

REMOVAL OF AN OBSTRUCTION FROM A TUBE BY A COLLAPSING BUBBLE

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ABSTRACT

The use of a collapsing bubble to clear an obstruction (in the form of a steel ball) near a tube, submerged in water, is studied with high speed photography. Tubes in horizontal and vertical configurations are studied. The bubble is generated via an electric spark discharge. The flow in the tubes resulting from the expansion of the bubble, or the high speed jet from the collapsing bubble pushes the ball away from the tubes and therefore clears the obstructions. In a case where air-backed tube is used, the bubble jets away from the tube. The resulting water plum at the hole (water-air interface) removes the blockage. The speed of the ball can be as high as 1 m/s shortly after the collapse of the bubble. Further studies are required to translate the phenomena observed to clinical applications such as the removal of blood clots in vessels or the clearing of blocked transplanted tubes.

INTRODUCTION

The use of a collapsing bubble for electronics cleaning, sonochemistry, and biofilm removal have been extensively studied [1,2,3]. It is known that a collapsing bubble will move and jet toward a solid boundary with a high jet speed of about 100 m/s [4,5,6]. This high speed jet is responsible for the cleansing effect of electronics wafers, and in an ultrasound bath. In this study, the motivation was to make use of the high speed jet from a collapsing spark bubble to remove an obstruction in a tube. This is applicable in several medical applications such as the removal of blocked transplanted tubes and clotted blood vessels. The cavitation bubbles can be generated by laser, ultrasound or a shock wave. Although a spark bubble is used here, the physics involving the bubble

dynamics can be translated to other types of cavitation bubbles (by laser or sound waves).

EXPERIMENTAL SETUP

We make use of a previously build up simple circuit as shown in Fig. 1, and details about the circuit has been documented in previous publications by the authors [6,7]. It consists of a capacitor of 5300 μ F charged up to 57 V, via a 1 k Ω load resistor. The capacitor is then discharged through two very thin wires. A spark bubble is created at the position of the wire crossing. The phenomenon is studied via a high speed camera (Photron SA 1.1, USA) at a framing rate of 16,000 frames per second.

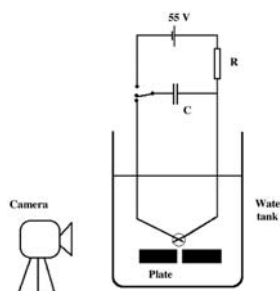


Fig. 1 The experimental setup and the electrical circuit for the creation of the spark bubble. The capacitor C is of 5300 μ F, and the resistor R is of 1 k Ω . The spark is created at the crossing point of two electrodes when the switch is turned to discharge the capacitor.

Fig. 2 shows the acrylic tube used in Experiment 1 with dimensions given. A hole of 2.5 mm in diameter is drilled through the acrylic block. A steel ball of 2.5 mm and 56 mg is utilized (also in Experiment 2 and 3). The spark bubble is generated next to the blocked end where the steel ball is.

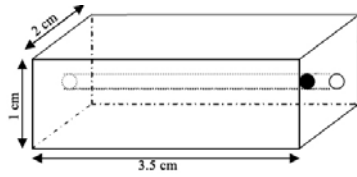


Fig. 2 The acrylic block used in Experiment 1. A steel ball is placed at one end of a tube drilled in the acrylic block. The steel ball is 2.5 mm in diameter, and weighs 56 mg. A spark bubble is to be created next to the steel ball.

For the second experiment (Experiment 2), an acrylic plate of 0.56 mm thickness is used. A hole of 2.0 mm is drilled through the plate, and a steel ball of 2.5 mm in diameter (56 mg) is resting on top of the hole. A spark bubble is generated from below as shown in Fig. 3. Similar setup is used for the third experiment (Experiment 3). The same steel ball and arrangement of positions are used. The plate in Experiment 3, however, is only of 1.3 mm thick. Also both structures in Experiment 1 (Fig. 2) and Experiment 2 are completely submerged in a water tank of 19 x 21 x 21 cm³. For Experiment 3, on the other hand, air is found on top of the plate on the side where the ball is resting.

