Point explosion in a bubble media. Research results and the prospects for the application

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Abstract. A point explosion (explosion of wires with an electric discharge energy of \( \approx 10^{10} \div 10^{3} \) J) in chemically inert and active bubble media was experimentally studied. The advantages of initiating bubble detonation by a point explosion are compared with the traditional method of initiating a plane shock wave. The possibility of detonation transfer during a point explosion in a bubble medium to the volume of an explosive gas above the interface between media is established. The dynamics of spherical shock and detonation waves in bubble media is investigated.

1. Introduction

The formation of a bubble detonation (BD) during the incidence of a plane shock wave (CW) from a gas onto a chemically active bubble medium occurs at a length of 2÷5 m. The BD is a soliton with pressure pulsations and energy release in the bubbles. The velocity of BD is greater than the equilibrium sound velocity \( c_0 \) in a bubble medium, but less than the sound velocity \( c_f \) in a liquid. To accelerate the time of formation of BD, it was proposed to explode short wires in a bubble medium [1,2]. In this case, a pressure profile and the velocity of BD is formed on 0.3÷0.5 m, and the critical initiation energy \( W^* \) is decreased by more than two orders of magnitude [2].

In this paper, to compare the parameters of the shock wave, the studies of a point explosion in a gas, liquid, and a bubble inert and reactive media are described. The experimental data are compared with the theoretical calculations [3,4]. Using the point initiation of BD, fundamentally new experiments were carried out on the transfer of detonation from a bubble medium to the volume of explosive gas above the boundary of the medium [5]. The mechanism and stages of the detonation transmission are established.

At present, the dynamics of the spherical shock and detonation waves in a chemically inert and active bubble media has not been practically studied. Aims of this paper is to show the possibility of the using a point explosion in various tasks with a bubble media, study the mechanism of the excitation and the features of the formation of a spherical BD during an electric discharge inside a reacting bubble media.

2. Experimental setup and methodology

The experiments were carried out in a vertical shock tube (internal diameter \( d=35 \) mm, length \( l=4.5 \) m) with movable copper electrodes on its top. The manganin wire with length \( \approx 9÷12 \) mm (0.26÷0.35 Ohm) was soldered between the electrodes. The capacitors \( C_1=2 \) and 50 \( \mu \)F were charged to a voltage of 4÷8 kV (\( W_0=16÷1600 \) J), the amplitude of the discharge current was 9÷18 kA. The coefficient of
the energy transfer to the wire is \( \frac{W_1}{W_0} \approx 67.5\% \), the energy released in the wire is \( W_1 \approx 10.8\div43.2 \) J and 0.27\(\div1.08 \) kJ.

The liquid in the tube is a mixture of 0.75\( \text{H}_2\text{O} + 0.25 \) glycerol (\( c_f \approx 1600 \) m s\(^{-1} \)), the gas in the bubbles is air or a mixture of \( \text{C}_2\text{H}_2 + 2.5 \) \( \text{O}_2 \). Bubbles 3\(\div4 \) mm in size were created at the bottom of the tube, the volume concentration was \( \beta_0 \approx 1\div4\% \). The pressure was measured by piezoelectric sensors (frequency 300 kHz, time constant \( \varepsilon \geq 1 \) s). The luminescence was measured by photomultipliers (PMT). Electrical signals were recorded by Tektronix TDS2014 oscilloscopes. Pressure measurement errors is 5\%, wave velocities in gas and liquid is 1\(\div3\% \) and in the bubble media is 5\(\div10\% \).

For the shooting, we used a Photron Fastcam digital optical camera located opposite the section with slits of 8\(\times 240 \) mm. The shooting speed is \( f_c \approx (1\div5.25) \times 10^5 \) frames s\(^{-1} \), flash time of a flash lamp is 1.8\(\div2.2 \) ms.

3. The results of the experiments

3.1. A wire explosion in the air
At a wire explosion (\( W_0 \approx 16\div1600 \) J), the SW is attenuated to a sound wave at the bottom of the tube. At the initial pressure \( p_0 = 0.1 \) MPa and \( W_0 = 625 \) J in the section between the wire and the piezoelectric sensor \( L_{0S} = 1.1 \) cm, the average velocity of the SW is 670\(\div700 \) m s\(^{-1} \), the duration of the first main compression region behind the SW front is \( \Delta t_{CW} \approx 50 \) \( \mu s \) and the drop of the pressure at the SW front is \( \Delta P = P - p_0 \approx 0.16 \) MPa.

