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EVOLUTION OF THE STRUCTURE OF VISCOELASTIC LIQUID MEDIA UPON PULSE VOLUME TENSION

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It is shown experimentally that the unbounded bubble cavitation in a highly viscous liquid (glycerin) can develop only in a regime of very slow volume tension of a liquid sample. Upon pulse volume tension, cavitation in the sample damps at the initial stage (the bubbles do not reach pronounced sizes) and fragmentation occurs because of perturbations generated on its free surface. The mechanism of bubble growth from micropores in a thixotropic medium (gel) is explained based on experimental results and theoretical estimates.

The process of pulse volume tension of a broad class of liquids and liquid-like media was studied experimentally by Stebnovskii in [1]. It is shown that during tension the low-viscosity liquids that have significant shear viscosity, the non-Newtonian highly concentrated liquid-disperse media (emulsions, suspensions, and pastes) with a low-viscosity liquid matrix, and a viscoelastic gel undergo the stages of bubble growth from cavitation nuclei, the formation of a foam structure, and disintegration of the foam into fragments. Therefore, at any stage of volume tension these media can be described by the rheological equations of state constructed in [2, 3]. However, in the case of pulse volume tension of glycerin, which is a Newtonian viscous liquid, the formation of a foam was not observed: the cylindrical glycerin volume became filamentary structures oriented along the axis of symmetry.

The present work deals with an experimental study of the specific features of the evolution of the structure of a glycerin sample at all the stages of its pulse volume tension and clarifies the mechanism of cavitation in the gel.

1. The first series of experiments was devoted to the initial stage of cavitation development in glycerin and this stage was compared with a similar process in a gel possessing high structural viscosity (its composition is given in [1]). The dynamics of the cavitation zone in the media mentioned above was studied on an experimental setup whose layout is shown in Fig. 1. Here 1 is the transparent tank filled with medium 2 to be examined, and 3 is the thin manganin wire whose explosion is initiated by an electric discharge of a high-voltage capacitor ($C = 1$ μF and $U \leqslant 15$ kV). The explosion of the wire results in generation of the cylindrical shock wave S in the medium. After its front reaches the liquid surface F, the rarefaction wave V is reflected to the medium, and bubbles are formed behind its front in the zone of tensile voltage Q from the cavitation nuclei. The process was recorded by high-speed photorecorder 4 with the use of shadow device 5 with pulse illumination 6.

Figure 2a and b shows the frames of the dynamics of the initial cavitation stage behind the front of the rarefaction wave reflected from the free surface F in glycerin and the gel, respectively. The energy parameters of the electrodischarge circuit are $C = 1$ μF and $U = 10$ kV upon loading of the glycerin sample and $U = 8$ kV upon loading of the gel. The distance from exploding wire 3 (see. Fig. 1) to the free surface of the medium to be examined is $h = 2$ cm, and the wire length is 3 cm.

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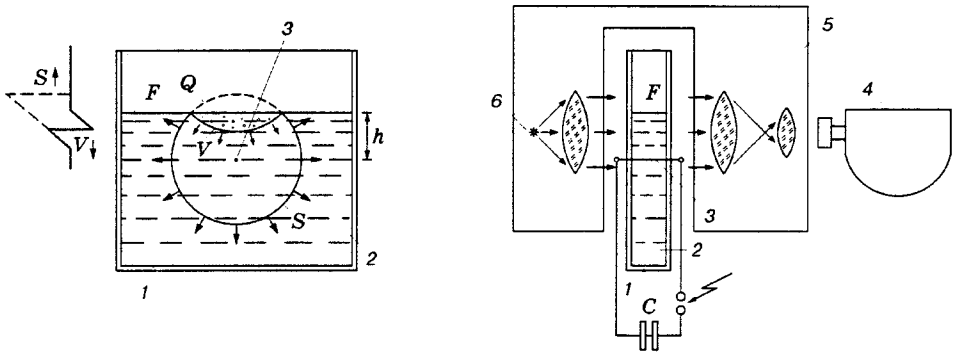

