EXPERIMENTAL STUDY OF THE STOCHASTIC NATURE OF WAVE PHENOMENA ON THE SURFACE OF A LIQUID FILM

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An experimental study was made of wave phenomena on the surface of a liquid film freely flowing down the walls of a vertical channel in the range of Reynolds numbers for film flow ($Re = \Gamma/\eta = 50$-2500, where Γ is the mass spray density and η is the dynamic viscosity) at various distances from the entrance. The working fluid (water) was fed into the operating section at a temperature of 15-30°C. The dependence of typical wave parameters on mode parameters was obtained.

Flow of a liquid film down a vertical surface is accompanied by the production and development of unorganized wave motion. Waves of rather arbitrary shape and frequency arise on the surface of a film subjected to random perturbations under actual conditions where $Re \leqslant 2$-5 and at insignificant distances from the entrance with considerable development of wave motion being noticeable in proportion to the film flow. This leads to a situation where the wave amplitudes even for small spray densities become commensurable with the average thickness, and also exceed it, at sufficient separation from the entrance. Many authors studying gravitational flow of a liquid film in experimental test stands with short working sections $L \leqslant 3$ have pointed out the intensification of wave motion along the channel. Furthermore, even in the laminar-wave region of flow (1-$6 \leqslant Re \leqslant 200$-$500$), saturation of wave perturbations on the surface of a liquid film over the entire length of the channel was not observed in the experiments. There is no information on the nature of the gravitational flow of a liquid film along the surface of channels longer than 3-4 m [1]. At the same time, the development of power, chemical, and refrigeration machinery and the desalinization of water require the use of long channels. The design of heat- and mass-transfer equipment of high output presents great difficulty at the present time, since the physical picture of the flow remains totally unexplained.

In this work, an experimental study was made of the nature of wave phenomena on the surface of a liquid film flowing down the walls of a long channel for a sufficiently broad range of spray densities (Re = 50-2500) in a device described earlier [1].

A capacitative method of measurement and direct photography were used to study wave perturbations [1-3]. The capacitative method of measurement provides an opportunity to record instantaneous thicknesses of the liquid film. From an analysis of oscilloscope recordings, one obtains both the average thickness and typical wave parameters ($\bar{\delta}$ is the average thickness; δ_* is the average thickness of the wall layer; δ^* is the average height of projections; ω is the frequency of wave perturbations). Direct photography was used to determine wave profiles.

The first wave perturbations on the fluid surface appear immediately beyond the entrance section and are ripples of small amplitude and varying wavelength. As the distance from the entrance increases, the amplitude of the waves grows, tending toward a constant value for a given spray density. The stabilization region for wave perturbations depends on spray density and the free path of the film.

The shape of wave perturbations varies rather strongly for free flow of a liquid layer down a vertical surface. The perturbations are in the form of ripples in the initial section

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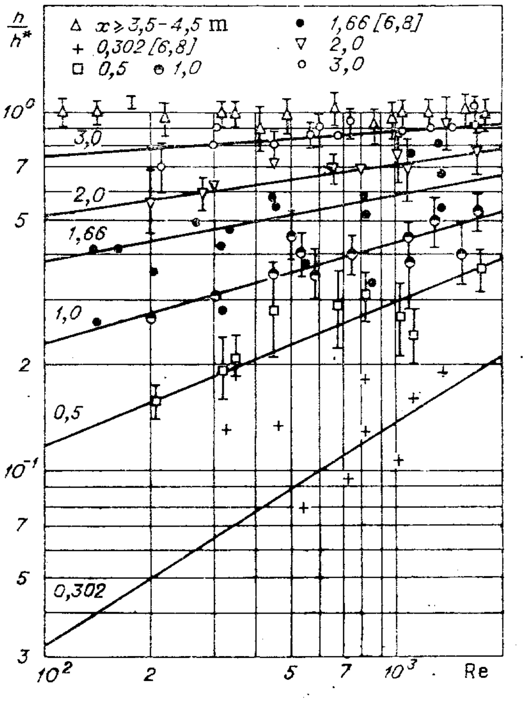

Fig. 1

for all experimental values of spray density; as the distance from the entrance increases, individual large waves appear which have completely definite amplitude, wavelength, and characteristic frequency.

