2. N. Mitsuishi, O. Miyatake, and M. Tanaka, Mem. Fac. Eng. Kyushu Univ., 28, No. 3, 207-221 (1969).
3. F. Beck, Chem.-Ing.-Tech., 35, No. 12, 837 (1963).

FORMATION OF THE DROP-SIZE SPECTRUM IN A GAS – LIQUID FLOW

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The deformation of the surface waves on a liquid film, the breakaway of liquid from the film, and the drop-size spectrum formed during wave destruction are investigated by using a holographic method.

The moisture suspended in the gas core of a dispersed annular gas–liquid flow is formed as a result of part of the liquid breaking away from the film on the channel wall. Up to now it has been established that the breakaway of liquid is realized principally from the crests of the largest, so-called 'perturbing' waves. The liquid stripped from the wave crest is subsequently taken into the gas core of the flow. The drop spectrum in the core of a dispersed annular flow is formed as a result of breakup and coagulation of the drops stripped from the film.

In this paper, the breakaway of liquid from a film running over the outer surface of a 6.0-mm-diameter pipe is studied using a holographic method [1, 2]. The liquid is inserted through an annular ~5-mm gap between two coaxial pipes. The tests were conducted with water, ethyl alcohol, and glycerin solutions (the viscosities of the aqueous glycerin solutions are $20 \cdot 10^{-6}$ and $140 \cdot 10^{-6}$ m^2/sec) at air speeds of 35-110 m/sec. The liquid flow rates per unit perimeter were 0.07-0.3 kg/m · sec for water, 0.2-0.5 kg/m · sec for alcohol, and 0.08-1.0 kg/m · sec for the glycerin solutions.

Deciphering the holograms showed that the disintegration of the surface waves is analogous to breakup of a liquid jet in a gas. The nature of drop formation around the film surface, like breakup of a jet, depends essentially on the viscosity of the liquid. In conformity with this, all liquids can be grouped into low-viscosity (water, alcohol) and high-viscosity (glycerin) liquids depending on the magnitude of the parameter $a\sigma/\rho_l \nu_l^2$. A study of the holograms showed the following sequence of wave destruction. The smooth monotonic character of the wave surface is spoiled first. Individual perturbations appear which grow with time and eventually develop a rather complex shape. The presence of one or more projections is characteristic for such a perturbed surface. One such projection can evolve into a jet flowing out of the film into the gas flow. The most characteristic, fully developed jet is shown in Fig. 1a. Waves and necks appear in the jet, and in the long run it dissociates into individual drops (Fig. 1b).

The formation of not one, but several, individual jets on the surface of one wave is possible at higher gas velocities.

It should be emphasized that in all these cases we speak of perturbations in the scale of the wave itself, when the wave as a whole takes part in the deformation and when we can speak about the internal motion of the whole liquid mass included in the wave. We refer to this type of wave surface destruction as dissociation. Dissociation is the main type of wave destruction at relatively low gas velocities. These velocities reach approximately 50 m/sec for water.

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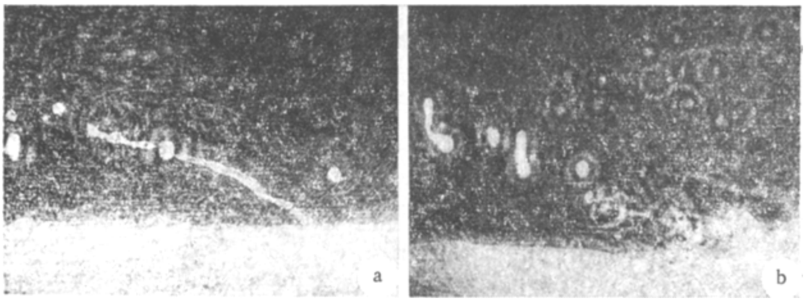

Fig. 1. Dissociation of the surface waves on a water film: a) jet taking form; being largest; b) jet breaking up into individual drops.

Not only the largest waves themselves are destroyed at higher velocities, but also the waves whose amplitudes are comparatively small turn out to be unstable. The frequency of these waves grows. The spacing between the unstable waves diminishes from 1-2 cm to several millimeters.

Numerous shallow perturbations, which are unstable and whose scale is an order less than the size of the wave itself, appear on the surface wave pattern at high gas velocities. Consequently, such wave turns out to be surrounded by a cloud of fine drops, which give rise to the "misty" appearance of the perturbing wave, as a number of investigators have remarked. We refer to this type of destruction as spray. The presence of spray does not exclude the possibility of wave dissociation, with the spray emanating not only from the wave surface, but also from the jet surface.