3.2. Point explosion in a liquid
At the explosion of a wire near the liquid boundary (10.7 cm), the pressure of the shock wave is changed at a length of \( \approx 0.3 \) m (see figure 1). Wave 2’ (signal 2) is departed from the lower part of the front of the wave 1 (signal 1) at the length of 7.5 cm. At the next sensor it is registered as wave 2” (signal 3). Wave 1 is converted to 1’ and then to 1’’, the duration of the shock wave \( \Delta t_{CW} \) decreases from 70 to 30 and then to 20 \( \mu s \). For the SW 1 \( \Delta P = 45.0 \) MPa and \( \Delta t_{CW} = 60\div70 \) \( \mu s \) at \( L_{0S} = 17 \) cm, after the same distance the SW is divided into two waves with the same total \( \Delta t_{CW} \) and \( \Delta P = 3.0\div5.0 \) MPa.

![Figure 1. Pressure waveforms in the shock wave during a point explosion in a liquid; \( W_0 = 625 \) J. Vertical scale, MPa div:\( 1 - 9.0 \), 2 + 9.7, 3 - 5.7.](image)

The average wave velocities 1, 1’, 1’’ measured along the front and the back edges are 1608 and 1615 m s\(^{-1} \), respectively. From the compression region 3 and 3’ (signal 1 and 2 correspondingly), a
long SW 3" (signal 3) is formed. SW 1 is attenuated due to the appearance of cavitation bubbles in it. Propagating through a gas-liquid medium, waves 3, 3' has a gentle front. SW 3" propagating through the fluid has a steep front after attenuation of the primary SW. For SW 3" $\Delta P \approx 7.0 \div 13.0$ MPa (0.34 m from the wire). This shock wave detected by sensors at the bottom of the tube (after 3 m) has a high intensity compared to the case of a wire explosion in a gas, weakly attenuates, and maintains a pulsating structure, $\Delta t_{cW} \approx 1 \div 1.5$ ms, $\Delta P \approx 1.9 \div 2.5$ MPa. The steepness and profile of the pressure front are changed, the spread of values $\overline{P}$ reaches 100 m s$^{-1}$. Despite of the value and the pressure profile $\overline{P}$, Therefore, the values of the average and instantaneous SW velocities in a liquid is practically equal.

3.3. Shock wave in a chemically inert bubble medium
The initial size of the explosion region is $\sim \varepsilon, \varepsilon \leq \lambda$, where the distance between the bubbles is $\lambda \approx 17 \div 10$ mm at $\beta_0 \approx 1 \div 4\%$. Therefore, a wire explosion can be considered as point explosion even at distances of $\sim \lambda$. At $\beta_0 \approx 0.8 \div 4.1\%$ (air bubbles) and $W_0 \approx 0.4 \div 1.6$ kJ, the SW pressure profiles are similar. Typical pressure oscillograms are shown in figure 2 ($L_{0S} = 17$ cm). In a bubble medium, pressure pulsations in SW are more pronounced than in a liquid. The two-wave structure is registered by the first sensor (figure 2, a, signal 1). Due to the bubbles in the first wave are divided apart into a small ones ($\leq 0.1 \div 0.5$ mm), the amplitude of the pressure pulsations of the first wave is greater than the one of the second wave [4]. At a distance of 0.3 m from the place of the explosion, the 1-st wave slows down the speed and the 2-nd almost catches up with the first, $\Delta t_{cW} \approx 0.5 \div 1.0$ ms.

![Figure 2](image)

**Figure 2.** Pressure wave forms during a point explosion in a bubble medium above (a – signals 1–3) and below (b – signals 1–3) of the tube; $W_0 = 0.9$ kJ, $\beta_0 = 1.15\%$. Vertical scale, MPa div$^{-1}$: a) 1–11.5, 2–9.7, 3–9; b) 1–0.49, 2–0.43, 3–0.45.

$\Delta t_{cW} > 10$ ms in a falling SW at the bottom of the tube. The reflected SW moves in a gas-liquid medium with small bubbles, the pressure pulsations in it are weaker than in the incident SW (figure 2, b). The quantities $\overline{P}$ and $\Delta P$ in the incident shock wave depend on $W_0$ and $\beta_0$. For fixed $\beta_0$ and $W_0$, the SW velocity is approximately 2 times lower than the velocity at the top.