Fig. 1

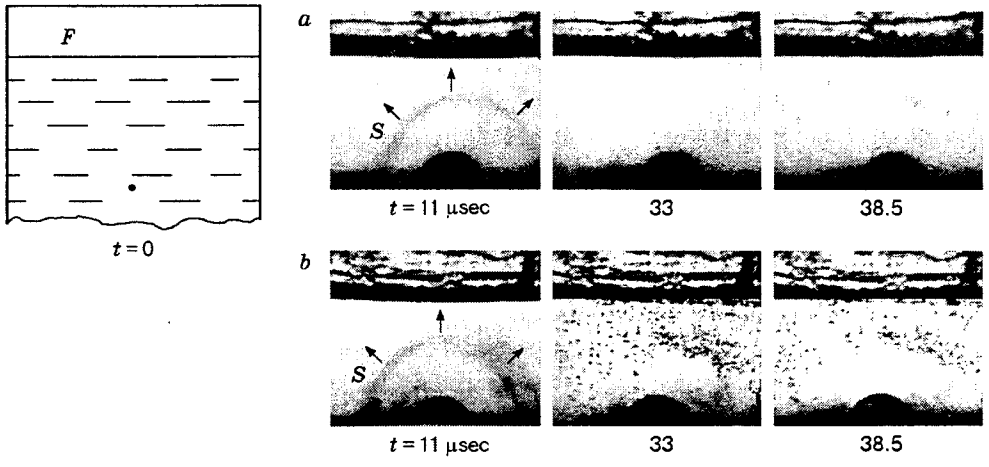

Fig. 2

A comparative analysis shows the absence of significant bubble cavitation in glycerin, whereas even for a lower value of the energy of shock-wave loading of a structured viscoelastic gel, one can observe quite an intense cavitation. (For $U \geqslant 10$ kV, in the gel, at the unloading stage the growth of bubbles passes to the formation of a foamy structure.) This supports the assumption of [1] that in the case of glycerin, which has great shear viscosity, at the initial stage of bubble growth the energy dissipation is so intense that cavitation damps rapidly owing to the high velocity of their expansion. This assumption is in agreement with the result of a test experiment on the volume tension of a glycerin sample in a transparent cylinder from which a piston located above the glycerin surface was put forward slowly (with a velocity of approximately 1 cm/sec). It was found out that upon a very slow volume expansion, cavitation bubbles grow unboundedly in glycerin up to the formation of a foamy cellular structure, i.e., the evolution of the morphology of the medium is similar to the formation of foamy cells in low-viscosity liquids [1]. This effect is due to small viscous losses in the neighborhood of the slowly growing bubbles.

2. We now consider the mechanism of growth of cavitational bubbles from micropores in the volume tension of a gel sample, which has significant structural viscosity and, hence, shear elasticity. To do this, we estimate shear stresses in the vicinity of a micropore in the gel in the unloading-wave zone. We ignore the effect of the interphase tension γ at the micropore–gel interface, assuming that $|2\gamma/R| \ll |P_1|$, where R is the micropore radius and P_1 is the pressure in the gel on infinity. Then, placing the origin of the spherical coordinate system (r, θ, φ) at the center of the micropore and denoting the pressure in it by P_2, we write the following boundary conditions for the radial component of the elastic stresses in the gel:

$$\sigma_{rr}\Big|_{r\to\infty} = -P_1, \qquad \sigma_{rr}\Big|_{r=+R} = -P_2. \tag{1}$$

Using the solution of the classical problem of determination of the stress field in a boundless elastic medium

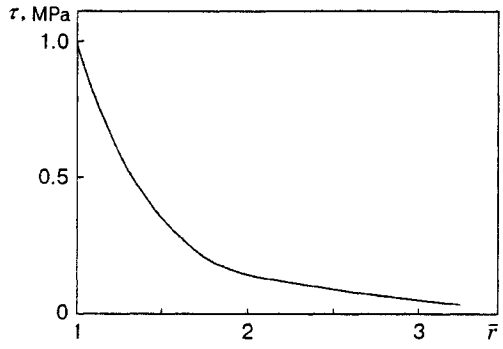

Fig. 3

with a spherical hollow of radius R [4], with allowance for the boundary conditions (1) we obtain the ratios for determining the basic components of the stress tensor:

$$\sigma_{rr} = -P_1\Big(1 - \frac{1}{\bar{r}^3}\Big) - P_2\frac{1}{\bar{r}^3}, \quad \sigma_{\theta\theta} = \sigma_{\varphi\varphi} = -P_1\Big(1 + \frac{1}{2\bar{r}^3}\Big) + P_2\frac{1}{2\bar{r}^3}, \quad \bar{r} = \frac{r}{R}. \tag{2}$$

