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THE DETONATION WAVE IN A RING BUBBLES LAYER

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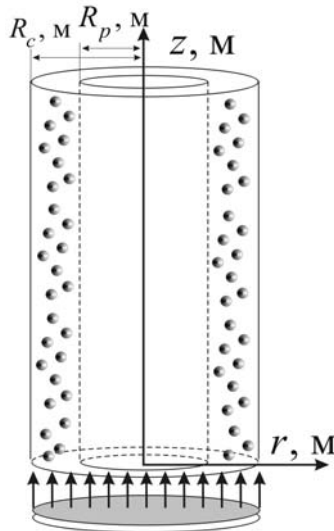


Fig 1. The Circuit settlement areas.

R_c - the radius of pipe, R_p
 and $\Delta R = R_c - R_p$ - the
 radius and the thickness of
 the ring bubbles layer

The evolution of a detonation wave in the ring bubbles layer located in a pipe is considered. The opportunity of existence of the detonation wave extending with constant speed and amplitude is shown.

Let in a pipe filled with fluid contains the ring bubbles layer limited to cylindrical surfaces at which forming axes Z (see fig. 1) are parallel. And, gas inside the bubbles explosive (for example, mix $C_2H_5+2,5O_2$).

At the moment of time $t=0$ for the bottom end of a pipe ($z=z_0$) on all radius R_c the piston with some speed starts to influence or pressure upon the piston is set. It is required to determine dynamics of wave process in system at $t > 0$, in depending on parameters of a problem.

For the description of this movement, we shall write down system of the macroscopical equations of weights, numbers of the bubbles, pulses and pressure in the bubbles in approach of cylindrical symmetry [1]:

$$\begin{aligned} \frac{d\rho_i}{dt} + \rho_i \frac{v_r}{r} + \rho_i \left(\frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} \right) &= 0 \quad (i=l, g), \\ \frac{dn}{dt} + n \frac{v_r}{r} + n \left(\frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} \right) &= 0, \\ \rho \frac{dv_r}{dt} + \frac{\partial p_l}{\partial r} = 0, \quad \rho \frac{dv_z}{dt} + \frac{\partial p_l}{\partial z} = 0, \quad \rho = \rho_g + \rho_l, \\ \frac{dp_g}{dt} = -\frac{3\gamma p_g}{a} w - \frac{3(\gamma-1)}{a} q, \quad w = \frac{da}{dt}, \quad \left(\frac{d}{dt} = \frac{\partial}{\partial t} + v_r \frac{\partial}{\partial r} + v_z \frac{\partial}{\partial z} \right), \\ \alpha_l + \alpha_g = 1, \quad \rho_i = \rho_i^0 \alpha_i, \quad \alpha_g = \frac{4}{3} \pi n a^3, \quad \rho = \rho_g + \rho_l, \end{aligned}$$

where a – radius of the bubbles, γ – a parameter of an adiabatic curve for gas, p_i – pressure of a phases, ρ_i^0 – true density of the phases, α_i – volumetric contents of the phases, q – intensity of heat exchange, n – number of the bubbles in unit of volume, w – radial speed of the bubbles. Speeds v_r and v_z correspond to movement on coordinates r and z . The bottom indexes $i=l, g$ mark parameters of liquid and gas phases.

A radial movement is described by the following equations

$$w = w_R + w_A, \quad a \frac{dw_R}{dt} + \frac{3}{2} w_R^2 + 4\nu_l \frac{w_R}{a} = \frac{p_g - p_l}{\rho_l^0}, \quad w_A = \frac{p_g - p_l}{\rho_l^0 C_l \alpha_g^{1/3}},$$

here, ν_l – is the fluid viscosity, C_l – is the sound velocity in the liquid.

We assume that the fluid is acoustically compressible and the gas is calorically perfect:

$$p_l = p_0 + C_l^2(\rho_l^0 - \rho_{l0}^0), \quad p_g = \rho_g^0 RT_g, \quad \frac{T_g}{T_0} = \frac{p_g}{p_0} \left(\frac{a}{a_0} \right)^3$$

here R is the gas constant. Here and in what from here and below, the subscript 0 denotes the parameters related to the initial undisturbed state.