3.4. About the speed of SW
There are difficulties associated with measuring the velocity of the shock wave, and especially at small $\beta_0$. Due to a gently sloping front and unstable wave structure, the beginning of the shock wave cannot be accurately determined. It is even more difficult to measure $\overline{P}$ near the place of the explosion of the wire, where the shock wave is short, unstable, and bubbles are destroyed in it. The SW attenuation based on the measurement reaches 30\%–50\%. If we compare $\overline{P}$ with the theoretical formula for
calculating the speed of the shock wave, then it is more correct to choose that \( t_1 \) and \( t_2 \) at which the SW pressure get constant on the oscillograms.

To compare the theory and experiment, a procedure is proposed for calculating the average velocity of the shock wave, using the experimental approximation of the decrease in the pressure amplitude over the distance. Comparison of the values \( \overline{V} \) with theory [6–8] was carried out at a great distance from the wire. In this case, the speed difference calculated by the above formulas did not exceed 20 m s\(^{-1}\). Despite of the good agreement of experiment and theory, the theoretical formulas cannot be considered reliable, since the models assumed that the shock wave is stationary (without loss).

3.5. *Initiation of BD by a wire explosion*

The experiments were carried out at \( \beta_0 \approx 1÷4\% \) with a mixture of C\(_2\)H\(_2\)+2.5O\(_2\). The characteristic oscillograms of pressure and glow in the shock wave during a wire explosion are shown in figure 3. Here \( L_{os} = 0.17 \) m, the PMT optical inputs are located opposite the piezoelectric sensors. At the wire explosion, a superimposed BD wave is formed with the luminescence of the bubbles, \( \Delta t_{CW} \approx 100÷150 \) \( \mu \)s, the amplitude of the pulsations is 20÷70 MPa (figure 3, a). During movement, the wave is converted into a stationary BD, its averaged pressure profile becomes close to conoidal (figure 3, b). The experimental results prove the presence of a resonant shock-wave mechanism of initiation of bubble detonation. The optimal initiation of BD occurs at \( W_0 \approx (1.1÷1.2)W^* \) (faster than at \( W_0 \gg W^* \), where \( W^* \approx 15÷20 \) J).

![Figure 3. Oscillograms of pressure (signals 1, 2) and glow (a – 3, 4; b – 4) at the top \((a)\) and below \((b)\) of the tube during a point explosion in a bubble medium; \( \beta_0 = 4\% \), \( W_0 = 1225 \) J. Vertical scale: \( a) \) 1 – 11.4 MPa div\(^{-1}\), 2 – 22.4 MPa div\(^{-1}\), 3 – 10 V div\(^{-1}\), 4 – 2 V div\(^{-1}\); \( b) \) 1 – 33.4 MPa div\(^{-1}\), 2 – 15.4 MPa div\(^{-1}\), 3–5 V div\(^{-1}\).](image)

The velocity \( D \) of the stationary BD is independent of \( W_0 \). Due to the heterogeneity of the medium at \( \beta_0 = 1\% \), the spread in the values of \( D \) is increased (figure 4). The data obtained are close to the values of \( D \) in [1-5], where the initiation of the BD was carried out by the shock wave created by undermining the gas mixture in the initiation section.
3.6. Detonation transfer from a bubble medium to an explosive gas volume

The experiments were carried out at wire immersion depths $L \approx 1 \div 35$ cm. For $L = 35$ cm, the parameters of the BD wave are close to stationary at the moment of its emergence on the surface of the bubble medium. For each $L$, for $\beta_0 = 1, 2, 3, \text{ and } 4\%$, the probability $p$ of detonation transfer from the bubble medium to the gas volume above the boundary of the bubble medium was determined. The time between the arrival of the BD to the boundary of the medium and the ignition of the gas above it is $t_1 \approx 0.1 \div 1.5$ ms. The value of $t_1$ does not depend on $\beta_0$ and $L$.

On figure 5, a time $t$ is counted from the moment the current is applied to the wire. The arrow shows the position of the sensor $S_1$. At $t = 0.85$ ms, a bubble ignition 1 cm from the surface of the medium was detected in the BD wave moving from the bottom up. Bubbles closer than $8 \div 10$ mm from the boundary of the medium do not ignite, since the degree of compression in them is $<3 \div 4$ due to the unloading of the pressure wave. At the frame $t = 1.25$ ms, the medium moving upward is foamed. At $1.65 < t < 2.24$ ms, the observation region is opaque. Ignition in the mixture volume ($t = 2.24$ ms) occurs at $t_1 = 1.35$ ms (the luminescence of the flash lamp has stopped). After transition to detonation, the wave moves upward through the foamy medium at a speed of $V_1 \approx 1500$ m s$^{-1}$. At $t = 2.4$ ms, the
detonation wave leaves the field of view, and the glow disappears. At \( t \geq 2.55 \text{ ms} \), a reflected blast wave arrives from above with a speed of \( V_2 \approx 800 \text{ m s}^{-1} \). The measurement errors of \( V_1 \) and \( V_2 \) are 15%.