From the Tresca plasticity condition [5]

$$\tau_{\max} = (\sigma_{\theta\theta} - \sigma_{rr})/2 = \tau_*,$$

according to which the plastic properties of a material begin to be manifested only when the maximum shear stress $\tau_{\max}$ reaches a value of τ_* that corresponds to the yield point of this material, with allowance for (2) we obtain

$$\tau_{\max} = -\frac{3}{4\bar{r}^3}(P_1 - P_2) = \tau_*, \qquad P_1 < 0. \tag{3}$$

If $\tau_{\max} > \tau_*$ at the boundary of the pore (for $\bar{r} = 1$), from (3) one can determine the radius of the external boundary of the spherical plasticity layer around the pore in which this pore extends:

$$R_1 = R\Big[\frac{3(|P_1| + P_2)}{4\tau_*}\Big]^{1/3}.$$

It follows from the experiments that the pressure in the front of the compression wave S incident on the free surface F (see Fig. 1) at which cavitation develops in the gel is equal to $1.5 \cdot 10^6$ Pa. (The pressure was registered by the standard method with the use of pressure gauges.) Therefore, assuming that the pressure is atmospheric in the micropore in the initial state, and a negative pressure $P_1 = -1.5 \cdot 10^6$ Pa is established in the gel for $\Delta\tilde{t} < 10^{-5}$ sec behind the front of the rarefaction wave reflected from the free surface (since the time of pressure increase in the compression-wave front is of the order 10^{-6} sec and its duration is $5 \cdot 10^{-5}$ sec), from (3) we obtain the distribution of the maximum shear stresses in the vicinity of the pore (Fig. 3); we note that $\tau_{\max} = 10.5 \cdot 10^5$ Pa for $\bar{r} = 1$ on its surface. Since, in this case, the pore expands, according to the experiment, one can consider that the threshold shear stress for $\Delta\tilde{t} \simeq 10^{-5}$ sec at least does not exceed the value of $\tau_* = 10^6$ Pa.

With allowance for the aforesaid, the mechanism of growth of a cavitation bubble from a micropore in the gel is as follows. If a shear stress $\tau_{\max} > \tau_* = 10.5 \cdot 10^5$ Pa is formed in the vicinity of a micropore for $\Delta\tilde{t} < 10^{-5}$ sec, the structure of the medium fails with a rate exceeding the rate of its restoration; as a result, the structural viscosity of the medium decreases abruptly, i.e., the medium becomes a sol. This makes the pore expand in the regime of a bubble in the spherical layer of a low-viscosity liquid until the rate of fracture of the structure becomes smaller than the rate of its restoration. Then the bubble growth terminates, and the medium again acquires the properties of an elastic gel with frozen-in pores which are already large. With sufficient kinetic energy in the gel, the unbounded growth of bubbles can occur with subsequent formation of cellular structures, which then can disintegrate into fragments.

If this physical model of cavitation in the gel is correct, for $\tau_{\max} > \tau_*$, in contrast to the Newtonian low-viscosity liquid [6], the modulus of shear G in the gel should decrease with increase in the shear-strain

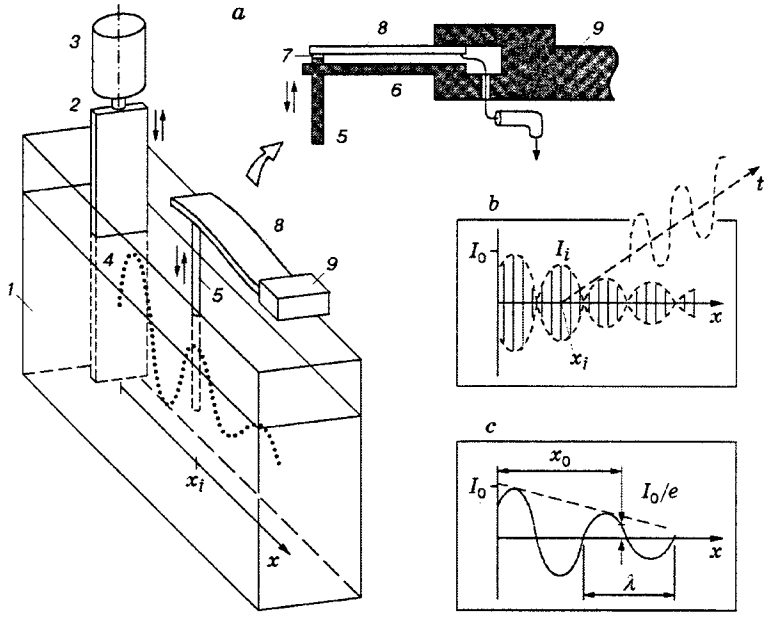

Fig. 4

rate δ' (at least, in the range of small δ'), since, as has already been noted, the shear strength of the gel depends on the ratio between the rates of the competing processes of fracture and restoration of the space skeletons from ultradisperse elements giving elastic properties to the gel. Since the rate of restoration of the gel structure does not change at constant temperature, the rate of its fracture in the gel should increase with δ' and, hence, the shear strength should decrease, i.e., the quantity G should decrease.

