COLLAPSE OF A FILM OF FLUID DRAINING OFF THE RIM OF A PLATE IN A GAS SLIPSTREAM

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The breakdown of a draining film, the formation of a spectrum of drop dimensions and its deformation in a gas flow, and the influence of the thickness of the rim and the physical properties of the fluid on the process of film collapse are studied by the holographic method.

The breakdown of a draining film is investigated holographically [1, 2]. A fluid film is created on the surface of a horizontal plate placed in an air flow. The fluid is fed through three rows of 1-mm-diameter apertures located 50 mm from the rear rim with a spacing of 2 mm. The distance from the rim is selected experimentally such that the movement of the fluid in the film is steady and at the same time there is no fluid removed from the film surface. The front and rear rims are sharpened to an angle of 5° in order to reduce the perturbation of the gas flow when the plate is inserted into it. The thickness of the rear rim is varied from 0.05 to 4 mm. The wake behind the plate is holographed beginning right from the rear rim and then at 150 mm down the flow. The experiments are carried out with air velocities of 45-120 m/sec with water, ethyl alcohol, and an aqueous solution of glycerin. The rates of fluid flow in the experiments are 0.065-0.465 kg/m·sec for the water; 0.075-0.175 kg/m·sec for the alcohol; and 0.245 kg/m·sec for the glycerin solution. The water and the alcohol can be treated as low-viscosity fluids for the process under investigation, and the glycerin solution with a viscosity of $\nu_f = 120 \cdot 10^{-6}$ m²/sec can be treated as viscous. The following sequence in the collapse of a film of draining fluid can be established by visual study of the holograms obtained. A continuous film comes directly off the edge of the plate. The length of this continuous section is not great (3-4 mm) and is dependent on the velocity of the gas and the flow rate of the fluid. The continuous film later disintegrates into a number of separate streams which subsequently disintegrate into separate drops. With high rates of fluid flow per unit of the perimeter, however (in our experiments $Re_{film} = 465$), "little tongues" are formed together with the streams when the film collapses. The transverse dimensions of these formations may be one order of magnitude greater than the diameter of the streams and their length is, on average, twice as great as the length of the streams. The subsequent breakdown of the "little tongues" occurs with the formation of streams, but cases of the detachment of whole lumps of film are observed sometimes. Their breakdown may occur both with the formation of streams and during disintegration into separate drops. The number of these "little tongues" is, however, very low and the stream mechanism for the collapse of the draining film can be considered valid for the whole range of condition parameters under investigation.

Thus the problem of the collapse of a draining film and the formation of a spectrum of drop dimensions is reduced to an investigation into the breakdown of fluid streams in the presence of a gas slipstream.

The processing of the holograms produced shows that the number of streams into which the film disintegrates is, in practice, independent of the flow rate of the fluid, its viscosity, and of the thickness of the rim, but is governed primarily by the velocity of the gas and by the surface tension of the fluid. As σ is reduced, the number of streams occurring per unit width of the plate rises, which is probably related to the reduction in the length of the transverse waves in the film which are responsible for the disintegration of the film into separate streams.

The mean length of the nondisintegrating part of a stream is given in Fig. 1 as a function of the gas velocity. As the gas velocity increases, the length of the continuous part is reduced. Within the limits of accuracy no influence of the fluid flow rate and, consequently, of the fluid film thickness is revealed on the length of the nondisintegrating part of the stream.

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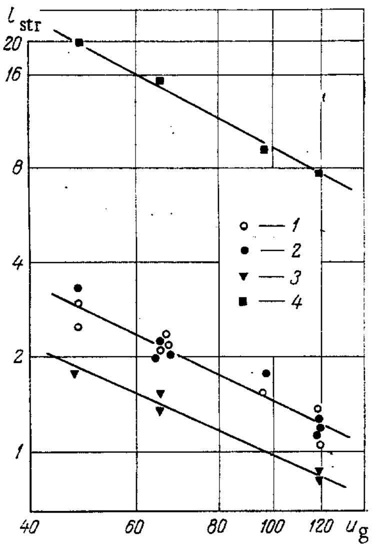