In figure 5, on \( S_1 \), \( \Delta P_1 = 13.35 \text{ MPa} \), on \( S_2 \), \( \Delta P_2 = 7.58 \text{ MPa} \). The average BD velocity between \( S_3 \) and \( S_2 \) is \( V_{23} \approx 400 \text{ m s}^{-1} \). A detonation wave in a foamy medium with an amplitude of \( \Delta P_1 = 0.81 \text{ MPa} \), then after 400 \( \mu \text{s} \) a backward blast wave from the gas volume (\( \Delta P_1 = 1.06 \text{ MPa} \)) and a reflected wave (gentle shallow pressure peak in 1.27 ms after the first detonation front) are sequentially recorded by the \( S_1 \) sensor (signal 1). The PMT detected the scattered glow of a flash lamp for approximately 2 ms, the glow of bubbles in section \( S_2 \) and then the glow of 30 and 120 \( \mu \text{s} \) opposite \( S_1 \), respectively, in a detonation wave and an explosive reflected wave.

Explosive gas is not initiated by the combustion products of the gas mixture in the bubbles directly at the boundary of the bubble mixture, the initial ignition occurs inside the foam medium. The volume of gas is initiated by a detonation wave propagating through the foam medium at a speed of 1500÷2000 m s\(^{-1}\) (moreover, much earlier than during adiabatic compression by a gas-liquid piston). If \( L \geq 4 \text{ cm} \), then \( p \approx 10.5 \pm 3.8\% \) and does not depend on \( L \).

When the wire is located near the boundary (\( L = 1 \text{ cm} \)) and the plasma discharge bubble can go beyond the boundary of the bubble medium, there is an additional possibility of the initiating by the exploding conductor or a heated plasma with the hot products. In this case, \( p \approx 63.5\% \pm 4.5\% \) is increased by about 6 times.

3.7. Spherical shock and detonation waves in a bubble medium
The experiments were carried out in a tube filled with water \( d = 0.6 \text{ m}, l = 1.49 \text{ m} \). A bubble medium was created in a telescopic tube from three sections \( d_i = 225, 232 \text{ and } 240 \text{ mm}, l_i = 0.5 \text{ m} \). The bubble sizes were 3÷4 mm, \( \beta_0 \approx 1÷2\% \). After the fall of the sections, a wire explosion occurred in the free column of the bubble medium.

The energy of the wire evaporation is \( W_2 \approx 6.5÷9.2 \text{ J} \), the melting energy is \( W_3 \approx 0.68÷0.97 \text{ J} \). At \( W_3 < W_1 < W_2 \) the conductor melts, but the shock wave does not form. Ignition of bubbles and excitation of BD do not occur from the molten wire.

With an increase in energy, when \( W_2 < W_1 < 10 \text{ J} \), a discharge plasma bubble either does not form or is poorly developed, and then a short, rapidly decaying shock wave forms. The energy of such a shock wave is not enough to excite the BD. In a chemically inert bubble medium (water – air bubbles), the shock wave has an oscillating structure and attenuates at a distance of several tens of centimeters.

At \( W_1 \geq 10÷13 \text{ J} \), the wire evaporates, the expanding plasma bubble creates a shock wave, and a self-sustaining detonation process occurs at a distance of 0.5÷1 m. At the initial stage of the explosion, the plasma bubble has the shape of a wire (short cylinder), then when it expands, the bubble becomes spherical. A spherical BD wave, after reaching the boundary of a bubble medium, takes the form of a plane wave, as in a conventional shock tube. At \( \beta_0 \approx 1÷2\% \), the BD propagates at a speed of \( D \approx 930÷750 \text{ m s}^{-1} \) (\( D \approx (8÷9)c_0, D < c_f \approx 1490 \text{ m s}^{-1} \)).

4. Conclusions
When studying a point explosion in chemically inert and active bubble media, new experimental results were obtained and the prospects of using a point explosion to solve scientific and applied problems were shown.

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