

3D crown spike of free surface induced by two bubbles

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Abstract. A specific physics called ‘crown phenomenon’ is discovered in the interaction between weak buoyancy bubbles and free surface. The ‘crown phenomenon’ is that a circle of the outer fluid appears to surround the middle spike of water after the jet impact of bubbles, and this kind of spike is defined as ‘crown spike’. In this study, the crown spike due to the coupling effect between two bubbles and free surface is studied both experimentally and numerically. In the experiment, copper wires in series connection are used to generate two in-phase bubbles and the bubble and free surface shapes are recorded by high-speed photography. In the numerical study, a three-dimensional model is established to simulate the bubble-free-surface interaction with a boundary integral method and then the motion of free surface is further simulated without regard to the effect of bubbles after the jet impact. The computation also traces the ‘crown phenomenon’, which is considered as a second spike related to a large high-pressure region formed after the impact. The large high-pressure region leads to a thick column of water on the free surface and then the column of water gradually increases to surround the first spike. Both oblique jets and crown spike are observed in the experimental and numerical results, and the favorable agreements of bubbles and free surface shapes validate the present model. The effect of the inter-bubble distance on crown spike is also investigated.

1. Introduction

The interaction between bubble and free surface has applications in printing [1] and water barrier [2]. Experimental observations show that a downward jet is formed by weak buoyancy bubbles near the end of collapse phase, while the free surface produces a spike moving upward [3]-[5]. It's clear that the motion of free surface is significantly influenced by the bubble-free-surface distance. Zhang *et al.*[6] observed a ‘crown spike’ after the jet impact with a high-speed camera, that is a circle of the outer fluid rises to surround the middle column of water, appearing a crown-like shape. There is little progress in the study about this specific physics, the main reason is that the toroidal bubble would collapse for a short period [7]. The method of ignoring the effect of toroidal bubble [8]-[10] has been used in the previous studies to avoid the difficulties in computation. The previous numerical method is taken as a reference for the simulation of crown spike and the main reasons are described as follows. An energy loss of about 70% occurs primarily at the minimum volume of bubble and the toroidal bubble after the downward jet would collapse soon. It is reckoned that the bubble loses energy continuously and that its influence on the free surface gradually becomes weaker. Li *et al.*[11] established an axisymmetric model to investigate the effects of parameter variation on spike pattern.

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After the jet impact, they further simulated the motion of free surface ignoring the effect of toroidal bubble. Moreover, Han *et al.* [12] established a three-dimensional model to simulate the crown spike in both single- and two-bubble cases.

In this paper, crown spike of free surface is studied through both experimental and numerical method. The motion of two bubbles and free surface is observed experimentally using a high-speed photography. Meanwhile, a three-dimensional model is established using a boundary integral method to simulate the interaction between two bubbles and free surface. The computation also traces the motion of free surface after the jet impact. The numerical solutions agree well with the experimental results with regard to bubble and free surface shapes, which confirms the validity of the present model. Detailed analyses are made for crown phenomenon in the present investigation, aiming to provide information for studying this specific physics.

2. Method

Based on potential flow theory, a 3D numerical model is used to simulate the crown spike of free surface. The flow is assumed to be irrotational, inviscid and incompressible, thus the velocity potential satisfies the boundary integral equation [13]:

$$\mathcal{G}\Phi(\mathbf{p}) = \iint_S \left(\frac{\partial\Phi(\mathbf{p})}{\partial n} \frac{1}{r_{pq}} - \Phi(\mathbf{q}) \frac{\partial}{\partial n} \left(\frac{1}{r_{pq}} \right) \right) dS \quad (1)$$

where the surfaces of two bubbles and free surface are denoted by S , $\mathbf{p}$ and $\mathbf{q}$ are the fixed point and the source point located on the liquid-gas interfaces, $\mathcal{G}$ is the solid angle at $\mathbf{p}$ which equals 2π , the normal derivative is defined as $\partial/\partial n = \mathbf{n} \cdot \nabla$ and $\mathbf{n}$ is the outward normal.

All the boundaries are discretized and finer grids are used in the central two thirds of the free surface for the simulation of crown spike, as shown in figure 1. The surface of each bubble is discretized into 1280 triangular elements and the free surface into 7792 triangular elements. The radius of free surface is 4.5 times of the maximum radius attained by the bubble [14].

