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FEATURES OF THE DYNAMICS OF DETONATION WAVES IN LAYERED BUBBLE SYSTEMS

ABSTRACT. The evolution of detonation waves in the vertical annular layer filled with a gas-liquid medium, with different bubble holdup and different ways of detonation initiation is investigated. The effects of the initial exposure to different parts of the pipe end and concentration of bubbly mixture on the formation of detonation waves and the dynamics of their distribution have been determined. It has been discovered that in case the bubble holdup is 1% and the bubble area and the external ring of the pure liquid are exposed to a hard knocker there is a detonation wave breakdown; the reasons for this phenomenon are given. The initiation mechanism of the detonation wave is considered. The initiation mechanism of the solitory matter wave when the bubble holdup is 3–4%, and the end of the annular layer and external layer of the pure liquid are exposed to a hard knocker has been described and its peculiar features against the other background have been given. The effects of the initial exposure method and bubble holdup at the moment of detonation have been investigated.

KEY WORDS. Detonation wave, initiation, bubble medium, heterogeneity, background wave.

Let us consider the two-dimensional axisymmetric wave disturbances in a liquid-filled tube containing an annular bubble layer bounded by cylindrical surfaces with the generating parallels of the axis z.

Figure 1 shows a diagrammatic representation of a gas-liquid system, which illustrates the tube with radius R_{CI} with the zone of the homogeneous bubble mixture with radius $\Delta R = R_c - R_p$ surrounded by cylindrical layers of 'clean' liquid. We assume that the gas in the bubbles is explosive (e.g. a mixture of acetylene and oxygen). System disturbances arise due to an impact on the tube end.

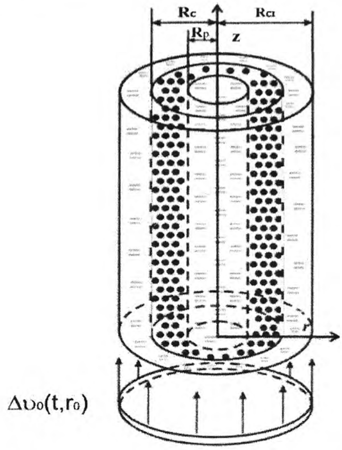

Fig. 1. Scheme objectives: a cylindrical annular bubble layer enclosed in the layers of 'clean' liquid.

To describe the wave motion, we write the system of macroscopic equations of mass conservation, the number of bubbles, and impulses and pressure in the bubbles in a cylindrical coordinate system [1, 2]:

$$\frac{d\rho_i}{dt}+\rho_i\frac{v_r}{r}+\rho_i\left(\frac{\partial v_r}{\partial r}+\frac{\partial v_z}{\partial z}\right)=0, \quad (i=l,g)$$

$$\frac{dn}{dt}+n\frac{v_r}{r}+n\left(\frac{\partial v_r}{\partial r}+\frac{\partial v_z}{\partial z}\right)=0,$$

$$\rho\frac{dv_r}{dt}+\frac{\partial p_l}{\partial r}=0,\ \rho\frac{dv_z}{dt}+\frac{\partial p_l}{\partial z}=0,$$

$$\rho\frac{dv_z}{dt}+\frac{\partial p_l}{\partial z}=0,\ \left(\frac{d}{dt}=\frac{\partial}{\partial t}+v_r\frac{\partial}{\partial r}+v_z\frac{\partial}{\partial z}\right),$$

$$\alpha_l+\alpha_g=1,\ \rho_i=\rho_i^0\alpha_i,\ \alpha_g=\frac{4}{3}\pi n a^3,$$

$$\rho=\rho_g+\rho_l,$$

where a – the radius of the bubble, γ – the ratio of specific heat for gas, p_i – phase pressure, ρ_i – true densities of the phases, α_i – cubic content of the phases, q – the heat transfer rate, n – the number of bubbles per a cubic unit, w – the radial velocity of the bubbles. Speeds v_z and v_r correspond to the coordinate motions z and r. The parameters of liquid and gas are marked with subindexes $i=l,g$.

Radial motion is described with the following equations [3]:

$$w = w_A + w_R,\ \frac{\partial w_R}{\partial t} = \frac{1}{a}\left(\frac{p_g - p_l}{\rho_l^0} - \frac{3}{2}w_R^2 - \frac{4\nu \cdot w_R}{a}\right),\ w_A = \frac{p_g - p_l}{\rho_l^0 C_l \alpha_g^{1/3}},$$

where $\tilde{N}_l$ – the speed of sound in liquid, ν_l – liquid viscosity.