In addition to the qualitative visual investigation of the surface-wave state of the liquid film, we measured its mean thickness, wave heights, and diameters of the jets formed during wave dissociation. A double-exposure method was used to determine the film thickness during the taking of the holographs.

Histograms of the water-wave amplitudes are presented in Fig. 2 for two different air speeds. As is seen, the spectrum of the wave sizes is sufficiently broad and will be broader, the lower the gas velocity. The largest waves can be considerably greater than the mean film thickness. All the waves on the film surface are plotted on the histograms, where only the fairly large ones are unstable. The lower boundary of the unstable-wave amplitudes is shown by arrows. The relative number of these waves is small at low velocities. Their fraction increases significantly with the gas velocity. The low boundary of the instability is simultaneously shifted toward shallower waves. The height of the perturbing waves usually exceeds the mean film thickness.

The mean wave size for low-viscosity liquids is approximately the same as the mean film thickness. The mean jet diameters are of the same order as the size of the unstable waves in the dissipation domain. A diminution in the mean jet diameters occurs for an increase in the gas velocity with a diminution in the unstable-wave size. A significant number of fine jets whose diameters are substantially less than the size of the waves themselves appear with spray in low-viscosity liquids i.e., at high gas velocities.

The theory of breakup of a low-viscosity liquid jet, considered in [3], can be used in a first approximation for a qualitative explanation of the mechanism of breakaway liquid from the film and the formation of the drop-size spectrum in a gas–liquid stream.

The pressure above the wave crest during a gas flow over surface waves turns out to be less than at its base. The presence of such a pressure drop contributes to the growth of the wave amplitude. The unbroken nature of the flow process is spoiled for a certain ratio between the flow velocity and wave size, and a pressure difference appears in the frontal and root zones of the wave. Circulatory motion of the liquid within the wave occurs as a result of this pressure drop. The liquid motion results first in deformation of the wave surface and then in its destruction under definite conditions. The presence of a large number of stable waves of comparatively low amplitude on the film surface indicates that the velocity of the flow around an individual wave should be sufficiently high so that the gasdynamic effect of the stream would be greater than the capillary pressure $\rho_g u_g^2 > \sigma / a$.

It follows from this condition that for water-wave sizes corresponding to the lower instability boundary, the streamline velocity should be

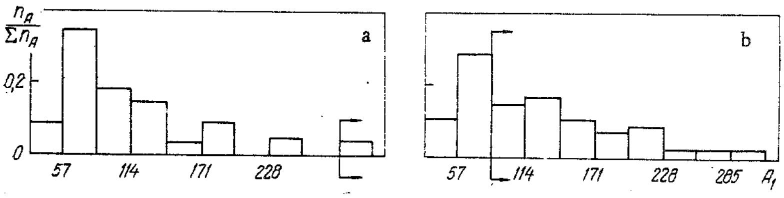

Fig. 2. Histograms of water wave amplitudes: a) $u_g = 55$ m/sec; b) 110, A_i, mμ.

$$u_g > \sqrt{\frac{\sigma}{\rho_g a}} \simeq \sqrt{\frac{72 \cdot 10^{-4}}{0.12\,(1-3) \cdot 10^{-4}}} \simeq 15\text{--}25 \text{ m/sec}$$

We cannot measure the gas velocity directly at the level of the wave height; however, the following estimate can be made. The gas-velocity profiles over a dry experimental pipe were measured. Since the contamination of the flow with drops is slight, it was assumed that the gas-velocity profile would be the same over the film surface waves. The gas velocity at a distance from the wall corresponding to the lower boundary of the unstable-wave amplitudes is taken as the magnitude of twice the critical velocity of the flow over the wave. According to such an estimate the critical velocity of the flow over a wave is 30-40 m/sec, i.e., is of the same order as according to the estimate presented above.

The spray phenomenon for a low-viscosity liquid jet is the loss of stability of the short-wave perturbations ($\lambda / d_{jet} < 1$). In application to the case under consideration, this means the loss of stability of the shallow capillary ripple waves on the surface of the large perturbing waves. The amplitude of these waves are on the order of 10^{-5} m and separate drops of approximately the same size appear with their destruction. The destruction of such waves is possible only at higher gas velocities than for wave dissipation. An analogous estimate shows that this velocity should be on the order of 70 m/sec.

