Journal of Applied Mechanics and Technical Physics, Vol. 48, No. 4, pp. 519–524, 2007

FRAGMENTATION OF LIQUID AND LIQUID-PLASTIC MEDIA UNDER UNSTEADY STRAINS

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UDC 532.528

Based on a qualitative analysis of results of experimental studies, the main mechanisms of fragmentation of polar liquids and liquid-plastic media under dynamic loading are determined. In the case of low-viscosity liquids, such mechanisms are thermodynamic instability of foam, hydrodynamic instability of initial disturbances of the free surface, and the action of capillary forces. In the case of a polar high-viscosity liquid, the main mechanisms are shear instability of the structure, responsible for stratification of the medium along the lines of local failure of structural viscosity, and the action of capillary forces. The main mechanisms acting in liquid-plastic structured media (gels) are "spalling" in the zone of tensile stresses if the time of their formation is smaller than the time needed for the gel to transform to the sol state, as well as thermodynamic instability of foam and the action of capillary forces after the medium transition to the sol state.

Key words: *liquids, structural viscosity, cavitation, plastic flow, fragmentation.*

As validated by numerous studies, viscous destruction of condensed media is caused by the growth of cavitation cavities and by macroscale plastic deformation with subsequent fragmentation of the loaded sample. The least considered stage is fragmentation of high-viscosity liquids and liquid-plastic media. Dynamic destruction of low-viscosity liquids (water, ethyl alcohol, acetone, etc.) was studied in more detail. Thus, in the case of volumetric extension of low-viscosity liquids, their destruction occurs owing to the development of unlimited bubble cavitation and subsequent formation of a thermodynamically unstable foam structure (see [1] and the references therein). Moreover, a low-viscosity liquid can be destroyed owing to the development of jet structures from the initial disturbances of the free surface [2], which are then fragmented under the action of capillary forces. According to [3], no fragmentation of the medium occurs in low-viscosity liquids under shear-induced deformation in the regime of a steady plastic flow (of the type of the Couette flow). At the same time, instability of the structure is observed in high-viscosity polar liquids, which leads to formation of zones with a local discontinuity of structural viscosity (DSV) [3]. Similarly, slip lines are formed in solid-plastic media under shear strains [4, 5]. For a liquid high-viscosity volume to be separated into fragments, however, the continuity of the medium must be violated. A question arises: How the discontinuities are formed in liquid and liquid-plastic media at the last stages of their destruction?

The stage of fragmentation of liquid and liquid-plastic media was studied with an experimental technique schematically illustrated in Fig. 1. The striker is accelerated by a gas gun described in [6]. A light double plastic-foam piston eliminates the meniscus on the free surface of the sample. An impact of the plate onto the membrane at a certain time t_0 generates a shock wave (SW) in the liquid sample (Fig. 2). After the SW front reaches the free surface, sample unloading begins: the wave energy transforms to the kinetic energy of the liquid sample moving upward in the channel and to the elastic energy of the sample owing to its extension along the axis of symmetry. As a real liquid always contains cavitation nuclei, however, the elastic energy of the sample is spent on formation of cavitation cavities in the medium. The character of deformation of the sample moving in the channel and the evolution of the cavitation process depend on the rheological properties of the medium considered and the character of its loading.

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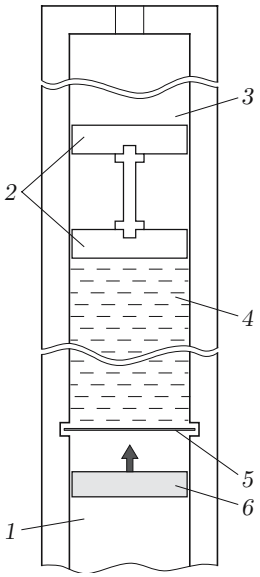