To study the dependence of G on $\delta'$and the volume concentration of pores α, a rheometric technique based on the known method of determinating G and the shear viscosity of the medium μ with the use of the degree of damping of the transverse (shear) simple monochromatic waves in it [7] was developed. The transverse wave is excited by an oscillating thin glass plate in its natural plane in the medium. Propagation of the damping transverse wave in the medium is registered by the optical shadow method. After that, using the measured wavelength λ, segment x_0, at which the wave amplitude becomes e times smaller, oscillation frequency of the plate ω, and density of the medium ρ, one can calculate (in the range of elastic oscillations) the real (G_1) and imaginary (G_2) parts of the complex modulus of shear $G^* = G_1 + iG_2$ from known relations [7]

$$G_1 = \frac{\omega^2\lambda^2\rho[4\pi^2 - (\lambda/\chi_0)^2]}{[4\pi^2 + (\lambda/\chi_0)^2]^2}, \qquad G_2 = \frac{4\pi\omega^2\lambda^2\rho\lambda/\chi_0}{[4\pi^2 + (\lambda/\chi_0)^2]^2}, \tag{4}$$

and determine the real modulus of shear of the medium under study

$$G = (G_1^2 + G_2^2)^{1/2}. \tag{5}$$

This method is applicable only to transparent media, because the shear-wave parameters are registered by the optical (shadow) method. In the present work, to register shear waves in optically opaque, pore (or bubble)-containing media, a piezoelectric gauge that permits one to register very weak shear oscillations of sound frequency was developed.

Figure 4a shows the layout of a modified rheometric device with the following principle of operation. A $10 \times 1 \times 0.03$ cm thin glass plate 2 is immersed into medium 1 in a narrow vessel shaped like a $20 \times 10 \times 1.5$ cm parallelepiped; oscillations of the plate in its own plane are initiated by vibrator 3. (The frequency of oscillations of the plate can range from 10 to 100 Hz in the case of viscoelastic liquid-like media and from 10 Hz to 1kHz in the case of low-elastic liquids.) The oscillating plate excites transverse (shear) wave 4 in the medium; damping, this wave propagates in the direction perpendicular to the plane of oscillation of the plate.

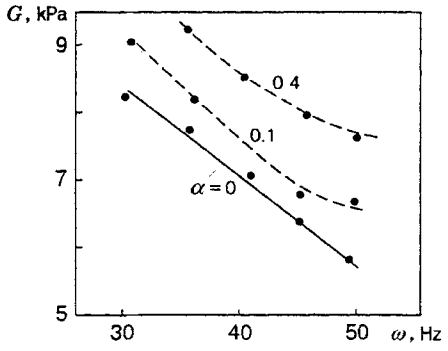

Fig. 5

The wave should have quite a small amplitude for the oscillations to satisfy the condition of linear elasticity of the medium. The thin, 0.2-cm-diameter hollow lyometal rod 5 is placed into the medium to be examined at a fixed distance from the plate and parallel to it. The rod is spring-controlled by elastic plate 6 from beryllium bronze. The transverse wave excites synchronous vertical oscillations of the rod which abuts the upper end face through insulator 7 against the free end of fixed thin plate 8 having the piezoelectric effect. Owing to the large length of the plate (3 cm), gauge 9, which operates as a sound remover of an electroplayer, has very high sensitivity: the small longitudinal displacements of rod 5 initiate flexural oscillations of the plate; as a result, owing to the piezoelectric effect, an electric signal that corresponds to the wave is formed in the plate. The metal case of gauge 9 is acoustically isolated from the carrier design of the device.

Locating rod 5 of the gauge at various distances x_i from plate 2, one can record the transverse-wave amplitude $I_i(t)$ at fixed points of x_i (path of its propagation in the medium). In Fig. 4b, the vertical lines correspond to the double transverse-wave amplitude registered by the gauge. Using the envelope of the family of these lines, the profile of the damping transverse wave $I(x)$ (Fig. 4c) is restored. After that, using this profile, the wavelength λ and the section of the path x_0 on which the wave amplitude damps by a factor of e are determined, and, finally, the modulus of shear elasticity of the medium G is calculated by formulas (4) and (5). The rheometer was adjusted in liquid media whose parameters are known from the literature.

