A Study of Shock Wave and Associated Phenomena Induced by Underwater Electric Discharge in a Narrow Container

著者	Koita　Taketoshi
学位授与機関	Tohoku University
学位授与番号	11301甲第15795号
URL	http://hdl.handle.net/10097/58630

氏　　　　　　名	こ いた たけ とし 小 板 丈 敏
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
学 位 論 文 題 目	A Study of Shock Wave and Associated Phenomena Induced by Underwater Electric Discharge in a Narrow Container (薄型容器内の水中放電誘起する衝撃波及び関連現象に関する研究)
論 文 審 査 委 員	主査　東北大学教授　大林　茂　　東北大学教授　大平　勝秀 東北大学教授　佐藤　岳彦　東北大学准教授　孫　明宇

論文内容要約

Underwater explosion emits an underwater shock wave, and generates a high pressure and high temperature bubble at the center. When the underwater explosion is performed near the free surface, a water jet can be formed above the bubble. The water jet can be formed more efficiently in a confined narrow container such as a tube than in the free space. Recently the water jet induced by the explosion in the narrow tube has been applied in the medicine as a catheter and a surgical jet knife. This water jet is also important in volcanology to investigate explosive volcano eruptions that are driven by expanding gaseous bubbles. In hydrodynamics and bubble dynamics, extensive studies have been conducted on the propagation of underwater shock wave, the water jet formation and the bubble evolution in the free space such as in the sea or a large water tank. On the other hand, the studies in the narrow tube were mainly focused on the characteristics of water jet outside of jetting apparatus. In the narrow tube, the interaction between the expanding bubble and the free surface is certainly affected by the effect of tube sidewall depending upon the tube size. The formation and the velocity of water jet are affected not only by energy and explosion depth but also by tube size, which has not been studied thoroughly so far. This thesis is devoted to the phenomena associated with the underwater explosion in a confined narrow tube and container, including water jet, cavitation and shock wave.

The thesis is organized as follows,

In Chapter 1, the background and the motivation of the present study is described.

In Chapter 2, the effects of the explosion depth and the tube size on the water jet formation induced by the explosion in a narrow tube were studied experimentally. In order to visualize the detailed development of water jet and primary bubble, experiments were conducted in a water tube with rectangular cross-section of 5 mm in height. The size of the tube is adjusted by varying its width. Three different tube widths, W = 5, 10, 15 mm, are tested. An almost 2-D underwater explosion was created by the technique of exploding wire using electric discharge. Three discharge energies are tested by varying power voltage, V = 4.0, 4.5, 5.0 kV. The explosion depth H is varied with ten patterns between 5 mm and 60 mm. Experiments were visualized directly with the high speed video camera. The dependence of the bubble evolution and the water jet formation on various control parameters is clarified from the recorded images. The trajectories of important flow features, such as the top of water jet, were measured from the sequential images. The water jet

velocity was calculated from the displacement between two images.

It is found that the water jet formation and the bubble collapse depend strongly on the explosion depth H for different tube widths and discharge voltages. Two types of water jet formation were observed. One is that the water jet is changed from the blunt-shaped jet to spray at the shallow explosion of H = 5 mm. The expanding primary bubble quickly merges with the air pockets that are formed near two sidewalls, and destroys the water surface at the very early stage, resulting in the spray jet. The other is that the water jet evolves from the blunt-shaped to the spike-shaped one, for the explosion depth greater than 10 mm. The formation of spike-shaped water jet is delayed as the explosion depth is increased. Four patterns of bubble collapse were observed for all tube widths and discharge voltages. The first pattern is that the expanding bubble destroys the free surface, and simultaneously loses its shape at the shallow explosion of H = 5 mm. The second pattern is observed at H = 15 mm and 10 mm, in which the bubble is merged with air pockets gradually. In the third pattern, for H = 20 ~ 30 mm, the bubble does not interact with the air pocket. It is penetrated by the downward and the upward jet inside it. The fourth pattern is in the great deep explosion, for H greater than 35 mm, the bubble contracts by itself due to the long distance between air pocket and the bubble.

The water jet velocity depends on not only the explosion depth and energy but also the tube width. The water jet velocity is gradually decreased as the explosion depth increases and as either the tube width or the discharge voltage decreases. In order to investigate further the effect of the tube width on the velocity of water jet, the jet velocity in the tube of the present experiment has been compared with that in the free space estimated by Kolsky and Kedrinskii formulas. We proposed an empirical formula of jet velocity in the tube taking account into the effect of tube width. This formula was constructed based on the Kedrinskii formula, by fitting the present experimental data.

The underwater shock wave emitted by the explosion reflects as the expansion wave from the water surface. The secondary cavitation was generated between the primary bubble and the bottom wall in the tube due to the pressure drop caused by the expansion wave. The volume fraction and the number density of secondary cavitation bubbles were measured quantitatively. This cavitation is the compressible and strongly unsteady phenomena.

