NOTATION

d_{str}, stream diameter; d_d, drop diameter; l_{str}, stream length; δ_{cr}, rim thickness; u, velocity; g_{film}, specific flow rate of fluid in film; ν, coefficient of kinetic viscosity; ρ, density; σ, coefficient of surface tension; g, acceleration of gravity; $Re_{film} = g_{film}/g\mu_f$, Reynolds number of film; We, Weber number.

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PROPAGATION OF SHOCK WAVES IN A MIXTURE OF LIQUID WITH GAS BUBBLES IN THE PRESENCE OF SMALL ADMIXTURES OF POLYMERS

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The effect of polyacrylamide dissolved in water on the structure of a reflected shock wave in a gas—liquid medium is studied. Successive recordings are obtained of the behavior of a gas bubble behind a shock wave in water containing admixtures of polyacrylamide.

The capacity of small admixtures of polymers to essentially alter the characteristics of the turbulent flow of a liquid is well known. A multitude of reports have been devoted to the investigation of this effect. At the same time, new aspects of the effect of admixtures of polymers on the properties of a liquid are always appearing.

One of the recently discovered effects is the effect of the destruction of barriers made of steel by jets of water with small polymer admixtures at pressures insufficient for destruction by pure water [1, 3]. Another effect of the action of polymer admixtures, which appears during the motion of shock waves in mixtures of a liquid with gas bubbles, is the topic below.

1. Experimental Installation

The experiments on the study of the motion of shock waves in a liquid with gas bubbles in the presence of polymer admixtures were carried out on an installation for which a diagram is presented in Fig. 1. The installation included a hydrodynamic shock tube with high-pressure (1) and low-pressure chambers (2). The low-pressure chamber was equipped with pickups 3 recording the variation in pressure in the shock wave. The distance between pickups is 240 mm. In addition, the low-pressure chamber is equipped with viewing windows for the observation of air bubbles floating up inside the tube. The bubbles behind the wave were photographed on stationary film with the help of a strobotron lamp with an assigned delay following the wave front. The experiments on the measurement of the parameters of pressure waves before and after the moment of reflection from the bottom were conducted with a concentration of gas bubbles of 1-10% by volume, with water adopted as the liquid. In the majority of tests the size of the gas bubbles was 2-5 mm. The intensity of the incident pressure waves was varied in the range of 3-20 atm with an initial pressure of 1 atm in the

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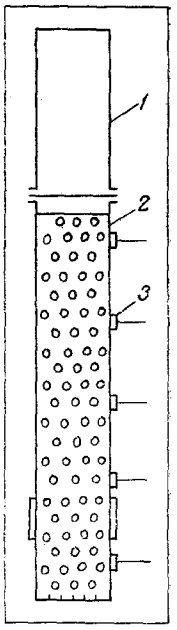

Fig. 1

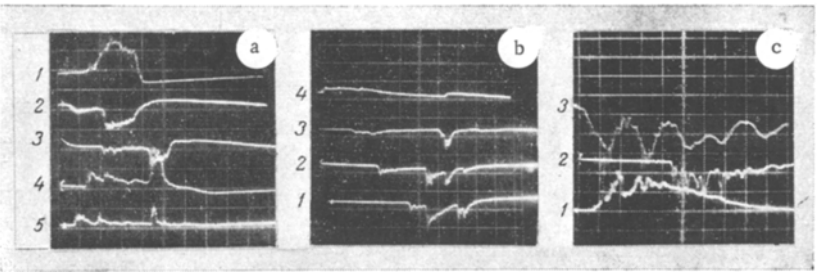

Fig. 2

Fig. 1. Diagram of experimental installation: 1) high-pressure chamber; 2) low-pressure chamber; 3) pressure pickups.

Fig. 2. Recordings of shock waves: a) gas—liquid medium without polymer; b) gas—liquid medium with 0.1% polymer admixture; c) structure of incident shock wave in gas—liquid medium with 1% polymer concentration.

medium. Suspensions of polyacrylamide with a molecular weight of $2 \cdot 10^6$ were used as the polymer admixture. The concentration (by weight) of the polymer was varied in the range of 0.1-1%.