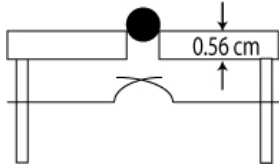


Fig. 3 Experimental setup for Experiment 2. A steel ball is resting on top of hole of 2.0 mm in an acrylic plate of 0.56 cm in thickness. The steel ball is of 2.5 mm in diameter, and weigh 56 mg. Experiment 3 has a similar setup. The only difference is the plate used in Experiment 3 is only 1.3 mm in thickness, and the plate is air-backed.

RESULTS

Experiment 1: Removal of an object inside a horizontal tube

For this experiment using the setup in Fig. 2, the ball is initially placed about 5 mm inside the tube. A spark bubble is generated next to it using the setup described in Fig. 1. As shown in Fig. 4, a spark bubble is seen at time $t = 0.06$ ms at 3.3 mm away from the bottom of the plate. It is seen expanding at $t = 0.20$ ms, and reaching its largest size (3.4 mm in radius) at $t = 0.83$ ms. Throughout the expansion phase of the bubble, the steel ball in the tube remains stationary. After reaching its maximum size, the bubble collapses ($t = 1.13$ ms) with a high speed jet towards the ball. The jet is seen to have moved inside the tube ($t = 1.53$ ms), and pushes the ball. The ball is displaced ($t = 10.1$ ms), and eventually drops out of the tube (not shown).

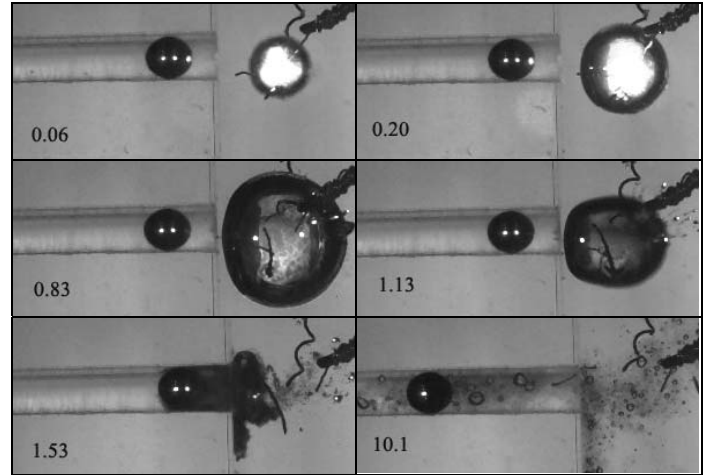


Fig. 4 Experiment 1: The sequence of bubble collapse and removal of the steel ball from the blocked end of the tubing. The framing rate used is 16,000 frames per second. The time in milliseconds from the first frame when a spark is first seen (taken to be $t = 0$ ms) for each frame is printed on the left bottom corner of the frame. Maximum bubble size (frame $t = 0.8$ ms) is 3.4 mm in radius.

From Experiment 1, it is shown that a blocked tube (by a steel ball) can be cleared by a collapsing bubble. Fig. 5 shows the position of the steel ball from $t = 0$ s to about $t = 0.16$ s when the ball drops out of the tube. It is seen that the ball barely moves during the expansion and collapse of the bubble (from $t = 0$ to $t = 0.0015$ s). However it is set into motion by the high speed jet from the collapsing bubble. It eventually slows down and drops out of the tube.

Position of the ball in function of the time

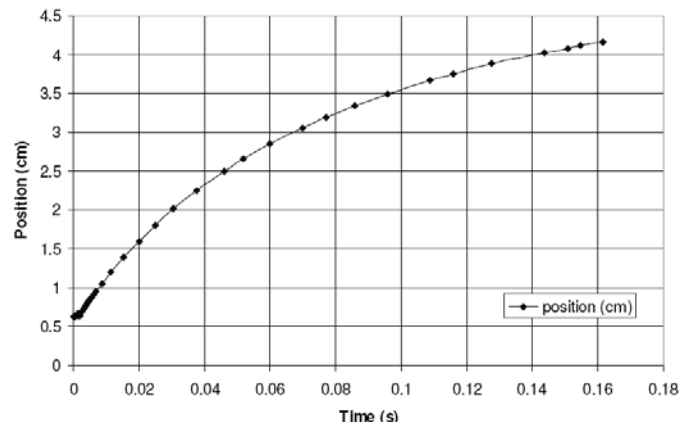


Fig. 5 Position of the center of the steel ball in time. The ball hardly moves during the expansion and collapse of the bubble. However the high speed jet from the collapsing bubble set the ball into motion. It eventually slows down and drops out of the tube.