The heat flux q is approximated by formula:

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

$$Nu = \sqrt{Pe}, \quad Pe \geq 100, \quad Nu = 10, \quad Pe < 100,$$

$$Pe = 12(\gamma - 1) \frac{T_0}{|T_g - T_0|} \frac{a|w|}{k_g}, \quad k_g = \frac{\lambda_g}{c_g \rho_g},$$

here $T_0 = const$ – is the fluid temperature, c_g and λ_g – is thermal capacity and thermal conductivity, Nu and Pe – is the Nusselt number and the Pekle number.

Under influence the piston in a pipe with a ring arrangement of bubbles the wave is formed at which distribution the bubbles make radial pulsations, and if the temperature of gas inside the bubbles reaches a critical value T_* , gas blows up, the temperature in gas thereof pressure in gas and in a liquid raise increases. This increase of pressure in a liquid "compresses" the bubbles, taking place before the formed wave and by that it can be realized detonation process and is formed the detonation wave. If the amplitude of an initial wave is small enough, and the temperature of gas in the bubbles does not reach value of temperature of ignition the wave picture is realized usual for bubbles fluid environments.

The ignition of the bubbles is taken into account under the instant circuit according to which at achievement of temperature of gas in the bubbles some value T_* (temperature of the ignition) the temperature in them instantly increases for size ΔT , corresponding the caloric content of a combustible gas mix in epy bubbles. Then parameters of a zone where there are chemical reactions, vary jump.

The technique of numerical calculation of the above-stated system of the equations is resulted in [1].

Let's consider dynamics of pulse pressure in a pipe with ring arrangement of the explosive bubbles, by impact of the rigid piston on an end face of a pipe formed. Initial and boundary conditions thus look like:

$$\text{at } t = 0: \quad a_0 = 1,5 \text{ mm}, \quad \alpha_{g0} = \begin{cases} 10^{-2}, & r > R_p \\ 0, & r \leq R_p \end{cases};$$

$$\text{at } z = 0: \quad v_z(t, r) = \begin{cases} \Delta v \exp\left(-\left(\frac{t - t_*/2}{t_*}\right)^2\right), & t \leq t_* \\ 0, & t > t_* \end{cases}$$

here $\Delta v = 10,5 \text{ m/c}$ - amplitude of an initial signal, $t_* = 0,1 \text{ mc}$ - characteristic extent of a pulse.

Calculations were carried out at the following thermal-physical parameters $p_0 = 0,1 \text{ MPa}$, $a_0 = 1,5 \cdot 10^{-3} \text{ m}$, $T_0 = 293 \text{ K}$, $T_* = 1000 \text{ K}$, $\Delta T = 3000 \text{ K}$, $\rho_{l0}^0 = 1115 \text{ kg/m}^3$, $\nu_l = 6 \cdot 10^{-6} \text{ m}^2/\text{c}$, $\rho_{g0}^0 = 1,3 \text{ kg/m}^3$, $\gamma = 1,35$, $c_g = 1,14 \cdot 10^3 \text{ J}/(\text{kg} \cdot \text{K})$, $\lambda_g = 2,51 \cdot 10^{-2} \text{ m} \cdot \text{kg}/(\text{K} \cdot \text{c})$, $C_l = 1700 \text{ m/c}$. Liquid – a mix of glycerin with water, gas – acetylene-oxygen mix ($\text{C}_2\text{H}_2 + 2,5\text{O}_2$).

On fig. 2 distributions of the pressure at the moment of time 0,85 mc are submitted. Fragments a , b and c differ various thickness of a bubbles ring so for a fragment a its size makes $\Delta R = 0,07 \text{ m}$, for a fragment b - $\Delta R = 0,05 \text{ m}$, for c - $\Delta R = 0,03 \text{ m}$. It is visible, that under influence of the rigid piston on an end face of a pipe in a bubble liquid there is a detonation wave which is distributed, not changing the amplitude and speed. Let's note, that the amplitude and speed of a

detonation wave are determined only by parameters of a bubble liquid and do not depend on characteristics of initial influence by the rigid piston.