We assume that liquid is acoustically compressible and gas is calorically perfect [4]:

$$p_l = p_0 + C_l^2\left(\rho_l^0 - \rho_{l0}^0\right),\ p_g = \rho_g^o R T_g,$$

where R – gas constant.

Here and below the parameters related to the initial unperturbed state are indexed with 0 underneath.

Heat flux q is given by the approximate finite relation [5]:

$$q = \mathrm{Nu}\lambda_g \frac{T_g - T_0}{2a}.$$

Nusselt number is determined from the condition [6] $\mathrm{Nu} = \begin{cases} \sqrt{\mathrm{Pe}}, \mathrm{Pe} > 100 \\ 10 \end{cases}$

where $\mathrm{Pe} = 12(\gamma - 1)\dfrac{T_0}{\left|T_g - T_0\right|}\dfrac{a|w|}{k_g},\ k_g = \dfrac{\lambda_g}{\tilde{n}_g \rho_{g0}}$

The temperature and pressure of the gas inside the bubble are defined by the equations [7]:

$$\frac{T_g}{T_0} = \frac{p_g}{p_0}\left(\frac{a}{a_0}\right)^3,\ \frac{dp_g}{dt} = -\frac{3\gamma p_g}{a}w - \frac{3(\gamma - 1)}{a}q$$

To carry out numerical experiments, we accept the following initial and boundary conditions: $t = 0, z > 0$ which correspond to the initial state of bubble mixture stopping in the tube:

$$p_l = p_0,\ \upsilon_r = \upsilon_z = 0,\ \rho_l = \rho_{l0}^0$$

$$R_p < r_0 < R_c : \alpha_g = \alpha_{g0},\ \rho = \rho_{l0}^0(1 - \alpha_{g0}) + \alpha_{g0}\rho_{g0}^0,\ p_g = p_0,\ a = a_0,\ w = 0$$

$$0 < r_0 < R_p,\ R_c < r_0 < R_{Cl} : \alpha_{g0} = 0,\ \rho_l = \rho_{l0}^0$$

On the symmetry axis $(r_0 = 0)$ and the tube wall $(r_0 = R_c)$ the conditions of liquid impermeability $\upsilon_r = 0$ are accepted [8].

To initiate a wave in the system, a hard ram tester affects the border $z = 0$ under the law [9]:

$$\upsilon_0(t, r_0) = \begin{cases} \Delta\upsilon_0\, exp\left(-\left(\dfrac{t - t_*/2}{t_*/6}\right)^2\right), & 0 < t < t_* \\ 0,\ t > t_* \end{cases} \tag{1}$$

where $\Delta\upsilon_0$ – the velocity amplitude, t_* – a typical impulse length.

The method of numerical calculation is presented in [10].

Numerical experiments were carried out at the following geometrical and thermal parameters of the system: $a^{(0)}_g = 1.5$ mm, gas—a mixture of acetylene and oxygen $(\tilde{N}_2 \acute{I}_5 + 2{,}5\hat{I}_2)$ [8]:

$$\rho^0_{g0} = 1.3 \text{ kg/m}^3, \quad \gamma_0 = 1.35, \; \lambda_g = 2.51\cdot10^{-2} \text{ J/(m} \cdot \text{s} \cdot \text{deg)},$$

$$c_g = 1.14\cdot10^3 \text{ J/(m} \cdot \text{s} \cdot \text{deg)}, \; T_* = 1000K, \; \Delta T = 3000K;$$

liquid—mixture of glycerine and water:

$$\rho^0_{l0} = 1130 \text{ kg/m}^3, \; \nu_l = 0.6\cdot10^{-5} \text{ m}^2\text{/sec}, \; C_l = 1700 \text{ m/sec}, \; p_0 = 10^5 \text{ Pa}, \; T_0 = 293\ K.$$

Indexes 1 and 2 in Figs. 2–4 correspond to the areas of bubble mixture and a 'clean' liquid.