It also follows from the theory that both long and short waves can simultaneously be unstable at high velocities. Our observations confirm this; both dissociation and spray occur simultaneously at high velocities. As an analysis of test results showed, the influence of the physical properties of the liquid (viscosity and surface tension) on the destruction of the film surface waves and drop formation in the flow core reduce mainly to the predominant influence of either kind of destruction – spray or dissociation.

Spray was not detected in tests with the glycerin solutions, for which the values of the surface tension are approximately the same as that of water but whose viscosities are 20 and 140 times greater, respectively. Most characteristic for glycerin is the increase in stability of the jet being formed during destruction of the wave. Very long thin jets (d_{jet} = 30 mμ, l_{jet} = 10-20 mm) were detected in an examination of the holograms in the stream.

In the case of ethyl alcohol, whose viscosity is approximately the same as that of water but whose surface tension is almost one third less, an abrupt increase in the spray intensity is characteristic. Spray is noted for alcohol in tests with air velocities on the order of 30 m/sec. As should be expected a diminution in the surface tension shifts the lower boundary of the perturbing-wave amplitudes toward shallower waves. At the same time, the mean and maximum wave sizes increase as compared with the data for water.

The maximum wave sizes, as well as their mean values, increase with the increase in the liquid viscosity. Hence, the lower boundary of the perturbing-wave amplitudes shifts toward coarser waves.

The growth in wave stability with the increase in ν_l is evidently associated with the increase in the time of deformation causing the wave destruction – the wave succeeds in reaching significant sizes before the liquid circulation therein produces a dynamic head sufficient to destroy it. The mean sizes of the liquid jet issuing from the wave during its destruction will diminish with both an increase in viscosity and a diminution in the surface tension.

Applying the theory [3] to an examination of the breakup process of a jet formed during destruction of the film permits making only qualitative estimates, since it is impossible to consider the jet velocity and diameter constant. At high velocities the length of the continuous part of a jet of low-viscosity liquid is estimated by the relationship

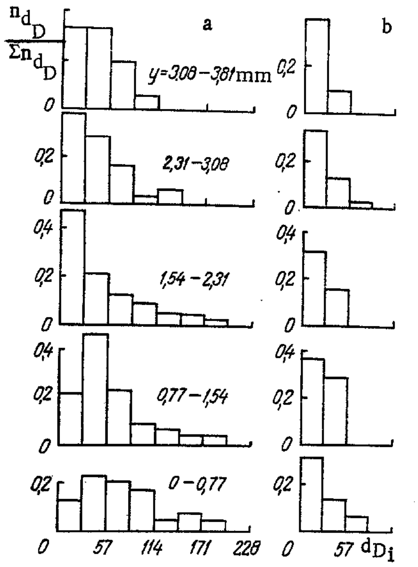

Fig. 3

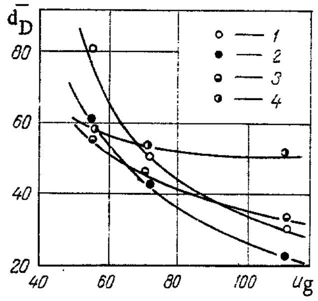

Fig. 4

Fig. 3. Histograms of the drop size of alcohol at different distances from the film surface: a) $u_g = 55$ m/sec; b) 110. d_{D_i}, μm.

Fig. 4. Mean drop size in the stream core: 1) water; 2) ethyl alcohol; 3) glycerin 20; 4) glycerin 140. $\bar{d}_D$, μm.

$$l_{\text{jet}} \sim \frac{d_{\text{jet}}}{2} \sqrt{\rho_l/\rho_g} \approx 15 d_{\text{jet}}.$$

The length of the waves formed on the jet is $\lambda \approx 4\ d_{\text{jet}}$. Considering the maximum drop diameter to be due to jet dissociation in a section of length λ, we obtain (for mean d_{jet})

$$d_{\max} = 1.82\lambda - (1-2)\ 10^{-4}\ \text{m}.$$

Besides such large drops, a large number of finer ones are also formed during jet dissociation. The diameter of drops being formed during spraying is $\sim 10^{-5}$ m. Therefore, a sufficiently broad spectrum of the drop size (10^{-5}-$2 \cdot 10^{-4}$ m) should be expected in the destruction of the wave surface of a low-viscosity liquid film.