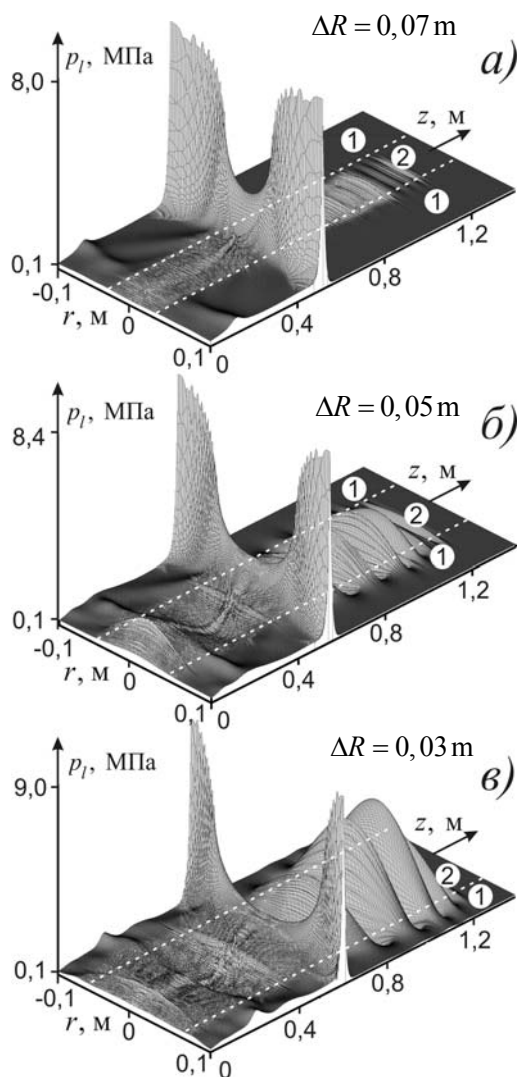


Fig. 2 Dynamics of a detonation wave in ring bubbles volume, located in a pipe of radius $R_c = 0,1\text{ m}$. Figures 1 and 2 mark areas of the bubbles and a "pure" liquid.

From rice 2 also it is visible, that the detonation wave extending in ring volume with amplitude about 8-9 MPa, generates in area of a "pure" liquid ($0 \leq r \leq R_p$) waves which, moving with speed of 1700 km/s, overtake a detonation wave. It is necessary to note, that for the waves extending on a "pure" liquid a border $r = R_p$ because of "acoustic softness" of the bubble environment is analogue of a free surface. The comparative analysis of fragments *a*, *b* and *c* shows, that the less width of a bubble layer, the more amplitude of pressure in the wave package extending on a "pure" liquid. So, for example, at thickness $\Delta R = 0,07\text{ m}$ (a fragment *a*) the amplitude of a detonation wave $\Delta p_l \approx 8\text{ MPa}$, and at thickness $\Delta R = 0,03\text{ m}$ the amplitude increases up to $\Delta p_l \approx 9\text{ MPa}$ though with increase in thickness of a ring layer power consumption of system increases and as consequence the amplitude of a detonation wave should increase.

The increase in amplitude of the detonation wave is connected to reduction of thickness of a bubbles layer that waves which are generated in a "pure" liquid by a detonation wave in case of small thickness of a bubble layer can draw in this layer and be distributed along a firm wall ($r = R_c$), and in a case when thickness such, that the waves extending on a "pure" ("clean") liquid, fade in a bubble ring then the effect of a compression a bubble layer practically is not shown.