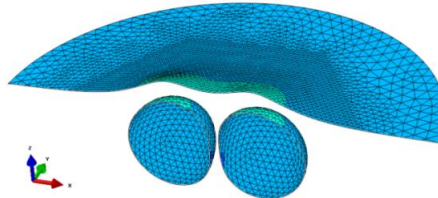


Figure 1. Discretization

Incompressible ideal fluid in unsteady irrotational flow domain satisfies Bernoulli equation, and dynamic boundary condition governing the motion of the bubbles and free surface is [7]:

$$\frac{d\Phi}{dt} = \frac{|\nabla\Phi|^2}{2} + \frac{P_\infty - P_c}{\rho} - \frac{P_{0,b}}{\rho} \left(\frac{V_{0,b}}{V_b} \right)^k - gz \text{ (for bubble surface)} \quad (2a)$$

$$\frac{d\Phi}{dt} = \frac{|\nabla\Phi|^2}{2} - g(z - d) \text{ (for free surface)} \quad (2b)$$

where P_∞ is the ambient pressure on the plane of the bubble centre at inception, P_c is the constant vapour pressure with $P_c = 0.5\text{bar}$ [14], $P_{0,b}$ and $V_{0,b}$ are the initial pressure and volume of bubble, k is the ratio of the specific heats of the gas which is taken as 1.25 [8], ρ is the fluid density, g is the gravitational acceleration, and d is the initial distance of the bubble centroid from free surface.

The kinematic boundary condition governing motion of bubbles and free surface is [7]:

$$\frac{d\mathbf{r}}{dt} = \nabla\Phi \quad (3)$$

where $\mathbf{r}$ denotes the spatial position of the fixed point $\mathbf{p}$ on the bubble surface or the free surface. In the computation, all variables are normalized: length is scaled with respect to the maximum radius R_m the bubble would attain in an infinite fluid; pressure with respect to P_∞ .

3. Results and discussion

Numerical results are compared with the experimental observations. Bubbles are generated via spark discharge using a 210V dc supply and copper wires with a diameter of 0.013mm are used as electrodes. Series connection must be assured to generate two in-phase bubbles. The details of the experimental arrangement and method can be found in Ref. [6]. The maximum radius of bubble is related to discharge voltage and the maximum radius of the bubbles is about 9.35 millimetres when the voltage is 210V (measured in an experiment where two bubbles don't influence each other). The inter-bubble distance is about 18.7 millimetres and the initial depth of bubble inception is $d \approx 9.35\text{mm}$. The numerical results are compared with the experimental observations and bubbles and free surface shapes are illustrated in figure 2.

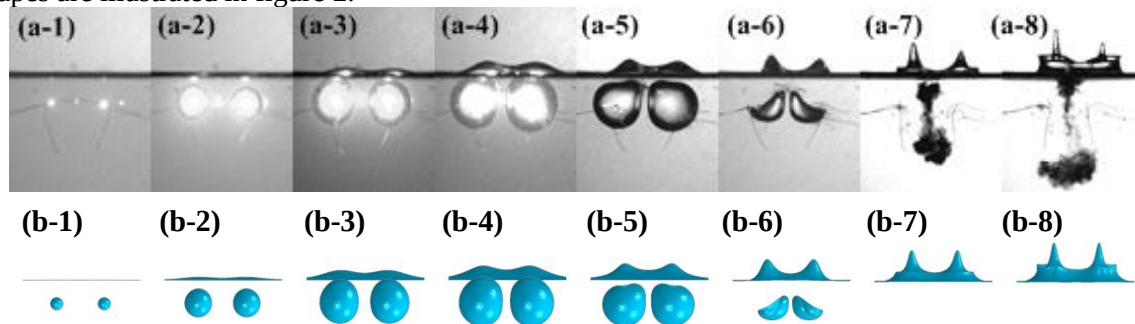


Figure 2. Comparison between (a) the experiment and (b) the BIM computation; the corresponding times in experiment are (a) 0.05ms, 0.45ms, 0.85ms, 1.60ms, 2.10ms, 3.00ms, 5.30ms, 8.60ms, and in computation are (b) 0.05ms, 0.31ms, 0.83ms, 1.46ms, 2.10ms, 3.06ms, 5.29ms, 7.11ms. The image width is 46mm and the height is 60mm.

It's shown that two bubbles are incepted simultaneously and then they begin to expand. After a while, free surface is slightly elevated by the expansion of bubbles which means the initial formation of the spike (shown in figure 2(a-3)). The bubbles attain the maximum radii at 1.600ms and the walls close to each other become flattened. Then the bubbles come into collapse phase and a downward jet is formed under the influence of the Bjerknes force. Meanwhile, the adjacent bubble restrains the bubble collapse and affects the direction of the water jet. Therefore, the water jet is directed away from the free surface with slight deviation to the neighbouring bubble, and oblique jets are obtained. The oblique jets are about to penetrate the bubbles at 2.10ms while the height of the spike keeps increasing affected by high-pressure region. It's noted that the jets hit the lower bubble wall (shown in figure 2(a-6) and figure 2(b-6)), because the presence of free surface dominates over the mutual interactions between two bubbles. In the experiment, each bubble collapses into two parts after the jets penetrate the bubbles. Then they continue to contract and attain a minimum volume at 3.20ms (results not shown here). Afterwards, most contents of bubbles move downward while the remnant contents slowly migrate upwards due to the weak buoyancy force. At 5.30ms a circle of the outer fluid rises to surround the middle spike, which is the 'crown phenomenon' mentioned above. And then the middle spike and the 'crown' continue to rise (see the profile of free surface at 8.60ms). The crown keeps rising and finally rolls up (results not shown here). In the BIM computation, the evolution of the free surface is further investigated after the jet impact and the 'crown phenomenon' in the experiment is obtained in the calculations. There is also a continuous increase in the height of the crown and the middle spike. It is reckoned that the 'crown phenomenon' is related to high-pressure region formed after the jet impact. Because the fluid is continually drawn in after the jets penetrate the bubbles, a large high-pressure region is formed but with a small pressure peak. A second spike is induced by the high-pressure region, which is the 'crown phenomenon' mentioned above. And the rim of the second spike rises fast, forming the crown around 8.60ms in the experiment.