It was also detected in processing the holograms that the maximum drop concentration is in a zone located at ~1 mm from the film surface. This is the zone of drop generation; the breakaway of liquid from the wave crest and destruction of the liquid jets occur here. The overwhelming part of the drops being formed is carried into the gas core of the flow. Intensive secondary breakup of the drops occurs in the generation zone. The majority of the large drops are deformed; many of them are in the breakup stage, where different breakup configuration are observed. Drops divided in two in the form of a dumbbell are encountered in the flow; they are destroyed at once, uniting as several individual drops which form a pocket-shaped thin film. In principle, drop coagulation is possible in such a stream, but we could not direct any act of coagulation on the holograms.

The primary process of drop breakup follows also from the nature of the deformation of the drop-size spectrum with distance from the film into the depths of the gas core (Fig. 3). The spectrum width decreases with distance from the film, the drops become finer, and the fraction of drops of most probable size increases somewhat. The most essential changes in the spectrum occur in the 2-2.5 mm zone. At large distances from the film the deformation of the drop-size spectrum is insignificant. In order of magnitude this zone corresponds to the thickness of the laminar boundary layer of the gas over a smooth film. Therefore, it is possible to to regard the boundary layer as the main drop breakup zone in a dispersed annular flow under the condition that the drop residence time in this region is greater than the breakup time. Estimates show that the breakup time for low-viscosity liquids is approximately 1-2 orders less than the residence time. Moreover, since the formation of the spectrum of the drop size proceeds principally because of their secondary breakup in the gas boundary layer, the influence of the liquid flow rate and therefore, of the film thickness on the mean drop size in the flow, turn out to be negligible. This is verified by test results. Characteristic for viscous liquids in a more uniform deformation of the drop-size spectrum, but without any very definite extremum in the drop-size distribution, depending on the gas velocity and being less noticeable with distance from the film surface.

The mean drop sizes for all the liquids studied are shown in Fig. 4 as a function of the gas velocity. The dependence of the mean drop size on the gas velocity is weaker for high-viscosity liquids than for low-viscosity liquids, where the mean drop size of the glycerin solutions is almost the same as for alcohol at low gas velocities.

In the case of a viscous liquid, thinner jets are formed and the drops obtained during dissociation of these jets will be finer. For low-viscosity liquids, the spray and secondary breakup of detached drops in the boundary layer intensify with the increase in gas velocity. The strong dependence of the mean drop size of a low-viscosity liquid on the gas velocity is evidently due to this. Hence, the drop sizes of a viscous liquid vary slightly with the increase in velocity, and the drops of a low-viscosity liquid turn out to be finer at relatively high gas velocities than for a high-viscosity liquid.

NOTATION

d, diameter; a, characteristic geometric size; A, wave amplitude; n_A, number of waves in the interval ΔA; n_{d_D}, number of drops in an interval Δd_D; u, velocity; τ, time; ν, coefficient of kinematic viscosity; ρ, density; σ, coefficient of surface tension.

LITERATURE CITED

1. V. N. Bykov and M. E. Lavrent'ev, Physics of Aerocolloidal Systems [in Russian], No. 7 (1972).
2. I. I. Paleev, F. A. Agafonova, V. N. Bykov, and M. E. Lavrent'ev, Énergomashinostroenie, No. 6 (1972).
3. V. G. Levich, Physicochemical Hydrodynamics [in Russian], Fizmatgiz, Moscow (1959).

PROBLEM OF DESCRIBING THE FLOW FIELD IN AN INJECTOR MIXING CHAMBER

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The use of a three-component flow model is proposed. The results of numerical calculations are presented and compared with the experimental results.

In order to describe the one-dimensional flow field in the mixing chamber of a condensing injector, the model of a continuous liquid jet has been used [1, 2], where it was supposed that the jet of liquid issuing from the liquid nozzle is not disintegrated, but remains complete in the entire part of the mixing chamber investigated. The numerical calculations, carried out on the basis of this model, have provided satisfactory agreement with experiment only in the case of heat-transfer coefficients from vapor to liquid which are orders of magnitude higher than the well-known values for film condensation. The latter means that the continuous liquid-jet model significantly reduces the surface of interaction of the phases. Since, in fact, a significant atomization of the liquid jet almost always is observed, it will be advantageous to revert to flow models where atomization is taken into account.

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