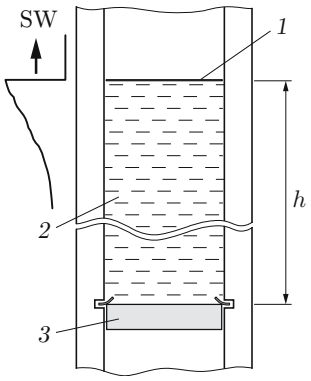


Fig. 1 Fig. 2

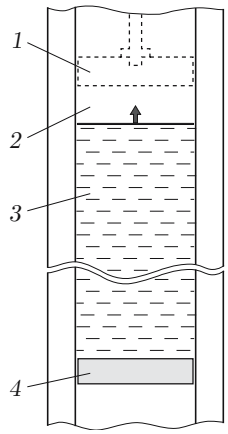
Fig. 1. Pulsed loading of a sample of an examined medium: 1) evacuated channel of a gas gun; 2) double piston made of plastic foam; 3) rectangular channel (1.8 × 1.8 cm) with transparent windows; 4) examined liquid sample (h = 6 cm); 5) easily broken thin membrane; 6) Plexiglas striker.

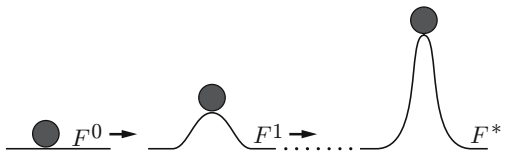
Fig. 2. Schematic of SW formation: 1) free surface; 2) liquid sample; 3) Plexiglas striker.

Experiments aimed at studying the mechanisms of medium fragmentation were performed with samples of water, glycerin, and gel (the gel was composed of water, polyvinyl pyrrolidone, propylene glycol, and disodium salt of ethylene ditetraacetic acid) loaded by an SW with an amplitude of $6 \cdot 10^7$–$12 \cdot 10^7$ Pa (the wave duration was $5 \cdot 10^{-6}$ sec). Different stages of sample unloading were recorded by a photocamera in the open-shutter mode with pulsed illumination. The results of these tests are described below.

Low-Viscosity Water Sample. At the initial stage of unloading, the low-viscosity water sample moves upward in the channel as a low-viscosity liquid piston cavitating as a result of longitudinal extension (Fig. 3). In the course of unlimited growth of cavitation bubbles, the water piston transforms to the state of a pseudo-plastic body [1]. As the size of the foam cells increases, the total area of the surface of their walls, i.e., the total free (surface) energy of the system F, also increases. The famous Lejenne–Dirichlet theory predicts that, if the free energy F has a minimum at a certain position of the system, such a position is stable; therefore, the system with a foam structure moves further away from the state of stable equilibrium with increasing F. Figure 4 shows the family of the energy surfaces of the system. The state of the system is seem to become more and more unstable with increasing F. Finally, a moment arises when a small fluctuation of some parameter of the foam structure initiates its transition to a more stable state, which is accompanied by the transition of part of the free energy accumulated in the system to the kinetic energy of reconstruction of the cell structure [7, 8]. The most probable "triggering" mechanism of such a process is a local fluctuation decrease in surface viscosity of the link (film) between the foam cells, which results in irreversible thinning of this film [9] and its subsequent breakdown by capillary forces. As a result, the equilibrium state of the neighboring cells is violated, etc.

As the foam-structured medium possesses structural viscosity, the diagram of velocities in the sample moving along the channel (Fig. 5) is typical of a shear flow with a corresponding field of shear stresses τ. For this reason, if the value of τ in some region of the flow exceeds the yield stress τ_*, segments of mutual slipping of foam layers are formed in the medium [8], which can initiate the formation of discontinuities in the foam structure. Figure 6a shows the photograph of the destroying water sample after its transition into the foam state under the action of tensile stresses. The picture clearly displays the separation of a foam fragment and the above-described discontinuities of the foam structure, formed owing to destruction of the foam cells and mutual slipping of the foam layers.





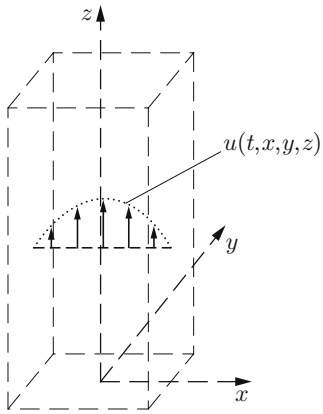


Fig. 3 Fig. 4 Fig. 5

Fig. 3. Loading of the water sample: 1) foam-plastic piston; 2) rectangular channel; 3) low-viscosity water sample; 4) Plexiglas striker.

