Detonation in bubble media: the effect of initial pressure

A I Sychev
Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia
E-mail: sychev@hydro.nsc.ru

Abstract. The influence of parameters of mono- and polydisperse, one- and multicomponent bubble media on the conditions of initiation, structure, propagation velocity, and pressure of detonation waves is experimentally investigated. It is established that the variation of initial pressure of bubble medium is an efficient method to control the parameters of waves of “bubble” detonation.

1. Introduction
Detonation is a dissipative process, i.e., the possibility of propagation of detonation waves is provided by energy release in a medium that compensates for the energy loss of detonation wave occurring due to the irreversible medium transformation. In bubble media, the substances able to release energy are in gas phase (in gas bubbles). When varying the initial pressure of medium with the specified volume concentration of gas phase, the mass concentration of gas and, hence, the energy content of the system change. Thus, the initial pressure of bubble medium is the parameter having influence on characteristics and defining the possibility of existence of detonation waves.

The phenomenon of detonation in bubble media (the “bubble” detonation) has a great generality: detonation waves are found in bubble media of different structures (mono- and polydisperse, one- and multicomponent ones) of qualitatively different types (“a chemically inactive liquid – the bubbles of a chemically active gas”, “a liquid fuel – the bubbles of gaseous oxidizer”). The goal of the work is to find general and specific features of detonation waves in different bubble media and, particularly, to study the influence of initial pressure of bubble media on the conditions of initiation, structure, propagation velocity, and pressure of detonation waves.

2. Experimental set-up
The research of detonation waves in bubble media was performed in a vertically-located shock tube of 40 mm internal diameter and 4.3 m high consisting of high-pressure and low-pressure sections with a bursting diaphragm between them [1]. The low-pressure section was filled with a liquid, in which gas bubbles were generated through a nozzle fixed on the end of the shock tube. The height of the column of bubble medium for the volume concentration of gas phase lying in the range $0.5 \leq \beta_0 \leq 6$ % was 3.55 m.

The “bubble” detonation was initiated by the shock waves generated in bubble media during the combustion of fuel gas (acetylene-oxygen stoichiometric mixture $\text{C}_2\text{H}_2 + 2.5 \text{O}_2$) in the high-pressure section of the shock tube; the amplitude (pressure) of initiating shock waves was varied by changing the initial pressure of gas mixture [1] (here, the amplitude of shock waves corresponded to pressure arising above the bubble medium during the combustion of fuel gas in a closed volume of the high-
pressure section of the shock tube [2]). This method of generating shock waves in gas-liquid media allows us to generate waves with amplitudes varying within a wide range [3, 4].

The parameters of detonation waves (propagation velocity, pressure, and duration) were defined with piezoelectric pressure sensors fixed along the shock tube. The signals of pressure sensors were registered by oscillographs OK-33M and S9-16. The luminescence of bubble media accompanying the process of propagation of detonation waves was detected by photoelectronic multipliers FEU-102 whose optical inputs were located diametrically opposite to the pressure sensors.

The following different chemically-active bubble media of the type “a chemically inactive liquid – the bubbles of a chemically active gas” are studied:

- one-component monodisperse media (OMM) are the systems, in which the liquid contains the bubbles of the same type of gas and of the same size: \( L(\alpha) = \beta_0 G \), where \( L(\alpha) \) are water-glycerin solutions for the volume concentration of glycerin \( \alpha = 0, 0.25 \text{ or } 0.5 \) (the viscosity of solutions \( \mu = 1.01 \cdot 10^{-3}, 2.27 \cdot 10^{-3} \text{ and } 6.84 \cdot 10^{-3} \text{ Pa·s} \) respectively), \( G \) are the bubbles of chemically active gas \((\text{C}_2\text{H}_2 + 2.5 \text{ O}_2)\) of specified diameter \( d_i = d_1, d_2 = 1.9 \pm 0.1 \text{ mm}, d_3 = 2.5 \pm 0.1 \text{ mm}, d_4 = 3.9 \pm 0.2 \text{ mm} \) or \( d_5 = 5.0 \pm 0.3 \text{ mm} \), \( \beta_0 \) is the volume concentration of gas phase of bubble medium;

- multicomponent media (PM) are the systems, in which the liquid contains the bubbles of several types of gas: \( L(\alpha) = (\beta_1 G_1 + \beta_2 G_2) \), where \( L(\alpha) \) are water-glycerin solutions \( \alpha = 0, 0.25 \text{ or } 0.5 \), \( G_1 \) is chemically active gas \((\text{C}_2\text{H}_2 + 2.5 \text{ O}_2)\), \( G_2 \) is chemically inactive gas Ar, He, N\(_2\) or H\(_2\), \( \beta_1, \beta_2 \) are the volume concentrations of gases \( G_1 \) and \( G_2 \), the total concentration of gas phase of bubble medium is \( \beta_0 = \beta_1 + \beta_2 \);