The comparison is favourable with respect to the bubbles and free surface shapes and there are three reasons for the difference in the profiles and the time. Firstly, viscosity effect and surface tension are ignored. Next, after the jets penetrate the bubble wall, we neglect the influence of the bubbles on the evolution of the free surface. At last, the initial condition in the computation makes a difference in the results. Generally speaking, favourable comparisons of bubble and free surface shapes are observed and the validity of our model is confirmed.

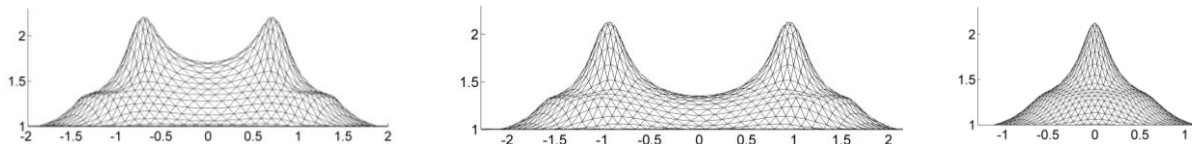


Figure 3. Crown spike induced by bubbles at the dimensionless time $T = 4.00$ with the inception depth $= R_m$. The dimensionless height of the central spike is (a) 1.18 when inter-bubble distance $= 1.6 R_m$ (b) 1.10 when inter-bubble distance $= 2.0 R_m$ and (c) 1.07 in single bubble case.

The crown spike shapes in single- and two-bubble cases at the same moment are illustrated in figure 3. In the computation, the crown phenomenon occurs earlier in two-bubble case than that in single-bubble case. If the inter-bubble distance decreases, a greater height of the central spike is noted. It's reckoned that the bubble-free-surface coupling effect is strengthened with the existence of another bubble and that more water volume is obtained in two-bubble case.

4. Conclusions

A 3D model is established to simulate crown spike of free surface in two-bubble case with a boundary integral method and the effect of bubbles after the jet impact is ignored. It's inferred that the crown is a second spike induced by the large high-pressure region formed after the jet impact. Experimental and numerical results are compared and the favorable agreements of bubbles and free surface shapes validate the present simplified model. Comparing the crown spike in single- and two-bubble cases, it's noted that the coupling effect between bubbles and free surface in two bubble case is stronger than that in single-bubble case. If the inter-bubble distance decreases, the coupling effect increases.

5. References

- [1] Patrascioiu A, Florian C, Fernandez-Pradas J M, Morenza J L, Hennig G, Delaporte P and Serra P 2014 *Appl. Phys. Lett.* **105** 014010
- [2] Kolsky H, Lewis J P, Sampson M T, Shearman A C and Snow C I 1949 *Proc. R. Soc. Lond. A* **196** 379
- [3] Gibson D C 1968 *The 3rd Australasian Conf. on Hydraulic and Fluid Mechanics* November 25-29, 1968 (Sydney, Australia) p. 210
- [4] Chahine G L 1977 *Trans. ASME Ser. I. J. Fluid Eng.* **99** 708
- [5] Blake J R and Gibson D C 1981 *J. Fluid Mech.* **111** 123
- [6] Zhang A M, Wang C, Wang S P and Cheng X D 2012 *Acta Phys. Sin.* **61** 084701 (in Chinese)
- [7] Wang Q X, Yeo K S, Khoo B C and Lam K Y 1996 *Comput. Fluids* **25**(7) 607
- [8] Dadvand A, Shervani-Taba M T and Khoo B C 2011 *Int. J. Adv. Manuf. Technol.* **56** 245
- [9] Fong S W, Adhikari D, Klaseboer E and Khoo B C 2008 *Exp. Fluids* **46** 705
- [10] Dadvand A, Khoo B C, Shervani-Tabar M T and Khalilpourazary S 2012 *Eng. Anal. Bound. Elem.* **36** 1595
- [11] Li S, Zhang A M and Wang S P 2013 *Acta Phys. Sin.* **62**(19) 194703 (in Chinese)
- [12] Han R, Zhang A M and Li S 2014 *Chin. Phys. B* **23**(3) 034703
- [13] Newman J N 1977 *Marine Hydrodynamics* (1st Ed.) (London: MIT Press) 131
- [14] Zhang A M and Yao X L 2008 *Acta Phys. Sin.* **57** 339 (in Chinese)

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