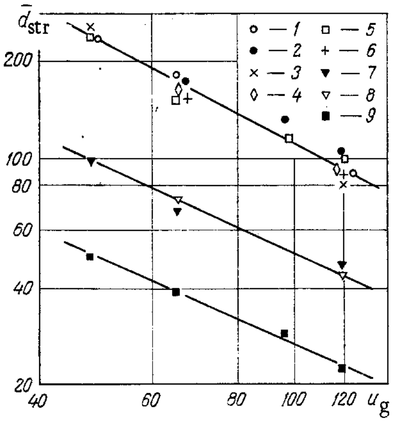

Fig. 1 Fig. 2

Fig. 1. Length of nondisintegrating part of a stream as a function of gas velocity: 1) water, δ_{cr} = 0.05 mm; 2) water δ_{cr} = 0.75 mm; 3) alcohol; 4) glycerin solution. l_{str}, mm; u_g, m/sec.

Fig. 2. Mean diameter of fluid stream as a function of gas velocity. Water, δ_{cr} = 0.05 mm: 1) g_{film} = 0.465 kg/sec·m; 2) g_{film} = 0.165; 3) g_{film} = 0.065. Water, δ_{cr} = 0.75 mm: 4) g_{film} = 0.465; 5) g_{film} = 0.165; 6) g_{film} = 0.065. Alcohol: 7) g_{film} = 0.175; 8) g_{film} = 0.075. Glycerin solution: 9) g_{film} = 0.245. $\bar{d}_{str}$, μ.

Analogous results are obtained with the statistical processing of the mean stream diameter. Data on $\bar{d}_{str}$ as a function of u_g are given in Fig. 2. For each separate fluid these experimental data can be described in a general way by the empirical relationship

$$\bar{d}_{str} = \frac{\text{const}}{u_g^{1.1}}, \tag{1}$$

where the const is dependent only on the physical properties of the fluid.

It follows from the theory of low-viscosity fluid-stream breakdown that with high relative gas and fluid velocities the ratio of the length of the nondisintegrating part of the stream to the diameter is independent of the velocities and is constant for a given pair of components. For the water and alcohol this ratio is $l_{str}/\bar{d}_{str} \simeq 15$.

The ratio of the length of the continuous part of the stream measured in the present experiments to its diameter is close for the water and alcohol to the theoretical and is independent within the limits of accuracy of the flow rates of the phases. Consequently, the length of the nondisintegrating part of the stream and its diameter, according to expression (1), should be independent of the fluid flow rate. The same result is obtained experimentally (see Fig. 1).

It also follows from the condition $l_{str}/\bar{d}_{str}$ = const that the dependence of l_{str} on the gas velocity should be analogous to the $\bar{d}_{str} = f(u_g)$ dependence and is determined by formula (1). It is clear from Fig. 1 that the $l_{str} = \varphi(u_g)$ dependence is close to that which follows from formula (1).

For viscous fluids the collapse of the film also occurs with the formation of streams. The formation of very long thin streams, similar to threads $l_{str}/d_{str} \geq 10^3$, is characteristic of these fluids and the collapse of the streams proceeds at considerably greater distances from the plate rim than does the collapse of low-viscosity fluid streams.

The collapse of low-viscosity fluid streams as a function of the relative gas velocity may occur under both disintegration and atomization conditions. As a result, the spectrum of the dimensions of the drops formed by the collapse of the streams will not be maintained down the flow.