- polydisperse media (PM) are the systems, in which the liquid contains the gas bubbles of different size: \( L(\alpha) = \beta_0 G \), where \( L(\alpha) \) are water-glycerin solutions \( \alpha = 0, 0.25 \text{ or } 0.5 \), \( G \) is a mixture of bubbles of chemically active gas \((\text{C}_2\text{H}_2 + 2.5 \text{ O}_2)\) of diameter \( d_1 + d_2 \) when the gas content is approximately equal to that for the bubbles of different size, \( \beta_0 \) is the volume concentration of gas phase of bubble medium.

### 3. Experimental results and discussion

The initiation of detonation is that the chemical energy of medium is actualized. The activation of chemical reactions is available under definite conditions, the main of which is an appropriate temperature of interacting substances. It is found that the propagation of shock waves in bubble media is accompanied by the phenomena indicating that the gas temperature reached high values during the bubble compression as pressure in the medium rose: in inert bubble media, the shock waves caused gas luminescence in the bubbles [5]; in chemically active bubble media, the shock waves ignited chemically interactive substances contained in the medium [1]. The energy release in chemically active bubble media initiated by a shock wave causes the formation of self-sustained wave process, i.e., a detonation wave. The phenomenon of detonation in bubble medium is found in [2].

The shock waves with amplitude of more than critical \( p_1^* \) [1, 2] are able to ignite chemically active substances and initiate a detonation in bubble media; here, the characteristics of detonation wave are independent of amplitude, duration, and method of generation of initiating shock wave and they are defined by the features and parameters of the bubble medium [2, 6, 7], i.e., the detonation in bubble media is an autowave process. The critical amplitude of shock wave \( p_1^* \) rises as the concentration of gas phase increases and the viscosity of liquid component of medium decreases and ranges within 1.7÷6.0 MPa in OMM for \( \alpha = 0, 0.25 \text{ and } 0.5 \) at \( \beta_1 \leq 6 \% \) and atmospheric initial pressure [2, 6, 7]. In the systems for \( \alpha = 0.5 \) at \( \beta_0 \leq 2 \% \) and initial pressure \( p \) ranging from atmospheric \( p_0 \) to 2 kPa, the “bubble” detonation is initiated by the shock waves with amplitudes \( p_1^* \leq 1.7 \text{ MPa} \).

In MM, at atmospheric initial pressure, the values of critical amplitude of initiating shock wave \( p_1^* \) depend both on the total concentration of gas phase of bubble medium and on the relation of concentrations of active and inactive bubbles [8]. Thus, in system \( L(0.25) = [\beta_1 (\text{C}_2\text{H}_2 + 2.5 \text{ O}_2) + \beta_2 \text{Ar}] \) at \( \beta_2 \leq 1 \% p_1^* \leq 1.7 \text{ MPa} \) (\( \beta_0 \leq 4 \% \)) and \( p_1^* = 3.4 \text{ MPa} \) (\( \beta_0 = 6 \% \)) \( \beta_0 = \beta_1 + \beta_2 \) is the total concentration of gas phase, \( \beta_1 \) and \( \beta_2 \) are the concentrations of bubbles \((\text{C}_2\text{H}_2 + 2.5 \text{ O}_2) \) and Ar, respectively; at \( \beta_2 = 0.3 \% p_1^* = 3.4 \text{ MPa} \) (\( \beta_0 \leq 4 \% \)).
2 \% p_1^* = 3.4 \text{ MPa} (\beta_0 = 4 \%) and \ p_2^* = 4.3 \text{ MPa} (\beta_2 = 6 \%). The values of critical amplitude \( p_1^* \) rise as \( \beta_0 \) and \( \beta_2 \) increase. In the systems for \( \alpha = 0.5 \), for the total concentration of gas components \( \beta_0 \leq 2 \% \) and initial pressure lying in the range from atmospheric one to 2 kPa, the “bubble” detonation is initiated by the shock waves with amplitudes \( p_1^* \leq 1.7 \text{ MPa} \).

