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# HIGH SPEED VISUALIZATION OF VAPOUR CAVITY NEAR BOUNDARIES

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## ABSTRACT

The original aim of the experimental program was to gain further insight into the mechanism by which cavitation bubbles cause damage to hydraulic equipment. A bubble is created by the discharge of a high voltage electric spark between two electrodes. High speed movie photography, up to 6500 frames per second, is used to capture the evolution of a bubble near a boundary. Measurements made on the centroid of the bubble show that the bubble is repelled from a free surface. However, when it is near to a rigid wall, it collapses towards the wall and gives rise to a high speed jet impinging on the wall. The experiments are in agreement with the prediction obtained by considering the Kelvin impulse associated with the bubble, a quantity obtained from global momentum conservation arguments.

Experiments reported in this paper were conducted for the case of a bubble near both a free surface and a vertical rigid wall. The bubble is found to distort asymmetrically as it collapses. Measurements were made on the change of volume of the bubble with respect to time and the trajectory of its centroid. The bubble is attracted in a downward direction towards the vertical boundary. Up to five pulsations of the bubble were recorded. The changing volume of the bubble gives an estimate of the energy dissipation. This particular study also has applications in the area of underwater explosions, although buoyancy would play a more dominant role than displayed in these experiments.

## INTRODUCTION

Cavitation, is a major problem in hydraulics as well as underwater acoustics. Leonhard Euler first mentioned the possible rupture of a liquid in 1754. At the turn of the century, with the boom in the shipping industry, cavitation damage evolved as a major problem for the design of ship propeller blades. Cavitation was first observed in the trials of the destroyer <u>HMS Daring</u> in 1893. Since then, the chemical, physical, and engineering aspects of cavitation have been the subject of intensive research. Investigations have been made of the process of bubble formation and collapse in the liquid, in pumps, turbines, propellers, dam spillways, and similar structures.

Generally, cavitation associated with hydraulic machinery is called *hydraulic cavitation*. The machinery parts most often affected by this type of cavitation are ship propellers, turbines, pumps, and hydrofoils. Cavitation associated with sonar is known as *acoustic cavitation*.

Non-uniformity of flow in hydraulic machines may cause the pressure, even in a given cross-section, to vary widely. There may thus be, on the low pressure side of the rotor, regions in which the pressure falls to values considerably below atmospheric. If the pressure at any point in a liquid falls considerably below the vapour pressure, the liquid will be in tension and then 'tear apart' forming a large number of small bubbles. These bubbles are carried along by the flow, and on reaching a point where the pressure is higher, they suddenly collapse giving rise to high pressures, and in some circumstances a high speed water jet. Any solid surfaces or boundaries in the vicinity has a profound influence on the water jet. The boundaries may repel or attract the cavity bubble depends on the boundaries' properties. This alternate formation and collapse of vapour may be repeated with a frequency of many thousand times a second. Accompanied with the water jet is an intense pressure. The intense pressure, even though acting for only a very brief time over a tiny area can cause severe damage to the surface. The material ultimately fails by fatigue, aided perhaps by corrosion, and so the surface becomes badly scored and pitted. Associated with cavitating flow there may be considerable vibration and noise because of the collapsing bubbles and the unbalanced blades.

Study of cavitation and bubble dynamics has recently received very much attention particularly on bubble growth and collapse near solid boundaries. Some of the more notable studies on bubble dynamics can be found in Benjamin and Ellis (1966), Blake, Taib, and Doherty, (1986), Gibson (1972), and Plesset and Chapman (1971).

Collapse of a cavitation bubble near a plane solid boundary can be divided into successive stages:

(a) Axisymmetrical motion of the bubble wall and microjet formation towards the solid boundary.
(b) Microjet impact on the wall and torus structure formation.
(c) Final collapse of the torus.
(d) Shock wave emission.

It is clear that the liquid microjet is a dominant factor in cavitation damage. Immediately after jet impact on a rigid boundary, an impulsive pressure with a very short duration is produced and followed by a pressure fluctuation due to the stagnation pressure. Since the driving force behind this high speed microjet (130 m/s to 180 m/s) is a high pressure which is higher than the material yield point, the microjet is an effective factor contributing to the cavitation damage.

Tomita and Shima (1986), in their series of experiments, found that the behaviour of a liquid jet is closely related, directly or indirectly, to the generation of impulsive pressure, which contributes to damage-pit formation. By using a pressure transducer as well as by the photoelastic method, they found out that the impulsive pressure is strongly dependent on the distance of a bubble from a solid boundary. The modes of bubble collapse are dependent on the proximity to a boundary. In particular, for a bubble situated very close to a solid boundary, intensive impulsive pressures occur not only at the first collapse but also at the second collapse of a bubble. Also from the past experiments it has been related to the bubble size for a constant shock strength. In this paper we consider the behaviour of a vapour bubble near both a free surface and a vertical rigid boundary. We know from earlier studies that a pulsating bubble is attracted to a rigid boundary and repelled from a free surface. In our experiments the free surface will act as a "negative buoyancy" term on the bubble. These ideas are perhaps best expressed in terms of the Kelvin impulse.