Fig. 4. Energy level of the loaded system.

Fig. 5. Diagram of velocities in a sample with a foam structure moving in the channel.

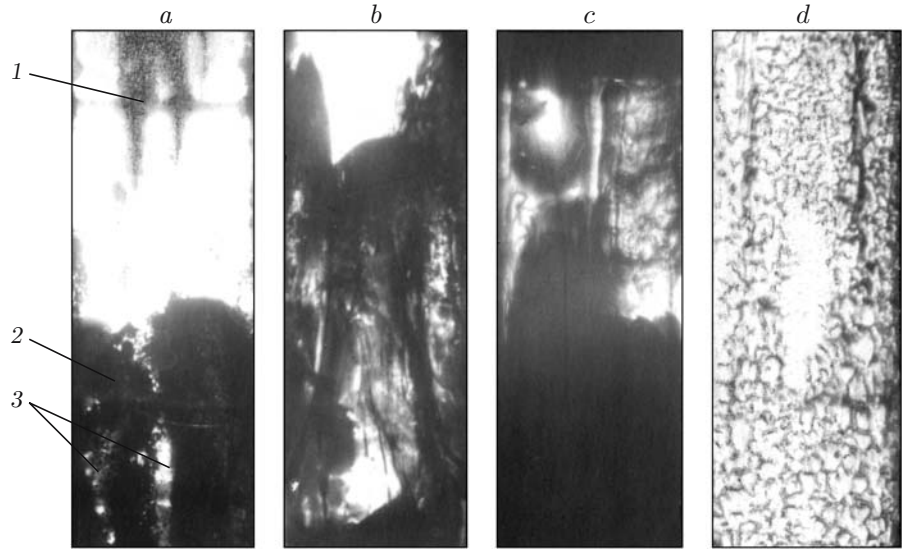


Fig. 6. Destruction of the structure of unloaded samples: (a) water; (b) glycerin; (c) gel in 10^{-3} sec after the beginning of unloading; (d) gel in $6 \cdot 10^{-3}$ sec after the beginning of unloading; 1) separating fragment of the foam structure; 2) foam state of the water sample; 3) discontinuity of the foam structure.

High-Viscosity Glycerin Sample. After the SW reaches the free surface, a high-viscosity glycerin sample loaded by a striker (see Fig. 1) moves along the channel in the absence of visible bubble cavitation in the liquid medium, which agrees with the previous results obtained in studying the specific features of cavitation evolution under shock-wave loading of glycerin [1]. Figure 6b shows the photograph of the glycerin sample moving upward in the channel at the stage of sample stratification into individual fibrous fragments ($1.5 \cdot 10^{-3}$ sec after the beginning of loading). Let us consider the mechanism of such fragmentation. In the course of motion of the high-viscosity glycerin sample along the channel, the Poiseuille profile of velocities is formed in the medium (see Fig. 5), i.e., the flow has a shear character. Moreover, as the flow is formed under shock-wave loading, the medium should have a velocity gradient whose direction coincides with the direction of motion of the free boundary of the sample. As was

