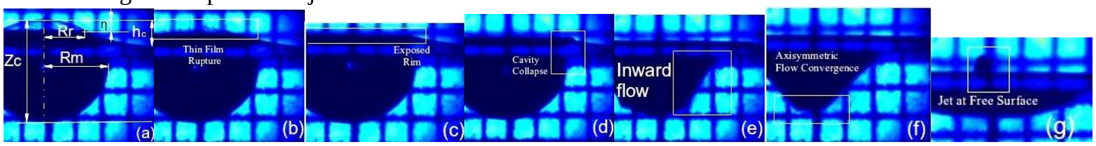

Fig 2: Different stages of bubble burst (from left to right) for bubble radius R= 2.19 mm, grid size is 1 mm. The time difference between the images from (a) to (d) is 1/3000 sec, the time difference between (d) & (e) as well as (f) & (g) is 5/3000 sec while (e) and (f) are separated by 2/3000 sec.

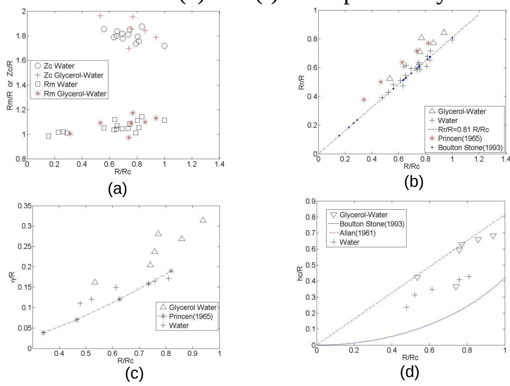

Fig 3: Variation of static parameters as a function of dimensionless radius R/R_c. The static parameters are as shown in figure 2(a).

For $R_v < R < R_c$, where $R_v = \rho\nu^2/\sigma$, the viscous -capillary length, by neglecting gravity effects, Duchemin et al. (2002) defined a viscous -capillary velocity scale, $V_v = \sigma/\rho\nu$. They then proposed that if viscous effects should be negligible, due to the high Re, then $V/V_v \sim (R/R_v)^{-1/2}$ implying that the jet velocity $V \sim ((\sigma/\rho)/R)^{1/2}$. This scaling matched the results from their simulations for $R/R_v > 2\text{x}10^4$, as could be seen in figure 4. However, the simulations of Boulton-Stone (1993) as well as our present experimental results show a 1/R scaling of jet velocity for $R/R_v > 2\text{x}10^4$. We expect this discrepancy to be due to the distortion of the bubble shape from the spherical shape assumed by Duchemin et al at larger radius. As could be seen from figure 3(a) deformation of the bubble from a spherical shape is not negligible for $R/R_c > 0.3$. The velocities of the jet in the glycerol-water solution also show a 1/R scaling, similar to that observed by Duchemin et al. (2002) in the same range of R/R_v. However the magnitude of the jet velocity is one order of magnitude lower than predicted by Duchemin et al.; viscosity seems to have much stronger effect than expected. Similar to that in Duchemin et al., there seems to be a viscous cut off at $R/R_v \approx 600$, below which jet velocity decreases with R. So to conclude, there seems to be only 2 regimes of jet formation from collapse of bubbles at the free surface. At larger radius there is a regime in which $V \sim 1/R$, while at a smaller R there seems to be a regime in which $V \sim R^n$, where n = 3. Physical explanations for these scalings are yet to be found.

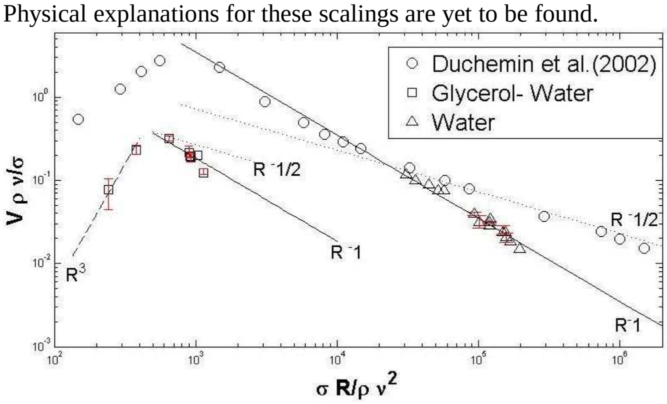

Fig 4: Dependence of jet velocity on bubble radius. Duchemin et al's scaling has been taken.

References

[1] B. W. Zeff, B. Kleber, J. Fineberg, and D. P. Lathrop.: Singularity Dynamics in Curvature Collapse and Jet Eruption on a Fluid Surface**,** *Letters to Nature*, 403, 401-404, 2000.

[2] F. MacIntyre.: Flow Patterns in Breaking Bubbles. *J. Geophys. Res*., 77(27):5211-5228, 1972.

[3] J. M. Boulton-Stone, J. R. Blake.: Gas Bubble Bursting at a Free Surface. *J. Fluid Mech* **254**:437-466, 1993.

[4] L. Duchemin, S. Popinet, C. Josserand, S. Zaleski. : Jet Formation in Bubbles Bursting at a Free Surface. *Phys. Fluids*, 14, 3000, **2002.**

[5] M. S. Longuet- Higgins.: Bubbles, Breaking Waves and Hyperbolic Jets at a Free Surface. *J. Fluid Mech*, 127:103-121, 1983.

[6] M. S. Longuet- Higgins and H. Oguz.: Critical Micro Jets in Collapsing Cavities. *J. Fluid Mech*, 290:183-201, 1995.