## THE KELVIN IMPULSE

One of the most recent theoretical development in bubble dynamic is to exploit the use of the Kelvin impulse to determine aspects of the gross bubble motion, such as the direction of movement of the bubble centroid. The Kelvin impulse can be regarded as the wrench required to generate the motion of fluid or solid boundary at any instant from rest. It was further postulated that the wrench was in fact that which would be required to counteract the impulsive pressure generated on the surface. Application of the Kelvin impulse ideas to cavitation bubble studies has been developed extensively over recent years. (See e.g. Blake, 1988, Blake & Cerone, 1982, Blake & Gibson, 1987 and Gibson & Blake, 1982). The Kelvin impulse for a bubble is defined as follows,

$$I = \rho \int_S \phi \mathbf{n} \, dS \qquad (1)$$

where
- $\rho$ = fluid density
- $S$ = surface of the bubble
- $\phi$ = velocity potential
- $\mathbf{n}$ = outward normal to the fluid

Expression (1) is related to the fluid momentum is a bounded finite volume and may be thought of as the apparent inertia of the bubble. Like in the case of a linear momentum, it can be used to determine the gross bubble motion in a cavitating liquid.

Previous studies (Blake 1988, Blake and Cerone 1982) have found out that one of the major influence on Kelvin impulse is its dependence on the inverse square of the distance from the boundary. The closer the cavitation bubble to a solid boundary, the more the impact force; and similarly, the further the distance away, the less the damage potential. In engineering application, the Kelvin impulse associated with cavitation bubbles should be minimal if the hydraulic machinery is to be preserved.

It has long been known if a cavitation bubble is placed near to a rigid boundary the bubble will be attracted to it. Conversely, if the bubble is placed close to a free surface the Bjerknes force will repel the bubble. In a stationary liquid a cavitation bubble is subjected to two forces, a buoyancy force and a Bjerknes force. At close distances to a boundary the Bjerknes force is dominant; that means for a free surface it repels, any rigid surface it attracts. It would be useful to determine the critical distance where Bjerknes force is effectively reduced and the buoyancy force becomes more important. In this study we consider the motion of a bubble near two boundaries, a vertical rigid boundary and an initially horizontal free surface (see Figure 1). Thus we might expect the bubble to be (i) attracted towards the vertical rigid boundary, (ii) repelled from the free surface, and (iii) driven vertically by buoyancy forces. Clearly, because these forces will not be in balance, asymmetric bubble motion will result.

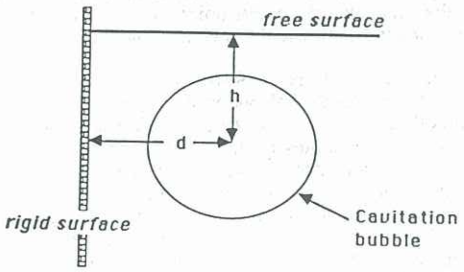



**Figure 1. Geometry for experiments and theory**

Figure 1 shows a sketch of the bubble in relation to free surface and a vertical rigid surface. The important parameters are the,

$$\beta = \frac{d}{Rm}, \qquad \gamma = \frac{h}{Rm} \qquad (2)$$

and the "buoyancy parameter",

$$\delta = \left(\frac{\rho g Rm}{\Delta p}\right)^{\frac{1}{2}} \qquad (3)$$

where

- $h$ = the initial distance of the bubble centre from the boundary.
- $R_m$ = the maximum bubble radius.
- $\rho$ = fluid density.
- $g$ = gravitational acceleration.
- $\Delta p$ = $p_\infty + \rho g H - p_c$
- $p_\infty$ = pressure inside the water tank.
- $p_c$ = saturated vapour pressure inside the bubble.
- $H$ = distance from the water surface to the bubble centroid.

Using the Kelvin impulse concept, Best and Blake (1990) developed the following formula for the angle, $\theta$, of the jet made with the normal of the vertical rigid boundary for underwater explosions. This formula is equally applicable to our experiments. The expression is

$$\theta = \tan^{-1}\left[\frac{2\gamma^2\delta^2 \, B(11/6,\, 1/2) - B(7/6,\, 3/2)\, F_z}{(\gamma^2/\beta^2)\, B(7/6,\, 3/2)\, F_x}\right] \qquad (4)$$

where $B(x,y)$ are Beta functions and $F_x$ and $F_z$ are integral expressions in terms of $\gamma$ and $\beta$.