2. Principal Results of Experiments

Photographic recordings of the pressure waves observed in pure water (Fig. 2a) and in water containing polymer admixtures (Fig. 2b) are presented in Fig. 2. The intensity of the incident wave is $p_1/p_0 = 15$ and the bubble concentration is 3%. Here p_1 is the pressure behind the wave and $p_0 = 1$ atm. The pressure scale for oscillograph beams 1-5 corresponds to the following values: 36.4 tech. atm/div. for beams 1-2 and 20.0 tech. atm/div. for beams 3-5. The time scale (along the horizontal) is 1500 μsec per division for all the oscillograph beams. The readings of the pickups in beams 5-1 in Fig. 2a reflect the evolution of the incident wave during its passage into the interior of the two-phase medium to the bottom of the low-pressure chamber. Then the parameters of the pressure wave reflected from the wall are recorded in beam 1 and its transformation during the ascent to the free surface is successively described in oscillograph beams 1-5. The initial surges in all the oscillograph beams correspond to the arrival of the pressure wave. Beams 1 and 2 are triggered with a delay relative to beams 3-5. In the recording of Fig. 2b the transformation of the incident and reflected waves should be traced from beam 1 to beam 4. In beam 1 the reflected wave appears 1500 μsec after the arrival of the incident wave.

The principal similarity in the photographic recordings obtained comes down to the identical nature of the motion of the incident pressure waves. The polymer admixtures do not affect the parameters of the incident waves. The velocity of propagation and the pressure in the wave are the same. One must only note a certain difference in the structure of the pressure variation in the relaxation zone behind the wave. Whereas in pure water containing bubbles the pressure oscillations after the wave always die out smoothly, in water with polymer admixtures one observes the growth of the oscillations at a certain moment following the wave. An example of such an effect is presented in Fig. 2c. Here the time scale is 600 μsec per division in oscillograph beams 1-2 and 150 μsec per division in beam 3, and it is clearly seen that intensive growth of the pressure oscillations is observed 100 μsec after the wave front.

A considerable difference in the parameters of the waves is observed in the propagation of the reflected wave in pure water containing bubbles and with a polymer admixture. Let us compare the readings of the

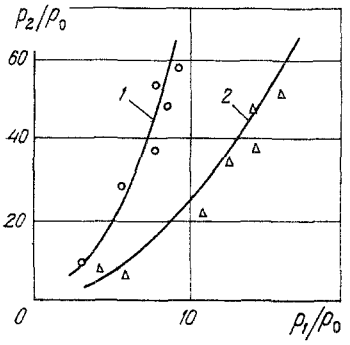

Fig. 3

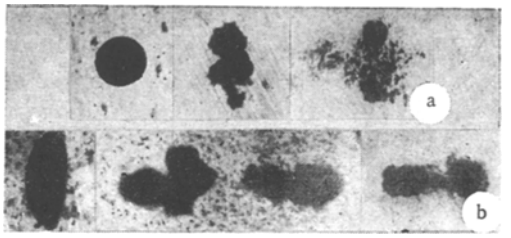

Fig. 4

Fig. 3. Experimental values of reflected wave as a function of incident wave: 1) in pure water containing gas bubbles; 2) in water containing gas bubbles and with dissolved polymer.

Fig. 4. Behavior of a gas bubble with a diameter $d_0 = 3.5$ mm in pure water (a) and behavior of a gas bubble with a diameter $d_0 = 5$ mm in water with a polymer concentration of 0.1% (b). Pressure at shock front $p_1 = 15$ atm in both cases.

pickups in oscillograph beam 2 of Fig. 2a and beam 2 of Fig. 2b. It is easy to see that the amplitude of the reflected wave is considerably lower in the second case (with a polymer admixture). It must be noted that in pure water containing bubbles the pressure behind the reflected wave is constant for a time of 2000 μsec, while in a polymer solution the pressure decreases sharply immediately behind the front. Thus, the pressure pulse in the reflected wave proved to be reduced by 6-8 times because of the polymer admixture. Because of the closeness of the rarefaction wave to the front in a polymer solution the rarefaction wave interacts with the leading front and the reflected wave dies out as it propagates through the two-phase medium.

The results of the measurement of the intensity of the reflected wave in water containing bubbles [2] and in a polymer solution containing bubbles are presented in Fig. 3 (curves 1 and 2, respectively). The pressure ratio p_1/p_0 in the incident wave is laid out along the abscissa and the ratio p_2/p_0 of the pressure in the reflected wave to the initial pressure p_0 is laid out along the ordinate. Curve 1 corresponds to measurements in water containing bubbles and curve 2 to measurements in water containing bubbles with a polymer admixture in an amount of 1 and 0.1%. It is seen that a change in the weight concentration of polymer by 10 times does not affect the pressure in the reflected wave.