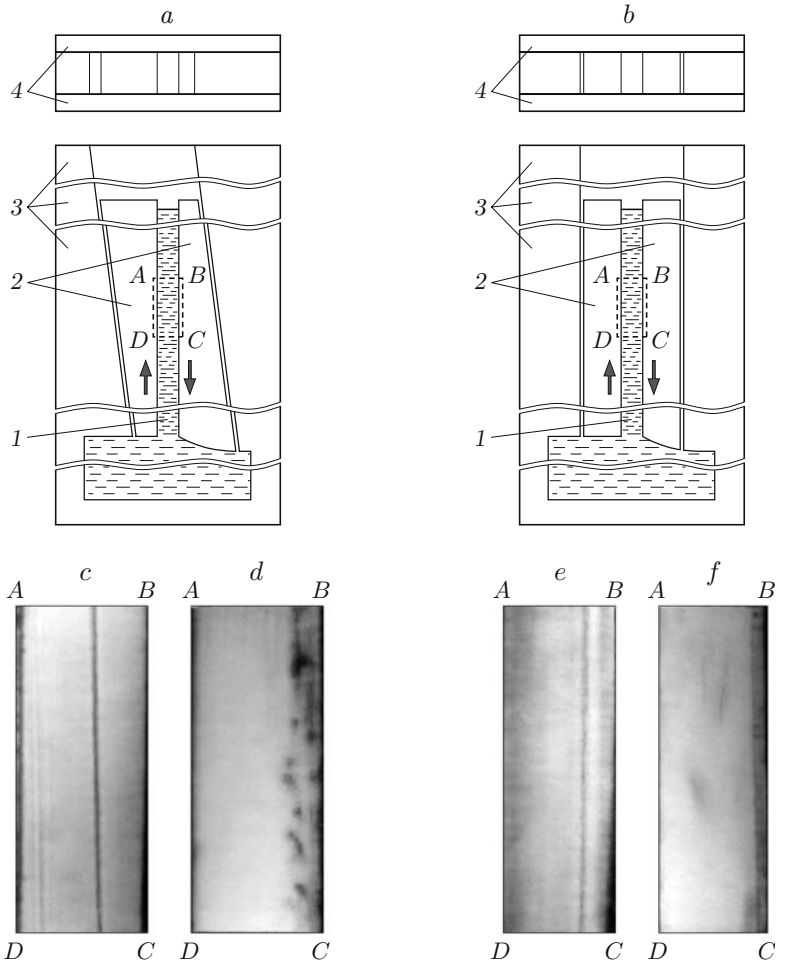


Fig. 7. Shear flows of liquids in plane channels: (a) formation of opposing flows with transverse extension; (b) formation of opposing plane–parallel flows: 1) liquid sample; 2) two plates moving in the opposite directions; 3) guides for the plates; 4) transparent plane–parallel walls; (c) shear flow with transverse extension in a glycerin sample; (d) shear flow with transverse extension in a water sample; (e) plane–parallel shear flow in a glycerin sample; (f) plane–parallel shear flow in a water sample.

noted above, however, pulsed extension of glycerin behind the SW front does not have enough time to form bubble cavitation in the medium.

According to [3], in the course of the shear flow in glycerin, DSV-containing zones are always formed. These are narrow zones (aligned with the liquid flow) where the structural viscosity is almost an order of magnitude lower than the initial value. As the flow velocity decreases toward the channel walls, flow stratification occurs. Under intense shear loading of solid-plastic materials in regions where slip lines are formed, the structural viscosity also decreases because the substance transforms to an atom-vacancy state [4], which favors macroscale shear deformation.

It is known that cavitation bubbles in high-viscosity liquids can grow until they reach a size substantially greater than the visible limit (0.01 cm) [10] under the condition that the field of tensile stresses exists much longer than the time of the action of the unloading wave Δt^*. Hence, as the time of motion of the glycerin sample is $\Delta\tilde{t} \gg \Delta t^*$, tensile stresses may arise in zones of tangential discontinuities under certain values of the shear strain rate [11]. With this fact borne in mind, we performed test experiments, as schematically depicted in Figs. 7a and 7b, to elucidate the possibility of cavitation development in glycerin during the time $\Delta\tilde{t}$. The liquid sample, the plates, and the guides on both sides were bounded by transparent plane–parallel walls. The plates slid along the guides with a velocity of 20 to 100 cm/sec (depending on liquid viscosity).