An important quantity characterizing the wave motion in a liquid film is the amplitude of the waves. It should be pointed out that a single criterion for the evaluation of the amplitude structure of the process has not been developed thus far. Thus, local values of the film thickness in the highest wave crest are taken as the characteristic amplitude in [4-6]. In [3, 7], a relative value for the amplitude is calculated from the ratio between the size of a projection on an oscilloscope trace with respect to the line of average thickness and the average thickness of the film.

It is obvious that a quantity which takes into account the actual depth of the perturbations of a wave surface will be more representative than the height of the highest crests of the waves or a relative amplitude. This quantity is the average height of the wave perturbations ($h=\delta^*-\delta_*$).

In the range of spray densities investigated, the average height of the perturbations increases in the initial section ($x \leqslant 3.5$-4.5) and then remains practically constant for a given spray density.

The height of maximum wave perturbations is determined by the relation between the Galilean perturbation criterion ($Ga = h^* g\nu^{-2}$), which takes into account the effect of gravity on gravitational wave motion, and the Reynolds number for averaged motion ($Re = \Gamma/\eta$):

$$(Ga)_h^* = 106\,Re^{0.822}. \tag{1}$$

The height of wave perturbations depends significantly not only on spray density, but also on the free path (x) of the film. The variation of the heights of wave perturbations as a function of free path and Reynolds number is shown in Fig. 1 in the coordinates [h/h^*, Re) for x = 0.5, 1.0, 2.0, and 3.0. The experimental values for the height of wave perturbations are accompanied by the experimentally obtained variance. Experimental values of h obtained in [6, 8] are also given. The large spread should be explained by the smaller block of averaged points; individual realizations of the process are shown in the graph.

As follows from Fig. 1, an increase in free path leads to growth in wave perturbations. The rate of increase in perturbation height gradually slows down and the perturbation height $h=h^*$ at distances of 3.5-4.5 m.

The behavior in the initial section ($0.3 \leqslant x \leqslant 3.5$-$4.5$) as a function of free path and Reynolds number can be described by a relation of the form

$$h/h^* = A\,Re^n, \text{ where } A = 6.7\cdot 10^{-2}\cdot x^{1.95}; \quad n = \exp[-(0.66x+0.635)],$$

with Eq. (1) valid for $x \geqslant 3.5$-4.5 m.

As noted above, the formulation of an experiment and the interpretation of the known experimental data in the literature up to the present time do not completely provide an opportunity for a logical and complete description of the flow pattern. In the latest papers [3, 8, 9], the analysis of experimental data is limited to an evaluation of certain averaged quantities.

Therefore, the frequency should be determined through the spectral density of the intensity of a random process which describes the overall frequency structure of the process

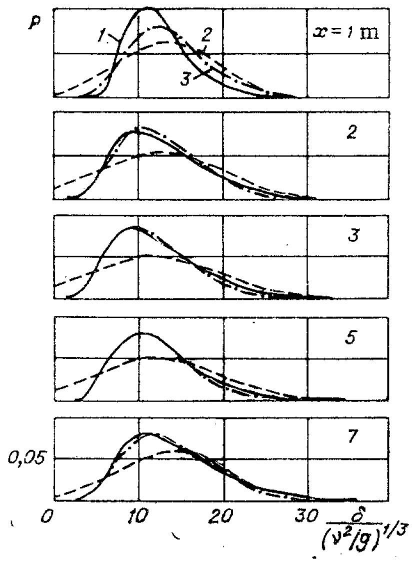

Fig. 2

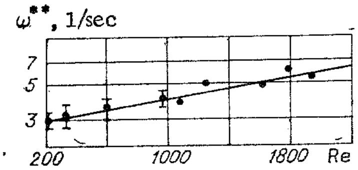

Fig. 3

through the spectral density of the average value of the square of the instantaneous thickness:

$$S(\omega) = \lim_{\Delta\omega \to 0} \lim_{T \to \infty} \frac{1}{(\Delta\omega)T} \int_0^T \delta^2(t, \omega, \Delta\omega)\, dt,$$

where ω is the frequency of the process; $\Delta\omega$ is the frequency quantization interval; T is the time for realization of a wave process.