In Chapter 3, the secondary cavitation induced by the discharge in the rectangular tube for V = 4.5 kV and H = 15 mm was studied numerically. The numerical simulation was carried out with the compressible two-pressure two-velocity two-fluid model. The phase change was calculated by the equilibrium cavitation model and the modified Merkle's cavitation model which was a non-equilibrium model. In the setup of the initial condition for the small bubble generated by the discharge, the initial pressure and the temperature of it were calculated with the absorption coefficient of energy transformation from the discharge energy. The present numerical simulation successfully resolves the secondary cavitation, water jet and bubble evolution in the tube.

Two numerical models based on different definitions of sound speed for the cavitation region were compared. One is the classic homogeneous sound speed, and the other introduces a modification, in which the liquid sound speed is adopted if the vapor volume fraction is below certain threshold value. The front velocity of the secondary cavitation zone can be predicted fairly well, although both models predict the front velocity slight faster than that of experiment. The definition of the sound speed of gas-liquid mixture has a significant impact on the front velocity. It is found that even the threshold value as low as 0.1 % may have a considerable impact on the maximum volume fraction and the front velocity of the second cavitation zone.

In Chapter 4, underwater shock waves and fine bubbles behind the shock waves in a narrow container were studied experimentally. The container is clamped by two plates with a distance of 5 mm. The phenomena were visualized from the front direction and the side direction of the container by the shadowgraph method. The pressure behind the shock wave was measured by a needle hydrophone probe. In the visualization from the front side, the front wall made of acyclic glass is tested. The multiple waves including the underwater shock wave are observed after the electric discharge when visualized. These waves were formed by the reflection of the shock wave at the glass wall because of the narrow container. The fine bubbles appeared behind the shock wave. The similar bubbles were also observed behind the shock wave emitted by the primary bubble rebound. This phenomenon has never been reported before. These bubbles behind shock waves depend on the discharge voltage. The voltage threshold found in the present experiment is 3.35 ± 0.05 kV. The pressure peak of the shock wave created by discharge and emitted by the rebound of the primary bubble reached about 18 MPa and about 9.4 MPa for $V = 4.5$ kV, respectively.

When viewed from the side direction, two wall materials are compared. One is made of acyclic glass, and the other is made of stainless steel. In both cases, the waves reflect from the front walls, and these waves interact at the center of the container. The timing for the formation of the bubble cloud matched well with the wave interactions at the center of the container visualized from the side. The formation of these post-shock cavitation bubbles is clearly related to the wave reflections from the front walls.

In Chapter 5, the conclusions is described.

In short, the dependence of the explosion depth and the tube width on the water jet formation and bubble evolution generated by the underwater electric discharge in the narrow rectangular tube has been investigated. The effect of the explosion depth and energy, the tube width on the water jet velocity has been studied. The secondary cavitation was studied numerically and the effect of the definition of the sound speed of gas-liquid mixture on the front velocity of cavitation zone was investigated. The propagation of underwater shock wave emitted by the discharge and the primary bubble rebound, and the generation of cavitation bubbles behind the shock wave in the narrow container has been studied experimentally. The results so far obtained are summarized:

(1) The explosion depth affects the water jet formation and bubble evolution generated by the electric discharge in the narrow rectangular tube.

(2) Two types of water jet formation were observed for varied explosion depths. One is that the water jet is changed from the blunt-shaped jet to spray at the shallow explosion of $H = 5$ mm. The other is that the water jet becomes from the blunt-shaped to the spike-shaped one, for the explosion depth greater than 10 mm.

(3) The interaction between the bubble and the free surface affects the bubble evolution and there are four typical patterns of bubble

collapse at different explosion depth for all tube widths and discharge voltages.

(4) The velocity of water jet depends on not only the explosion depth and energy but also the tube width. The empirical formula of water jet velocity in the tube was proposed based on the Kedrinskii formula. The standard deviation of error between the jet velocity of experiment data and of the present formula is less than 3.30 m/s. The present formula is valid for $H \leqq 30$ mm, with a discrepancy less than 15 %.

(5) The secondary cavitation is generated between the primary bubble and the bottom of the tube, which is due to the pressure drop caused by the expansion wave. The secondary cavitation bubbles disappear rapidly after the maximum volume fraction is attained. The volume fraction of secondary cavitation is less than 2.2 %. This cavitation is the compressible and strongly unsteady phenomena.

(6) The numerical simulation of secondary cavitations based on the compressible two-pressure two-velocity two-fluid model with both the non-equilibrium and the equilibrium cavitation model resolves well the formation and the disappearance of the strongly unsteady secondary cavitation.

(7) The definition of the sound speed of gas-liquid mixture has a significant impact on the front velocity. A simple test has been performed. If the gas volume is below certain threshold value of vapor volume fraction in a cell, the classic homogeneous two-phase sound speed is replaced by that of the pure water. When the threshold value is between 0.05 % and 0.1 %, the front velocity agrees best with the experiment data.

(8) In the narrow container, the multiple waves is formed by the reflection of the underwater shock wave generated by the electric discharge at the glass front wall because of the narrow container. The fine bubbles appeared behind the shock wave emitted by the discharge and the primary bubble rebound.

(9) The appearance of cavitation bubbles behind the shock wave matches well with the wave interactions at the center of the container. It is concluded that the formation of these post-shock cavitation bubbles is due to the wave reflections from the front wall surfaces.