The observed difference in the behavior of shock waves in gas-bubble—liquid two-phase media containing a polymer admixture can only be connected with the different nature of the motion of the gas bubbles. How such a difference is manifested is clearly seen from a comparison of the two motion pictures presented in Fig. 4. The variation in the shape of a gas bubble in pure water is shown in Fig. 4a. The size of the bubble is 3.5 mm. The intensity of the pressure wave is $p_1 = 15$ atm. The states of the bubble are recorded at times of 0, 140, and 720 μsec after the wave. The states of a bubble 5 mm in size in an identical pressure wave but in a solution of water and polymer at a concentration of 0.1% of the latter are recorded in Fig. 4b. The times of photography correspond to 0, 580, 650, and 1400 μsec after the wave. In the pure liquid the gas bubble is deformed in the direction across the wave and is then pierced by a central jet of liquid moving in the direction of the wave. In the solution of liquid and polymer the gas bubble is rotated 90°, as it were, and its deformation develops along the direction of the wave. The rate of destruction of the bubbles is greater in water than in the polymer solution. Evidently this difference in the nature of the destruction of a bubble is also important for the pressure level which develops during the reflection of the wave at the wall.

It only remains to clear up the question of the mechanism of the observed action of polymer admixtures on the behavior of gas bubbles in a liquid.

Thus, it is established in the work that upon the addition of small amounts of polymer to a liquid—gas-bubble system one observes a considerable decrease in the impulse in the reflected pressure wave.

NOTATION

p_0, initial pressure; p_1, pressure behind wave; p_2, pressure in reflected wave.

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ENTRANCE EFFECTS IN THE FLOW OF VISCOUS LIQUIDS IN CYLINDRICAL NOZZLES

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The pressure losses up to the entrance to nozzles in the flow of inelastic liquids in wide ranges of viscosities and flow rates are determined. An empirical equation is proposed for calculating entrance pressure losses.

The flow of a viscoelastic medium in the initial section of a cylindrical channel has been studied in numerous theoretical and experimental reports. The considerable interest in this problem is explained by its urgency for engineering application (such as the extrusion of polymer solutions and melts through short nozzles or spinners in obtaining chemical filaments), on the one hand, and by the great complexity of the observed phenomena, on the other. The unsteady flow of polymer systems is characterized by the simultaneous development of plastic and elastic deformations and the effect of thixotropic destruction of the structure; the conditions of the formation of the velocity profile at the entrance to a cylindrical channel also exert a certain effect. Whereas in a rotary viscosimeter one is able to separate the reversible and irreversible deformations experimentally, with flow in a capillary such a separation is impossible in principle, and is done by various indirect methods.

To allow for the additional energy expenditures before the nozzle entrance and in the section of unsteady flow one usually uses the so-called "inlet" correction l_{in}, which in a number of reports [1-4] is considered as a parameter of the viscoelastic behavior. However, in [5] it has been shown that the strength of the structure must create a large entrance effect, so that in the general case the possibility of using measurements of inlet corrections as a method of estimating the highly elastic properties of a system is connected with the relationship of the effects of the development of plastic reversible deformations and of destruction of the structure.

The published data relative to the quantity l_{geom}, the "geometrical" or "Couette" correction, which determines the additional energy losses due to the reorganization of the velocity profile at the nozzle entrance, are contradictory. Couette [6] found that the value of the inlet correction is equivalent to the fictitious lengthening of a capillary by five to six radii ($l_{geom} = nR$, $n = 5$-6). In [7, 9] l_{geom} was equal to 1.146R. Barr [8] took $n = 0.9$. Schurz [10] indicates that according to the literature data $n = 0.5$-1.0, but he notes in this connection that the direct determination of l_{geom} is possible only in measurements on inelastic liquids. The authors of [2, 11] assume that l_{geom} is negligibly small in comparison with l_{in} and does not depend on the discharge velocity; in [3, 12], conversely, it is noted that the energy dissipated in the entrance zone depends on the velocity gradient and can have rather large values.

And there is no single opinion on the question of where the additional pressure drop takes place: Some investigators [1, 2] assume that the entire end effect is concentrated in front of the entrance to the capillary; others [9] declare for two components characterizing the pressure drops up to the entrance to a nozzle and in its initial section.

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