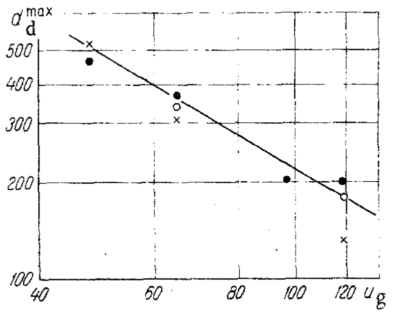

Fig. 3

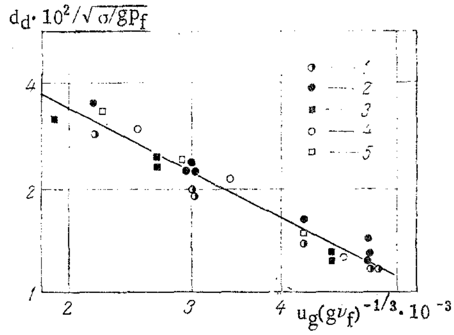

Fig. 4

Fig. 3. Maximum dimensions of drops of water in spectrum. Notation as in Fig. 2.

Fig. 4. Correlation of experimental data on mean dimensions of drops in wake behind plate rim and in a two-phase flow: 1) water, δ_{cr} = 0.05 mm; 2) water, δ_{cr} = 0.75 mm; 3) alcohol, δ_{cr} = 0.05 mm; 4) water, two-phase flow; 5) alcohol, two-phase flow.

The mean dimensions of the drops are reduced as the distance from the rim increases while the length of the breakdown zone rises to 80-100 mm.

A drop formed during the disintegration of the stream is accelerated in the gas flow. It may break down if the local Weber number $We = [(u_g - u_d)^2 d_d \rho_g] \sigma$, recorded from the local relative gas velocity, is greater than an We_{cr}. If $We < We_{cr}$ the drop cannot break down. The possibility of breakdown can be realized if the critical drop deformation time is less than its acceleration time to $We = We_{cr}$. As shown by the evaluation made in our case this condition is virtually always met.

On this basis all further processing of experimental data is made for two flow sections: L = 15 mm (initial spectrum) and L = 130 mm (final spectrum). Histograms of the drop dimensions are plotted for each of these sections for all sets of conditions and their mean dimensions are determined.

The initial drop dimension spectrum is shaped by the disintegration of the fluid streams. According to the theory of low-viscosity stream breakdown under disintegration conditions, the stream disintegrates into separate sections λ_{max} in length. The magnitude of λ_{max} is determined from the condition for maximal instability of the oscillations on the surface of the stream and for the case under examination:

$$\lambda_{max} \approx 4\bar{d}_{str}.$$

Correspondingly, when the streams collapse, drops of equally great mass with a stream section λ_{max} in length will be formed. The diameter of these drops is related to the stream diameter by the relation

$$d_d = 1.82\bar{d}_{str}. \tag{2}$$

Since the stream diameter is not dependent on the fluid flow rate and is governed only by the gas velocity, the dimensions of the drops formed during the disintegration of the streams should also be independent of the fluid flow rate and the influence of the gas velocity should be described by relationship (1). The line on Fig. 3 describes the drop diameters calculated in this way using the empirical relationship $\bar{d}_{str} = f(u_g)$ given in Fig. 2 to determine the mean stream diameter. For comparison purposes the experimental values of the maximum drop diameters of the water in the spectrum are laid down in Fig. 3. As can be seen, the correspondence between the calculated and experimental values is perfectly satisfactory.

The mean drop dimensions fall as the gas velocity rises and within the experimental accuracy are independent of the fluid flow rates. The absolute values of the mean drop dimensions in the initial spectrum are of the same order of magnitude as the stream diameters. The mean drop dimensions in the final spectrum are 15-30% less than in the initial spectrum.

Experiments designed to study the breakdown of a film draining off the blunt rim of a plate (δ_{cr} = 0.75 mm) show that the breakdown mechanism remains essentially the same as for a sharp rim. In this case, however, the formation of "little tongues" and the detachment of lumps of film are observed at lower fluid flow rates. These special features are obviously related to the formation in the wake behind the plastic zone of inverse currents, generating additional perturbations in the flow of fluid film and an overflow of the fluid across the end surface of the plate in both the transverse and the longitudinal directions, etc. The effects indicated are amplified as the rim thickness is increased, which is also corroborated by the experiments with a plate having a rim thickness of 5 mm. In the experiments a roll of fluid, thicker along the edges of the plate, is formed on the rim. Fluid is torn off the roll in the form of separate drops, lumps, and streams and the tearing process is irregular in nature unlike the stream mechanism for the collapse of a film draining off a sharp rim. For a rim with $\delta_{cr} < 0.75$ mm and $g_{film} < 0.465$ kg/m · sec, however, these special features do not alter the pattern of film disintegration significantly compared with $\delta_{cr} = 0.05$ mm.