In Fig. 2 it can be seen the dynamics of wave propagation in time of 0.5 msec for the case of the cubic content of the bubble mixture α = 1% at different ways of initiation: Fig. 2a corresponds to the impact on the whole tube end, Fig. 2b—to the impact on the bubble ring. It is seen that a detonation wave is initiated in the bubble ring in both cases. In the case of impact on the tube end (Fig. 2a), in all the layers: both in the area of the bubble rings, and in a 'clean' liquid, the waves of significant amplitude are produced. If an impact is made only on the annular bubble layer (Fig. 2b), the background waves in a 'clean' liquid are almost invisible.

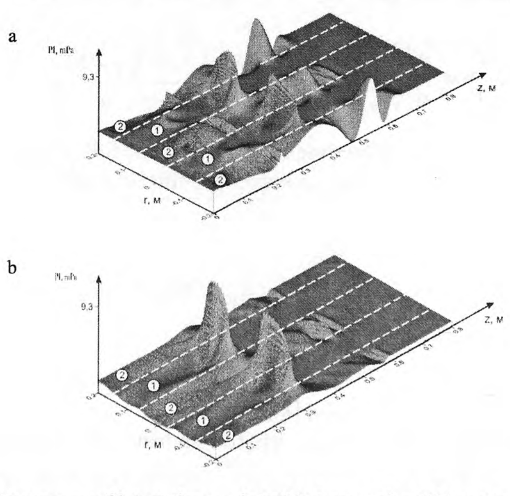

Fig. 2. Pressure profiles at time point of 0.5 msec for different ways to initialize wave disturbances

The impact with a hard ram tester on various sections of a tube end influences the ignition time of the gas-liquid mixture. When the volume ratio of bubbles is equal for all the cases, the ignition occurs faster in case of the impact on the tube end. The ignition occurs a little later in case of a simultaneous impact both on the bubble ring and the outer ring of 'clean' liquid. In the last instance it occurs when there is an impact on the ring. It should be noted that at increasing the volume of bubbles' concentration, more time is required to form detonation waves.

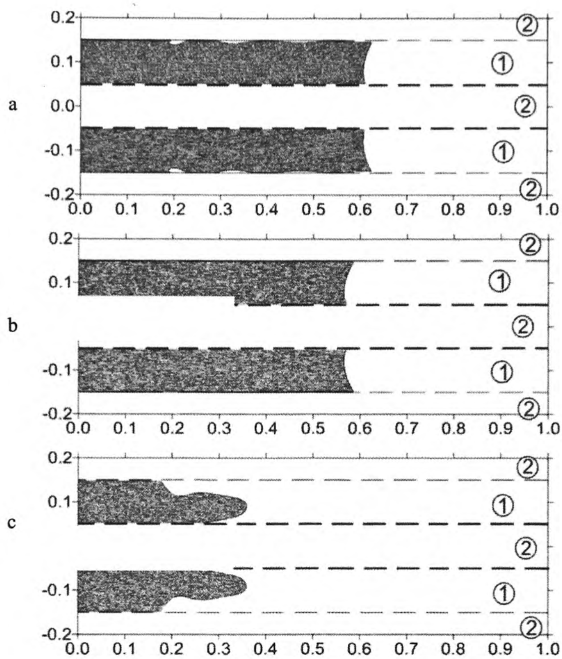

Fig. 3. Areas of ignition at time point of 0.73 msec for various methods of initial impact on the system

Figure 3 shows the areas of ignition for various methods of initiation of the initial pulse and the cubic content of 0.01 bubbles. Figure 3a corresponds to the case when on the boundary $z = 0$ a hard ram tester impacts the whole pipe cross section by law (1). Figure 3b corresponds to the case when on the boundary $z = 0$ a hard ram tester impacts a ring bubble layer. Figure 3c corresponds to the case when on the boundary $z = 0$ a hard ram tester impacts simultaneously the bubble area and the outer ring of 'clean' liquid by law (1). As it is seen from Fig. 3d, in case of initial simultaneous impact with a ram tester on the bubble and 'clean' liquid rings there are some areas that function as the across areas of ignition. It happens due to the wave compression from the outer layer of the 'clean' liquid. Thereby, it weakens the detonation wave and prevents its further propagation. As a result, a solitary matter wave breaks.