## EXPERIMENTAL PROCEDURE

The cavitation test rig utilizes a spark discharge technique to generate a vapour cavity in the water. The technique involves local heating and vaporization of the liquid through application of a thermal impulse.

A similar type of test rig was also employed by Benjamin and Ellis (1966). The test rig was later modified to allow free fall condition in experiments conducted by Gibson (1968). This method produces a single bubble each time. Utilizing electric current at high potential difference to create a thermal impulse which almost instantaneously form a bubble in the liquid.

Electrodes which transmit a high voltage current are submerged in the test liquid. One of the electrodes passes through a vertical perspex plate, which is clearly evident in Figure 2. They are housed in a perspex tank. The viewing side of the tank is made up of a rectangular perspex box, 250 mm by 162 mm. A 25 mm thick flat window was recessed into the front face of the cylinder. The cavitation tank is placed on a wooden platform which is in turn supported by a steel structure.

After the spark is generated the motion is recorded by a NAC high speed camera. The film is later analysed and the images digitized for computer analysis.

## ANALYSIS OF EXPERIMENTS

As an illustration of the high speed photographic, Figure 2(a), (b) and (c) shows photographic information obtained for the case $\beta = 1.98$, $\gamma = 3.95$ and $\delta = 0.05$, a case when buoyancy forces are quite weak. The bubble shape is digitized and analysed to obtain the volume and centroid (two components). Calculations for the example shown in Figure 2 are illustrated in Figure 3.

Figure 3(a) shows the calculated volume of a bubble as it changes through four pulsations. Figure 3(b) shows the movement of the centroid of the bubble. It is clear from these figures that bubble remain almost stationary during the growth phase. When it collapses, it accelerates downward and towards the wall. Figure 2(b) shows the formation of a jet at first collapses of the bubble. The jet is just visable and it dips at an angle of 22° with the normal of the wall. In the second pulsation, the bubble collapses developing a prominant jet at a steady angle of 48° as shown in figure 2(c). Further examples similar to the materials shown in Figures 2 and 3 can be found in Wong (1988).

Some results are tabulated in Table 1. Here the angle $\theta_2$ is referred to the jet angle during the second pulsation. The jet angle, $\theta$, derived from equation (4) underestimates the measured angle, $\theta_2$. This is as expected since equation (4) is derived under the assumption that the bubble remains stationary at all times.

| film No. | $\gamma$ | $\beta$ | $\delta$ | $\theta_2$ | $\theta$ | Remarks |
|---|---|---|---|---|---|---|
| 7 | 3.95 | 1.98 | 0.05 | -48 | -38 | |
| 8 | 3.20 | 3.20 | 0.06 | - | -60 | no jet visible |
| 9 | 4.97 | 2.49 | 0.07 | - | -22 | no jet visible |
| 10 | 4.19 | 2.24 | 0.05 | -53 | -38 | |
| 11 | 6.20 | 2.33 | 0.06 | 0 | -15 | |
| 12 | 18.97 | 9.48 | 0.03 | -25 | +26 | |

**Table 1.**

A sample of results

$\theta_2$ : jet angle at 1st rebound

$\theta$ : jet angle from equation (4).

The energy, E, dissipated by the bubble is given by

$$E = \Delta p \Delta V \qquad (5)$$

where $\Delta V$ is the change of maximum volume of bubble between two pulsations

It is found that a large portion of the total energy is dissipated before the second pulsation, which covers the period of about 3 mini second.

As shown in Table 2, the value of $\Delta V/R_m{}^3$ is orderly dependent on $\beta$, a parameter for the distance from the wall. It is evident that less energy is being dissipated by the bubble when it is nearer to the rigid wall.

| film No. | $R_m$(cm) | $\Delta V/R_m{}^3$ | $\beta$ | $\gamma$ | $\delta$ |
|---|---|---|---|---|---|
| 7 | 5.1 | 2.81 | 1.96 | 3.92 | 0.05 |
| 10 | 3.6 | 3.10 | 2.22 | 4.17 | 0.05 |
| 11 | 6.5 | 3.39 | 2.31 | 6.15 | 0.06 |
| 9 | 8.0 | 3.60 | 2.50 | 5.00 | 0.07 |
| 8 | 6.2 | 3.52 | 3.23 | 3.23 | 0.06 |
| 12 | 2.1 | 2.01 | 9.52 | 19.05 | 0.04 |

**Table 2**

$\Delta V/R_m{}^3$ increases with $\beta$ up to $\beta = 3.23$.