After operation of spring devices, the plates start moving in the opposite directions, which forms opposing liquid flows "entrained" by the plates. It was found [11] that a zone with a DSV is formed in the region of opposing flows in the glycerin sample. In the case of the flow described by the scheme in Fig. 7a, however, the vertical opposite motion of the plates is simultaneously accompanied by their motion away from each other in the horizontal direction, and the width of the channel filled by the liquid increases from 0.4 cm to 0.7 cm. For this reason, tensile stresses are artificially sustained in the DSV-containing zone during 0.1–0.2 sec. In the case of the opposite motion of the plates, as is shown in Fig. 7b, the distance between the plates remains equal to 0.4 cm, and a zone with a DSV is formed in the glycerin sample without tensile stresses acting on the sample. In addition to experiments where we studied the possibility of development of bubble cavitation in the DSV-containing zone under the action of tensile stresses in glycerin samples, we performed similar tests with water samples. The processes were recorded by a video camera, a video tape recorder, and a computer.

The test series provided the following results. In the glycerin sample, the action of tensile stresses on the DSV-containing zone does not cause visible bubble cavitation. In other words, even if the bubbles do grow, they do not have enough time to reach the visible size (approximately equal to 0.01 cm), and the DSV-containing zones in Fig. 7c are almost the same as those in Fig. 7e formed in the absence of tensile stresses (see Fig. 7b). For comparison, Fig. 7d shows the photograph of the segment of the water sample where opposing flows are formed under the action of tensile stresses (see Fig. 7a), while the field of tensile stresses is absent in opposing flows of water in Fig. 7f (see Fig. 7b). As it could be expected, DSV-containing zones are not formed in water samples [3], but intense bubble cavitation has enough time to develop in the field of tensile stresses in low-viscosity water (see Fig. 7d), in contrast to high-viscosity glycerin.

It follows from the results of the experiments performed that no visible cavitation process is observed in DSV-containing zones in the glycerin sample even if they are affected by tensile stresses during 0.1–0.2 sec. The governing role in the process of fibrous fragmentation of glycerin observed in $1.5 \cdot 10^{-3}$ sec after the beginning of loading (see Fig. 6b) belongs to flow stratification in terms of viscosity (into DSV-containing zones) and to motion of the resultant layers of the liquid along the channel axis with different velocities.

Gel Sample. At the initial stage of pulsed loading by the striker (see Fig. 1), the behavior of the gel sample is similar to the behavior of an elastoplastic body. Discontinuities ("spalls") are formed in the sample under the action of the field of tensile stresses behind the front of the rarefaction wave reflected from the free surface of the sample. Figure 6c shows the photograph of the process in 10^{-3} sec after the beginning of unloading, which shows that fragmentation of the gel sample at the initial stage is similar to destruction of a solid-plastic material [4, 5]. Further on, however, shear stresses initiate gel restructuring (drastic decrease in its structural viscosity to the level of the Newton viscosity), and the gel transforms to the sol state (colloidal liquid containing fine particles called micelles) where the cavitation process develops. Finally, the medium acquires the properties of a foam structure (see Fig. 6d). (The photograph was taken $6 \cdot 10^{-3}$ sec after the beginning of sample destruction.)

An analysis of the fragmentation process at different stages shows that the first stage of fragmentation proceeds in the regime of destruction of the solid-plastic material if the characteristic time of formation of the rarefaction wave in the gel is smaller than the period of gel restructuring (time of the phase transition of the elastoplastic gel into the colloidal liquid state called sol). Later the sol cavitates in the field of tensile stresses (caused by the gradient of mass velocity in the sol) and transforms to the foam state; after that, the foam structure is destroyed under the action of capillary forces, as in the case of the water sample.

Thus, the experiments performed imply that fragmentation of polar liquids and liquid-plastic media is determined by the following mechanisms. In the case of a low-viscosity liquid transformed into a foam structure owing to development of unlimited cavitation and owing to free-surface disturbances, fragmentation is caused by the action of capillary forces. In the case of a high-viscosity polar liquid, fragmentation occurs owing to stratification of the medium along the lines of discontinuity of structural viscosity, caused by structural instability of the liquid under shear strains. In the case of an elastoplastic gel, fragmentation at the initial stage of unloading is caused by formation of "spalls," and later (after destruction of the medium structure and its transition to the foam state) fragmentation occurs under the action of capillary forces.

The results obtained in the present work are necessary for constructing a generic physical model of viscous destruction of liquid and liquid-plastic media.

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