Figure 4 shows the dynamics of wave propagation and the corresponding area of ignition in the bubble area under the impact of a ram tester on a sidewall the annular bubble layer and the outer layer of 'clean' liquid. Bubble concentration is 3%. Figure 4a shows that detonation originates in the border area of 'clean' liquid where an impact on the tube end initiates a wave with amplitude of 11.7 mPa. The amplitude of the wave in the bubble ring is almost unnoticeable. This effect is due to the difference in acoustic impedances: acoustic impedance $\rho_l^0 C_l$ for 'clean' liquid is significantly higher than the similar parameter of the bubble mixture, whereby the amplitude of waves in the bubble area and 'clean' liquid differ in more than 10 times. Figure 4b shows that a detonation wave with amplitude of 7.5 mPa originates in the bubble area. It is formed as a result of the propagation of the wave along the radius of the tube towards its center occurring in the outer layer of 'clean' liquid. Thus, detonation initiated in the bubble area is not caused by the impact of a ram tester on the bubble medium but by the impact of the shock wave of 'clean' liquid, which is shown in Fig. 4a. The emerging detonation wave propagates further along the outer generating lines of the tube, keeping the amplitude of 10.1 mPa, which can be seen in Fig. 4c and Fig. 4g. The areas of ignition indicate that detonation originates in the bubble area locally at the border with 'clean' liquid (Fig. 4a) then the area of ignition extends to the opposite border with 'clean' liquid (Fig. 4b), and further it extends along the axis z. It should be noted that a small area at the boundary with the outer ring of 'clean' liquid remains free from detonation due to the compression of the detonation wave in the area. The described process of initiating ignition and the formation of a detonation wave in the bubble layer is observed while an initial simultaneous impact on the bubble ring and the outer ring of 'clean' liquid has the volume ratio of bubbles of 3–4%. In other considered cases: with the same impact and the volume ratio of bubbles of 1–2%; under the impact on tube end; under the impact on bubble ring, ignition extends from the end of the bubble ring, covering the entire bubble area.

Thus, it has been studied the geometry effect of the initial pulse and cubic content of bubbles on the process of initiation and propagation of detonation waves in the annular layer filled with a gas-liquid medium and bounded by cylindrical surfaces with generating parallels of axis z.

It has been found out that under different conditions of implementing initial pulse, various patterns of wave disturbances are specified. There are differences in the time of detonation. When the concentration of bubble mixture rises, the process of solitary matter wave formation takes more time. It is shown that in case of impact with a ram tester on the tube end (except the central cylindrical area of 'clean' liquid with the volume ratio of bubbles of 1%), detonation solitary matter wave breaks due to the compression of background waves. When the volume ratio of bubbles is 3–4% due to a high amplitude pressure in 'clean' liquid, initiation of detonation can occur not because of the impact on the bubble ring, but due to the compression of the bubble ring by the pressure wave originating in the area of 'clean' liquid.

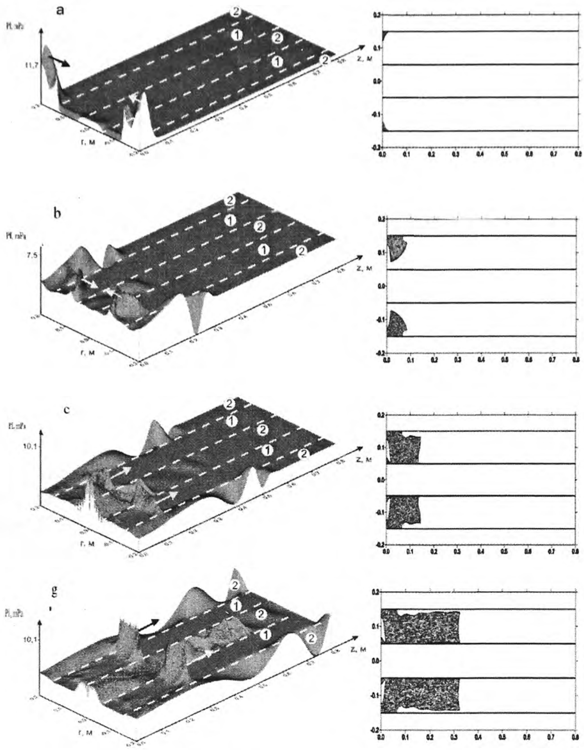

Fig. 4. Pressure profiles and related areas of ignition at time points of 0.06 msec, 0.20 msec, 0.35 msec, and 0.71 msec

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