On rice 3 a dependence of pressure amplitude and speed of a detonation wave on width of a bubble zone ΔR is submitted at radius of the pipe $R_c = 0,1\text{ m}$. It is visible, that the increase in width of a ring layer results in reduction as pressure amplitudes, and speed of a detonation wave. For example, at

thickness of a bubble zone $\Delta R = 0,02\text{ m}$ speed of a detonation wave is equal 940 km/s, and the

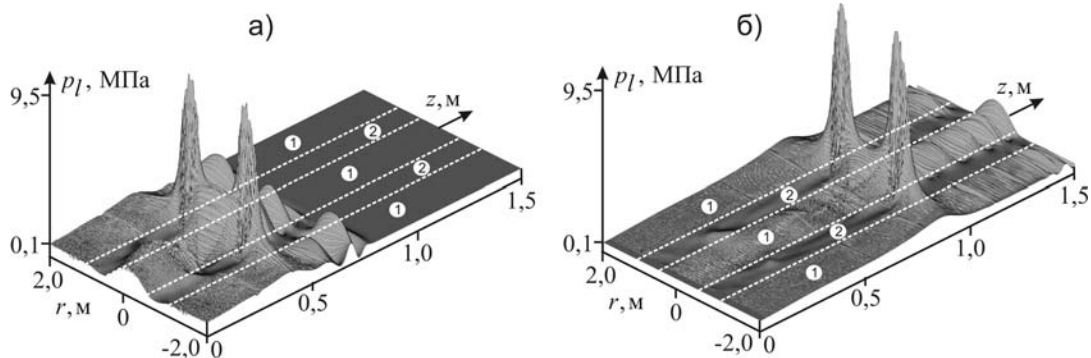


Fig. 4 The dynamics of the detonation waves in the ring bubble layer located in great volume of a liquid at thickness of a bubble layer of 0,05 m. Other parameters and designations same, as on fig. 2

amplitude reaches(achieves) value 10 MPa, and at $\Delta R = 0,07$ m speed decreases up to 750 km/s, and amplitude – up to 8 MPa.

On fig. 4 a structures of the pressure waves are submitted in a case when the ring bubble layer is in great volume of a liquid, i.e. in this case on border of settlement area nonreflecting conditions [2] are accepted. Fragments *a* and *b* on rice 4 would correspond to the moments 0,5 ms and 1,0 ms. It is visible, as the detonation wave extending on a ring layer which generates the background wave having speed in area of a "pure" liquid, big speeds of a detonation in this case is formed. Besides it is necessary to note, that because of additional compression by the background wave extending in a "pure" liquid outside of a ring the amplitude of the detonation wave more, than in a case resulted on fig. 2 though all other parameters of system are identical.

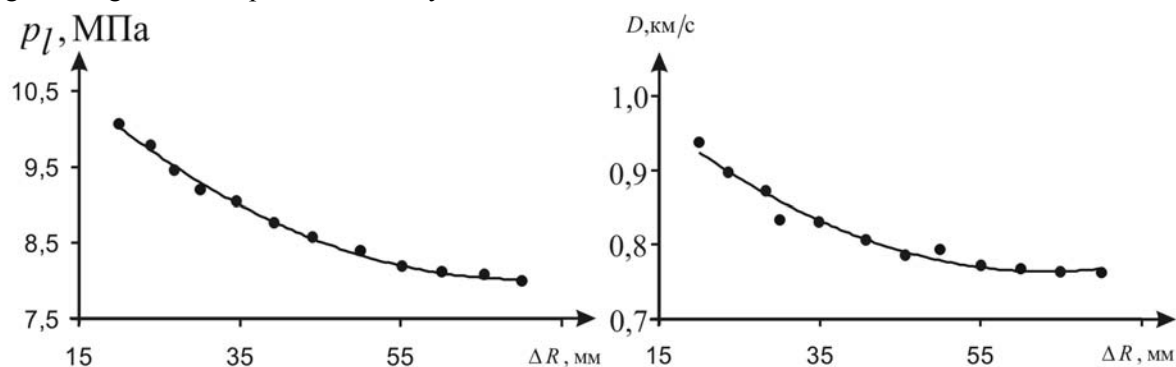


Fig.3 Dependence of the pressure amplitude and speed of a detonation wave on width of a bubbles zone. Parameters of system same, as on fig. 2

Thus, it is established, that in the ring layer of the bubble liquids with explosive gas inside the bubble the detonation wave can to be formed and distributed, which the amplitude and speed with reduction of thickness of the bubble ring increase because of compression by the background wave extending on a "pure" liquid.

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