The values of critical amplitude of initiating shock wave \( p_1^* \) in PM at atmospheric initial pressure rise as the concentration of gas phase increases and the viscosity of liquid component of medium decreases [9, 10]: \( p_1^* = 1.7 \) and 1.7÷3.4 MPa in the systems for \( \alpha = 0.5 \) and 0.25, respectively at \( 0.5 \leq \beta_0 \leq 6 \% \). In OMM, the smallest values of critical amplitude \( p_1^* \) are observed in the systems for gas bubbles of diameter \( d = d_1 \); for \( \alpha = 0, 0.25 \) and 0.5 \( p_1^* = 1.7 \div 6.0 \text{ MPa} \). In PM, for \( \alpha = 0 \), the self-sustained regimes of detonation are absent: for the amplitudes of initiating shock waves up to 6.0 MPa, we observe only “overcompressed” detonation waves decaying with weakening of the sustaining initiating shock wave. In the systems for \( \alpha = 0.5 \) at \( \beta_0 = 0.5 \% \) and initial pressure ranging from atmospheric one to 10 kPa, the “bubble” detonation is initiated by the shock waves with amplitudes \( p_1^* \leq 1.7 \text{ MPa} \).

The detonation waves in OMM have a pulsation pressure profile (figure 1) [8]. The pulsations of pressure are the result of generating shock waves by the gas bubbles ignited after being compressed in the detonation wave. The ignition and combustion of the gas mixture in bubbles is also accompanied by the light radiation detected by photoelectronic multiplier FEU-102 (figure 1), and, moreover, by the change of electrical conductivity of the bubble medium [12]. The stochasticity of pressure pulsations and light radiation is due to the chaotic distribution of gas bubbles in the liquid. The registered amplitude of pressure pulsations, whose duration is 3÷5 \( \mu \text{s} \), reaches 15÷30 MPa.

The waves of “bubble” detonation in MM and PM (as in OMM) are solitary waves with pulsation profile of pressure [8–10]. The quantitative characteristics of detonation waves depend on the type and parameters of the bubble medium. In the studied PM, the duration of detonation waves \( \tau \) (the time characteristics of detonation waves in bubble media measured at a level of 0.1 from the maximum pressure value) equals approximately 120 \( \mu \text{s} \). In OMM, the duration of detonation waves is defined by the size of gas bubbles and equals approximately 25, 30, 40 and 50 \( \mu \text{s} \) in the systems for gas bubbles of diameter \( d = d_1, d_2, d_3, \) and \( d_4 \), respectively [11]; here, the duration of detonation waves is independent of the concentration of gas phase and features of the liquid component of bubble media. The presence of gas bubbles of different size in PM causes the increasing the duration of detonation waves in comparison to that in comparable OMM, i.e., in the systems containing gas bubbles whose diameter lies in the range of bubble size in PM. The increase in duration allows the detonation wave to interact with the gas bubbles of different size.
Interacting with the detonation wave, the shape of bubbles is distorted (figure 2) [11]. At some stage of compression, the cumulative jet of liquid piercing the bubble is formed.

![Figure 2: Photoregistering (a) and kinogram (b) of gas bubbles in the detonation wave. α = 0.25, β0 = 1 %, d = 5.1 (a) and 2.4 mm (b); p = p0.](image)

The compression of gas bubbles occurs in the heterogeneous pressure field of the detonation wave with pulsation structure. The averaging of pressure pulsations makes it possible to obtain the effective pressure profile of the “bubble” detonation wave (figure 3) [13] (the signals from pressure sensors were averaged by using a standard procedure of digital oscillograph S9-16 over 10 points at discretization time equal to 1 μs). The effective pressure of detonation waves reaches 6÷8 MPa in all studied systems at atmospheric initial pressure [8–10, 14]. Behind the detonation wave, the pressure is close to that in an unperturbed bubble medium.

![Figure 3: Oscillograms of pressure of detonation wave before (a, c) and after (b, d) averaging of pressure pulsations. OMM; α = 0.5, β0 = 0.5 %; p/p0 = 1 (a, b) and 0.02 (c, d).](image)

Detonation in bubble media is a stationary process. The wave of “bubble” detonation propagates at constant velocity that is more than equilibrium velocity of sound in a bubble medium, but less than the velocity of sound in a liquid. The velocity of detonation waves is independent of the conditions of initiation and is defined by the medium parameters. The velocity of detonation waves $D$ decreases as the concentration of gas phase $\beta_0$ rises. In OMM, for $0.5 \leq \beta_0 \leq 6$ % and atmospheric initial pressure the
velocity of detonation waves $1350 \geq D \geq 450$ m/s. Here, the linear size (length) of detonation waves $\lambda$ (the spatial characteristics of detonation waves in bubble media determined by the wave duration $\tau$ and its propagation velocity $D$: $\lambda = D \cdot \tau$) is $2÷9$ cm. The velocity of detonation waves decreases with decreasing the viscosity of liquid component of the system (the essential influence of liquid-component viscosity of bubble media on the critical conditions of initiation, parameters, and the limits of propagation of detonation waves [1, 2, 6–11, 14, 15] – the effect of “viscosity” [15] – is explained by the influence of viscosity on the state of bubble surface during the compression in detonation wave and, as a result, on the value of energy loss of gas bubbles).