The thickness of the film is determined through density distribution of the random process, which establishes the probability laws for the behavior of the instantaneous thickness as a function of the governing parameters:

$$P(\delta) = \lim_{\Delta\delta \to 0} \lim_{N \to \infty} \frac{1}{N} \left(\frac{n_i}{\Delta\delta}\right),$$

where $\Delta\delta$ is the thickness quantization interval; N is the sampling volume for the random process; n_i is the number of realizations in a given thickness interval.

A comparison of the experimental curves for the density distributions of the instantaneous thickness (curves 1, Fig. 2) shows that the main contribution to the density distribution can be described by the function

$$\varphi = \frac{1}{2^{m/2}\Gamma\left(\frac{m}{2}\right)} \left(\frac{\delta}{\sqrt[3]{\frac{\nu^2}{g}}}\right)^{\frac{m-2}{2}} \exp - \frac{\delta}{2\sqrt[3]{\frac{\nu^2}{g}}}, \quad m = \bar{\delta}\Big/\sqrt[3]{\frac{\nu^2}{g}} + 2;$$

$\Gamma(m/2)$ is the gamma function.

The function φ is the density distribution of a quantity χ^2, that is defined as the sum of squares of random quantities each of which is distributed normally with zero average value and variance of one,

$$\sum_1^m \left(\frac{\delta\Big|\sqrt[3]{\frac{\nu^2}{g}} - \bar{\delta}\Big|\sqrt[3]{\frac{\nu^2}{g}}}{\sigma}\right)^2 = \chi^2.$$

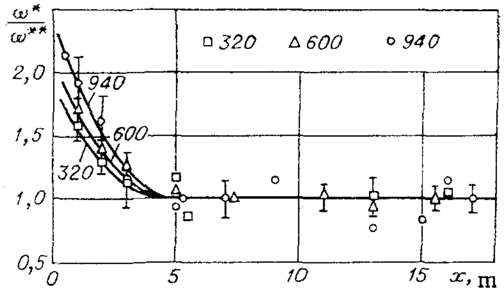

Fig. 4

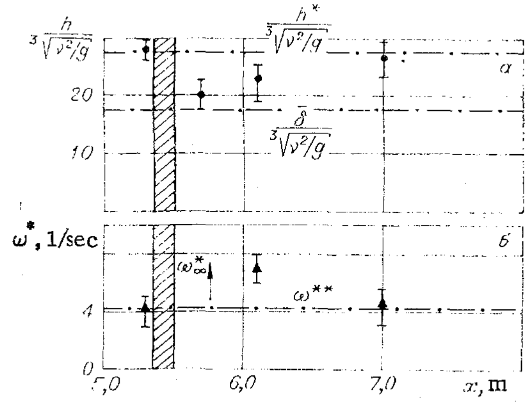

Fig. 5

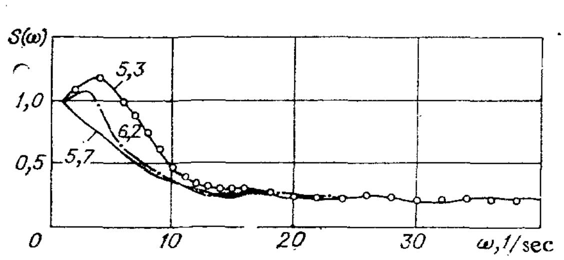

Fig. 6

The function φ is a particular case of the more general theoretical gamma distribution (Γ).

As follows from Fig. 2 (Re = 600, x = var), the function φ (curves 3) does not take into account the increase in asymmetry of the process because of the increase in the contribution from waves of greater heights ($>\bar{\delta}$) with the development of wave motion along the channel. A marked deviation from the distribution is observed in the initial sections of the channel where wave motion is still insufficiently developed and the contribution from values of instantaneous thickness close to the average value is rather large. A comparison of the distribution curves also shows that the normal distribution law (curve 2, Gaussian distribution) for a given variance of the process cannot be used for a description of the probabilistic structure of the process.