Based on this technique, the dependence of the modulus of shear elasticity of the gel G on the pore concentration in it α and the frequency of the shear wave ω and on the shear strain that characterizes the shear-strain rate of the medium δ' were measured. As a result, it was found that with increase in ω, and, consequently, δ', the modulus G decreases (Fig. 5; points refer to the experiment), supporting the proposed physical model of cavitation development in the gel: the higher the shear-strain rate, the more intense failure of the gel structure and the more rapid decrease in its shear elasticity. It is noteworthy that, for a fixed value of ω, the higher the pore concentration α, the larger the G owing to the increase in the total elasticity of the pore surfaces, which is due to interphase tension. This result agrees with the character of the influence of the bubble concentration on the shear elasticity of low-viscosity liquids: for $\alpha > 0.9$, water acquires the properties of an elastic foam.

3. To study the evolution of the structure of the glycerin sample at the last stage of its volume expansion, a large-frame (8 × 12 cm) camera, which allows one to resolve the thin structure of the medium, was employed at the experimental setup (see Fig. 1) instead of high-speed photoregister 4. The desired stage of the process was recorded (with a fixed open shutter of the camera) by means of pulse illumination which operates at a given moment of time. Figure 6 shows the scheme of explosive formation and the photograph of the structure of a glycerin dome, which is formed after wire 1 explodes under the free surface of glycerin F. The photograph fixes the dome structure in $1.5 \cdot 10^{-3}$ sec after the front of the shock wave S has arrived at the free surface. An analysis of the evolution of the structure of the glycerin dome shows that its fracture occurs because of the development of initial perturbations on the internal surface of the dome, which contains a few bubbles, rather than because of the unlimited growth of cavitation bubbles, as in the case of water

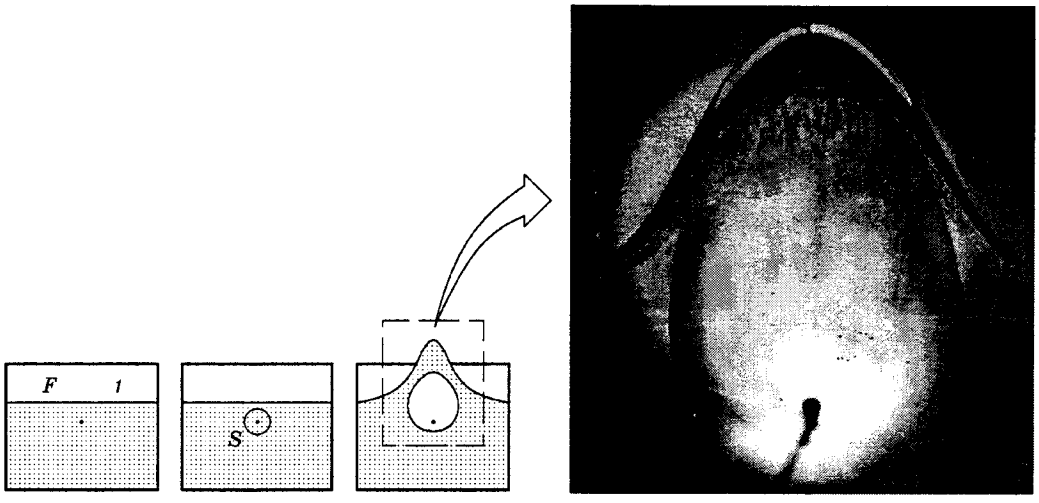

Fig. 6

[8]. With time, these perturbations become jet structures, which are then disintegrated into fragments by capillary forces. (In the case of axisymmetric expansion of the cylindrical glycerin sample, as shown in [1], the medium becomes filamentary structures oriented along the axis of expansion.)

Thus, the glycerin samples can fail in two ways. Upon a very slow volume expansion of the sample, cavitational bubbles grow unboundedly in it, i.e., a foamy cellular structure that disintegrates into fragments is formed. Upon pulse volume expansion, cavitation damps at the initial stage; at subsequent stages, the growth of perturbations on the free surface of the sample contributes to the formation of jet structures that disintegrate into drops under the action of capillary forces. It is of interest to formulate a criterion that separates the two stages of fracture.

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