In MM, the presence of the bubbles of inactive gas in the system causes the decrease of the velocity of detonation wave propagation. This fact is the result of interaction of inactive-gas bubbles with detonation wave causing the increase of energy loss of detonation wave. The presence of the bubbles of inactive gas for concentration $\beta_2 \sim 0.5\beta_0$ in the system turns out to be critical: a detonation wave cannot exist under given conditions.

The values of velocity of detonation wave propagation in PM at atmospheric initial pressure for $\alpha = 0.5$ and 0.25 lie in the range of variation of detonation wave velocity in comparable OMM. In PM for $\alpha = 0$, a detonation is absent within the whole range of variation of gas phase concentration of the medium in contrast to the case in OMM: for $\alpha = 0$, a detonation wave is absent in the systems containing the bubbles of diameter $d \leq d_1$ (for $\beta_0 \geq 4\%$) and $d \geq d_4$ (for $\beta_0 \geq 2\%$) – there is the limit of propagation of detonation waves with respect to the diameter of gas bubbles [11].
Figure 4. Dependences $D(p/p_0)$. a) OMM; $\alpha = 0.5$, $\beta = 0.5$ (1, 2), 1 (3) and 2% (4); the distance from the surface of bubble medium $L = 3.10$ (1) and 2.55 m (2-4). b) MM; $L(0.5) - [\beta_1 (C_2H_2 + 2.5 O_2) + \beta_2 N_2]$; $\beta = \beta_1 + \beta_2 = 0.5 + 0.5 = 1$ (1) and 1 + 1 = 2% (2); $L = 2.85$ m. c) PM; $\alpha = 0.5$, $\beta = 0.5$%; $L = 2.85$ m.

When varying the initial pressure of medium, the structure of detonation waves in bubble media remains qualitatively identical (figure 3). Here, the initial pressure of bubble medium has an essential influence on the parameters of detonation waves [13, 16–18]. The decrease of the initial pressure of bubble medium causes the decrease of the velocity of detonation waves (figure 4); here the pressure of detonation waves decreases, but the duration of waves is almost unchangeable. In the investigated range of variation of initial medium pressure, the dependences $D(p/p_0)$ in OMM for different concentrations of gas phase of medium are close to linear (figure 4a); as the initial pressure of medium rises (up to 0.7 MPa), the velocity of detonation waves (in the systems “a liquid fuel – the bubbles of oxidizer”) tends to the velocity of sound in a liquid [15]. Dependences $D(p/p_0)$ in MM and PM have the form analogous to that in OMM (figures 4b, 4c).

The dependence of the parameters of detonation waves on the initial pressure of bubble media is due to accompanying change in the energy content of the system: with decreasing the initial pressure of the medium with the specified concentration of gas phase, the mass concentration of gas and, hence, the energy content of the system decrease; the action of this parameter turns out to be essential: the velocity of detonation wave propagation drops and the pressure decreases (the influence of the energy content of bubble medium on the parameters of detonation waves is studied in [19]).

4. Conclusion

The phenomenon of “bubble” detonation has a great degree of generality: detonation waves exist in systems differing in their features both quantitatively and qualitatively: in mono- and polydisperse, one- and multicomponent bubble media.

The shock waves with amplitude more than the critical one are able to initiate a detonation in bubble media. The values of critical amplitude of the initiating shock wave are determined by the parameters of bubble medium and features of gaseous and liquid components of the system. Detonation process is the result of collective interaction of gas bubbles uniformly distributed in a liquid: the gas bubbles ignited in the detonation wave radiate shock waves into the ambient liquid, which compress and ignite the bubbles located in front of the detonation wave.

The characteristics of detonation waves are independent of the initiation conditions and are determined by the parameters and physical and chemical features of bubble media, i.e., detonation is an autowave process. The structure of detonation waves is qualitatively identical in all studied media: the wave of “bubble” detonation is a solitary wave with a pulsation profile, the pressure behind which relaxes to the value close to that in an unperturbed medium in front of the wave. The duration of detonation waves in bubble media is determined by the size of gas bubbles and the effective (averaged over pulsations) pressure of detonation waves is determined by the energy content of the medium.

The variation of initial pressure of bubble media is the efficient method to control the parameters of the waves of “bubble” detonation.

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