In order to explain the mechanism of wave flow in a film it is necessary to know the dependence of the most characteristic frequency of the process ω^*, position of the maximum of the spectral density) on the governing flow parameters: spray density and film free path. An analysis of the behavior of the quantity ω^* as a function of Reynolds number and $\bar{x}$ showed that for each spray density there is a completely determined value of wave motion saturation frequency ω^{**}, which the most probable frequency ω^* reaches at 3.5-4.5 m from the entrance, remaining unchanged further along the channel.

The dependence of ω^{**} on Reynolds number is shown in Fig. 3 and is described by the expression

$$\omega^*/\omega^{**} = \exp(-ax+b),$$

$$a = \exp(4.1810^{-4}\mathrm{Re}-2.73),$$

$$b = \exp(6{,}44\cdot 10^{-4}\mathrm{Re}-1.562).$$

The variation of the most probable frequency ω^* as a function of free path and Reynolds number (numbers on the curves correspond to the Reynolds number) is shown in Fig. 4. As is clear from the curves presented, the relationship at 8-11 describes the behavior over the entire length of the channel rather well.

An increase in spray density and in the free path of the liquid film intensifies wave motion on the free surface. In the final analysis, the development of wave perturbations leads to separation of liquid from the film surface [1]. In the present work, an attempt was made to prevent separation through breakup of large waves by means of a device consisting of a number of longitudinally washed laminar ribs.

The advancing flow of liquid passed through a number of ribs with the initial wave structure in the flow changing significantly because of the breakup of large waves and intensive mixing of the liquid during its passage through the space between ribs.

There is absolutely no information in the literature on the interaction between an advancing wave flow and an obstacle and therefore the consideration of such an interaction is of great interest not only from the viewpoint of producing a "quasiplanar" film, but also as a first attempt at an experimental study of such an interaction.

The device consisted of ribs made of brass foil 0.1 mm thick. The rib height (h) was considerably greater than the (maximum) wave amplitude (δ). The length of the rib must be considerably greater than the length of a wave on the surface of the liquid film.

Preliminary experiments with 12, 24, and 36 ribs showed that a device with 24 ribs was most effective. The device was installed at 5.5 m from the entrance, i.e., in the region where saturation of wave motion has already occurred. Measurements of instantaneous thickness were made by the capacitative method [1] ahead of the device (x = 5.3) and at 0.2, 0.7, and 1.5 m beyond the device (5.7, 6.2, and 7.0 m from the entrance).

The variation in typical wave parameters because of passage of the liquid through the obstacle is shown in Fig. 5 (spray density Re = 850). The depth $h/\sqrt[3]{\nu^2/g}$ of wave perturbation (Fig. 5a) varies from the saturation value (in the section at x = 5.3 m) to a value close to the average thickness immediately after the damper because of the smoothing action of the device. With increasing downstream distance, restoration of the wave perturbation structure occurs, and at x = 7.0 m it is close to the steady-state value.

The energy spectrum of wave motion during passage through the obstacle undergoes a change in such a fashion that readjustment of the spectrum occurs with a change from the characteristic saturation frequency before the device ω^{**} to a spectrum typical of exponential noise with a correlation function of the form $R(\tau)=e^{-\alpha|\tau|}$.

In this case, there is no predominant harmonic in the spectrum (Fig. 6 shows a normalized spectrum for Re = 850 smoothed by means of a Bertlett window; the numbers on the curves correspond to the distance from the entrance section), and a flow of a quasiplanar film is observed with an amplitude close to the average thickness and with a frequency spectrum for exponential noise $S(\omega) = 1.160\omega^{-0.0504}$. Thus the introduction into the flow of external perturbations which are propagated over the entire thickness of the liquid film leads to "whitening" of the energy spectrum of wave motion.

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