When a low-viscosity fluid stream breaks down given high relative velocities of stream movement, the mean dimensions of the drops produced during the breakdown should be described by the following system of dimensionless parameters [3]:

$$\frac{\bar{d}_d}{\lambda} = f\left(\frac{\rho_g u^2 \lambda}{\sigma};\ \frac{\lambda}{D};\ \rho_f/\rho_g;\ \mu_f/\mu_g\right),$$

where λ is the wavelength of the unstable perturbation and D is the characteristic geometrical dimension.

The influence of ρ_f/ρ_g is not investigated in the experiments. From the condition $\lambda/\bar{d}_d$ = idem, since λ does not enter into the condition of unambiguity, we obtain

$$\frac{\bar{d}_d}{D} = f\left(\frac{\rho_g u_g^2 D}{\sigma};\ \mu_f/\mu_g\right). \tag{3}$$

It is established that the dimensions of the drops formed are not related to either the thickness of the plate rim, the thickness of the film on the plate, or any other of the geometrical dimensions involved in the unambiguity condition which are characteristic of the system. The process of the breakdown of a film of fluid draining off the plate rim has a great deal in common with the process of atomization of the fluid in pneumatic atomizers with high gas volumetric flow rates.

In the investigation into pneumatic atomizers in [4] it is established that with high gas volumetric flow rates the viscosity of the fluid does not influence the breakdown process. In addition, in general the mean drop dimensions are independent of the fluid flow rate and, thus, of the diameter of the fluid stream or any other geometrical dimensions such as the diameter of the nozzle.

With high gas volumetric contents and high relative velocities the collapse of the stream occurs under atomization conditions in which the shortwave ($\lambda < d_{str}$) perturbations on the surface of the stream are unstable. The drops formed during the collapse of shallow waves are weakly dependent on the dimensions of the actual streams. The $(\nu_f^2/g)^{1/3}$ parameter, compiled from the physical constants involved in the unambiguity condition, can be used as the scale for the criterial correlation of experimental data.

A preliminary analysis shows that the mean dimensions of the drops in the spectrum are proportional to the $(u_g^2/\sigma)^{0.5}$ magnitude. This is in good agreement with the results of [4].

Taking into account these comments, the relationship (3) can be transformed into

$$\frac{\bar{d}_d}{\sqrt{\sigma/(g\rho_f)}} = f\left[\frac{(g\nu_f)^{1/3}}{u_g}\right].$$

This relationship is used to correlate experimental data on the mean dimensions of the drops in the final spectrum for low-viscosity fluids (Fig. 4). The experimental data for the water and alcohol are described with an accuracy of ±20% by the criterial relationship

$$\frac{\bar{d}_d}{\sqrt{\sigma/(g\rho_f)}} = \frac{67.5\,(g\nu_f)^{1/3}}{u_g}. \tag{4}$$

It is interesting to compare formula (4) with experimental data on an investigation into the drop spectrum formed when fluid is torn off the crests of the waves in a film flowing along the walls of a channel in a disperse-circular flow. In both cases the spectrum of drop dimensions is formed as a result of breakdown of the stream of fluid and of the secondary breakdown of drops in the gas. The volumetric gas flow rates occurring per unit mass of the disintegrating fluid are in both cases fairly great. It can, therefore, be expected that the drop dimensions should be of the same order of magnitude. This comparison is shown in Fig. 4, where the hollow points denote experimental data on the mean dimensions of the drops in a two-phase flow for the water and alcohol. As can be seen, the relationship (4) can be used in the first approximation to determine the mean dimensions of drops in a two-phase flow.

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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