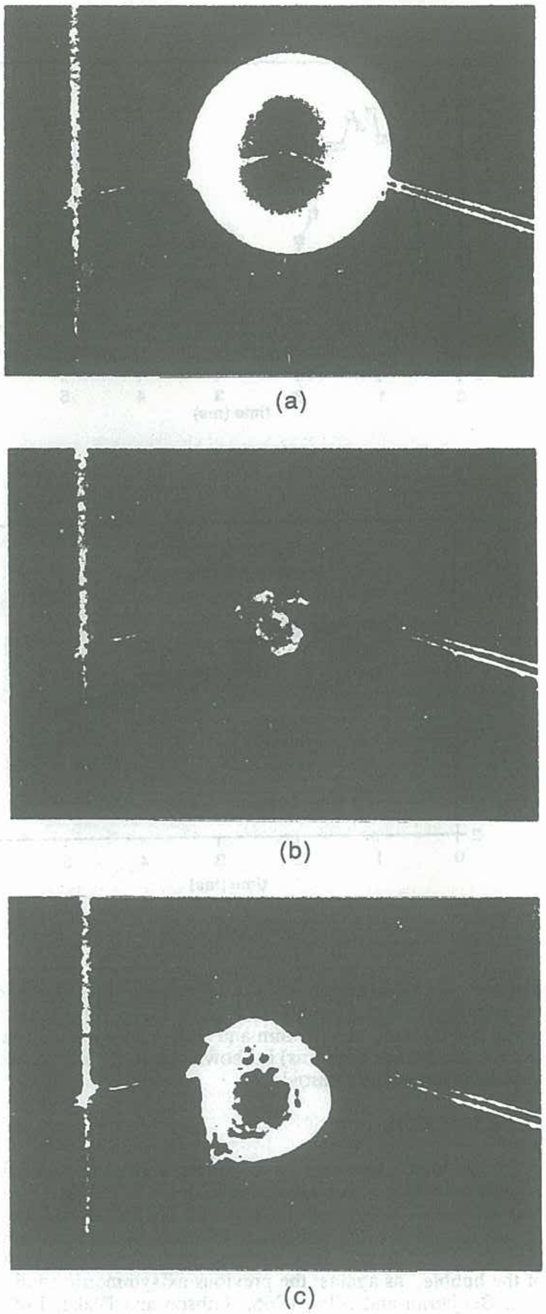
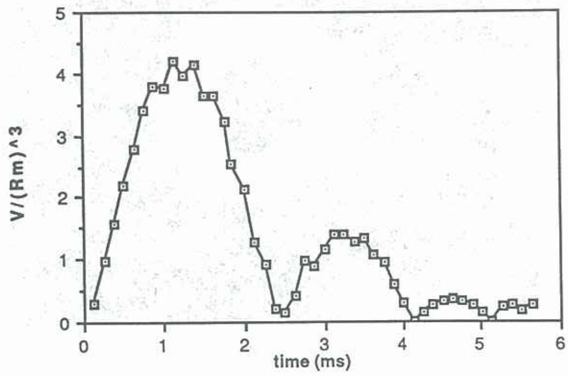
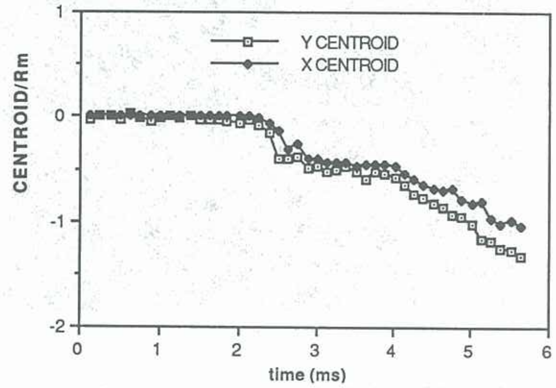



**Figure 2.** Examples of the high speed photography record for a bubble with dimensionless parameters $\beta = 1.98$, $\gamma = 3.95$ and $\delta = 0.05$. (a) Bubble at maximum size at $t = 1.846$ ms, (b) first minimum $t = 3.077$ ms and (c) 3.692 ms.




(a)




(b)

**Figure 3.** Examples of the digitized data for the experimental results shown in Figure 2. In dimensional terms h = 20 mm, d = 10 mm and $R_m$ = 5.06 mm. In (a) the volume versus time (ms) is shown and in (b) the x and y coordinates of the centroid.

CONCLUSIONS

In this paper we have reported on some recent experiments for a vapour close to both a vertical rigid boundary and a horizontal free surface. The bubble's motion is influenced by the presence of both boundaries and buoyancy leading to a genuine three dimensional behaviour of the bubble, as against the previous axisymmetric studies (e.g. Benjamin and Ellis, 1966; Gibson and Blake, 1982; Tomita and Shima 1986). In the experiments conducted so far the bubble migrants in a downward direction, away from the free surface, but towards the rigid boundary, with the high speed liquid jet threading the bubble from the rear. Future experimental studies will cover a wider range of parameters for comparison against the simple theoretical ideas developed from using the concept of the Kelvin impulse.

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