Fig. 6 shows the velocity of the ball as it moves along the tube. For a brief moment, a high velocity of 0.65 m/s is recorded. This is shortly after the high speed jet from the collapsing bubble hits the steel ball and sets it in motion.

Eventually the ball drops out of the tube with a velocity of 0.1 m/s at $t \approx 0.15$ s.

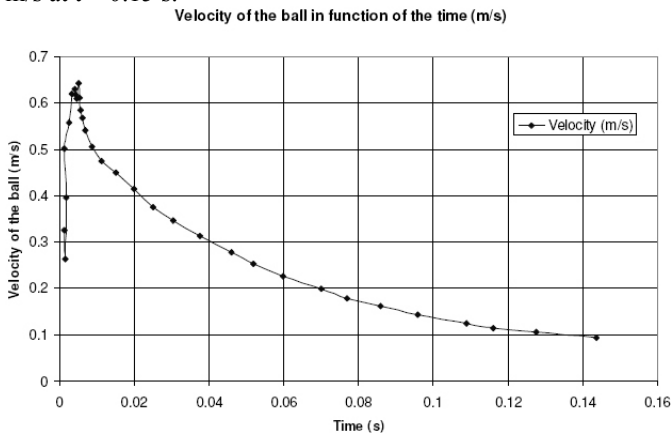


Fig. 6 The velocity of the steel ball versus time as it moves along the horizontal tube. A high speed of 0.65 m/s was achieved momentarily before the ball eventually moves out of the tube at a speed of 0.1 m/s.

Experiment 2: Obstruction removal from the opposite side of a vertical tube

In this experiment, an acrylic plate as shown in the first frame of Fig. 7 is used. A hole (representing a tube) of diameter 2.0 mm is drilled in the plate. The same steel ball (2.5 mm in diameter, 56 mg in weight) is placed resting on top of the plate where the hole is. The spark bubble is generated from below (3.1 mm away from the bottom of the plate), and is aligned to the hole. The bubble grows to its maximum size at $t = 0.6$ ms (Fig. 7). It then collapses ($t = 1.0$ and 1.13 ms) with a high speed jet towards the tube. The jet is seen to move through the tube and hits the ball ($t = 1.47$ ms). The ball is eventually removed from the top of the tube as shown in the last two frames of Fig. 7 ($t = 3.27$ and 9.97 ms).

It is noted that the average velocity of ball is as high as 1 m/s between the complete collapse of the bubble ($t = 1.3$ ms (not shown)), and the final frame ($t = 9.93$ ms) in Fig. 7. Also seen is a vortex ring behind the ball as it is displaced from the tube ($t = 1.47$ to 9.93 ms). The formation of the vortex ring at end of a tube where a spark bubble has collapsed on the other side has been reported before [6]. It could be due to the momentary negative pressure around the outlet of the tube due to the shock wave from the collapsed bubble at the inlet.

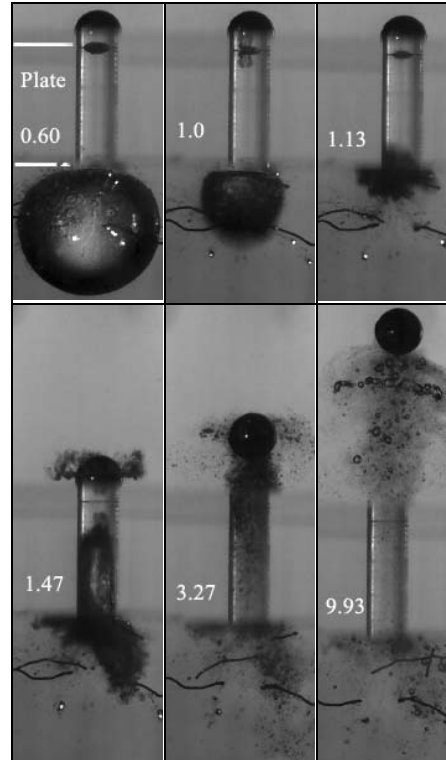


Fig. 7 Experiment 2: The removal of a steel ball from the top of a blocked tube by a collapsing bubble from below. The time for each frame is shown on the plate. The maximum bubble size at frame $t = 0.6$ ms is 3.2 mm. It is seen that the high speed jet from the collapsed bubble pushes the ball away from the top of the plate ($t = 3.27$ and 9.93).

Experiment 3: Obstruction removal from the opposite side of a vertical tube which is exposed to air

For the same setup as in Experiment 2, only that this time, on the other side of the plate, we have air instead of water. Also the thickness of the plate used is slightly thinner (1.3 mm) than that in Experiment 2. The same steel ball is used as an obstruction.

The bubble is placed rather far from the bottom of the plate (9.36 mm) (Fig. 8). The bubble achieves its maximum size (3.6 mm in radius) at $t = 0.40$ ms. However instead of jetting towards the plate, the influence of the free surface influence is felt and the bubble jets away from the plate instead. After the bubble collapses and jets away from the plate ($t = 1.53$ ms), a water plume is developed at the free surface interface where the hole is ($t = 5.67$ ms). This water plume pushes the steel ball away from the top of the plate ($t = 21.5$ ms).

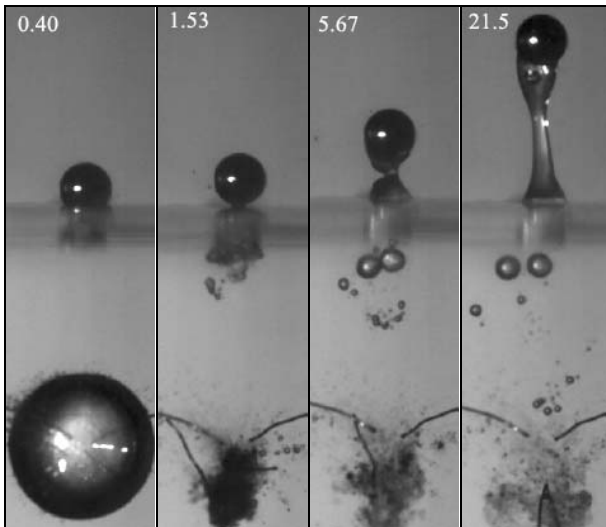


Fig. 8 Experiment 3: The removal of a steel ball from the top of a blocked tube by a collapsing bubble from below. The time for each frame is shown on the plate. The maximum bubble size at frame $t = 0.4$ ms is 3.6 mm. It is seen that the bubble jets away from the plate ($t = 1.53$) due to the influence of the free surface interface. The ball is removed by the water plume after the bubble collapses and moves away from the plate.

CONCLUSION

We have demonstrated the use of an oscillating bubble for the removal of an obstruction (a steel ball) in a tube. Three different scenarios for the blockage removal are investigated. In Experiment 1, a horizontal tube with a blockage at one end is used. The high speed jet from the collapsing bubble pushes the steel ball away from its original position. The momentum imparted from the jet sends the ball traveling along the length of the tube and eventually drops out of the tube.

When the tube is placed in a vertical manner, gravity plays a part. In Experiment 2, such a scenario is studied. The tube is blocked on top by a steel ball (which is used in Experiment 1). The collapsing bubble from below jets towards the tube and removed the steel ball from the top of the tube.

The third scenario is similar to Experiment 2. In Experiment 3, on the side where the steel ball is placed, air is present instead of water. A completely different phenomenon is observed. The collapsing bubble jets away from the tube. However, the ball is still removed by the water plume which develops on the free surface interface between the top end of the tube and the air medium.

This study clearly shows the capability of the use of a cavitation bubble for the removal of blockage in tube. The bubble can be generated by spark as presented here, or by other means such as laser, ultrasound or shock wave. Similar bubble dynamics would apply. This observation has far reaching impact on many medical and industrial applications where tube blockage is often encountered. For example in medical implant, cavitation bubbles generated by High Intensity Focused Ultrasound (HIFU) can be potentially used to remove the

blockage. This method is non-invasive and low cost compare to the traditional solution of a surgery. Further study will be carried out to ascertain the clinical viability of this approach.

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