INVESTIGATION OF THE GRAVITATIONAL FLOW OF A LIQUID ALONG THE WALLS OF A VERTICAL CHANNEL OF GREAT LENGTH

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An experimental study was made of the hydrodynamics of a film of liquid flowing over the external surface of a cylindrical channel, in the range of film-flow Reynolds numbers $R = \Gamma/\eta$ = 120-7200 (Γ is the mass irrigation density; η is the dynamic viscosity) at different distances from the inlet (x = 1-19 m).

With the free flow of a film of liquid down along the walls of a vertical channel, an unordered wavy motion appears and develops on the surface of the channel. An increase in the irrigation density or of the length of the path of the liquid film leads to an intensification of the wavy motion at the surface. At definite irrigation densities and at definite distances from the inlet intensification of the wavy motion leads to breakaway of the liquid from the surface of the film.

With low irrigation densities, at definite distances from the inlet there is stabilization of the wavy motion. The length of the stabilization section depends on the properties of the liquid and the irrigation density.

In a majority of the well-known earlier experiments, sections of limited length, not exceeding 3-4 m, were used. Therefore, even with relatively small irrigation densities, stabilization of the wavy motion over the whole length of the channel was not observed in the experiments. Data on the character of the free flow of a liquid over the surface of channels more than 5 m long are completely lacking.

In the present work an experimental investigation was made of the local characteristics of a film of liquid flowing freely down the vertical surface of a channel of long length, over a wide range of variation of the irrigation density (R = 120-7200). The investigation was made in an experimental unit with a working section made of steel Kh18N10T, with a length of 19 m and a diameter of 60 mm. The working section hung freely, attached to the tank of the distributing device. The working liquid (water at a temperature of 18-28°C) was fed from a tank with a free liquid level through the annular slit in the distributing device to the internal surface of the working section.

To study the motion of the film several experimental methods were used: the capacitance method of measurement, described in detail previously [1], direct photography, and measurement of the instantaneous mass-flow rate of the liquid, using a specially developed measuring device with an electrical pickup for the level.

The capacitance method of measurement permits recording the change with time of the local values of the thickness of the film δ; by analysis of the oscillograms it also makes it possible to obtain the mean values of the thickness in the cross section under consideration $\bar{\delta}'$, the mean thickness of the continuous layer near the wall δ_*, the mean height of the protuberances δ^*, and the frequency of the wavy perturbations of the surface of the film ω. Unfortunately, the possibilities of using the capacitance method of measurement in working channels with a great length are limited to a region of relatively low irrigation densities, since to record waves of great height requires a considerable gap in the condenser, which leads to a decrease in the sensitivity of the instrument. In the region of large irrigation densities, and of moderate breakaway, the method of direct photography of the surface of the liquid film is used. This method

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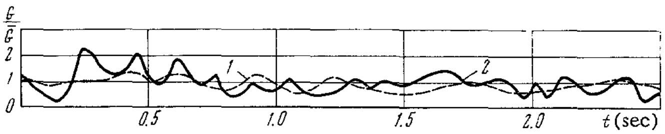

Fig. 1

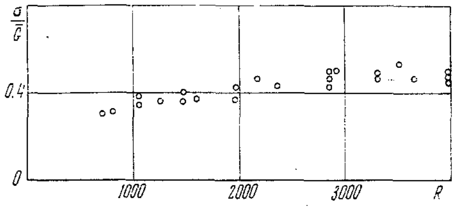

Fig. 2

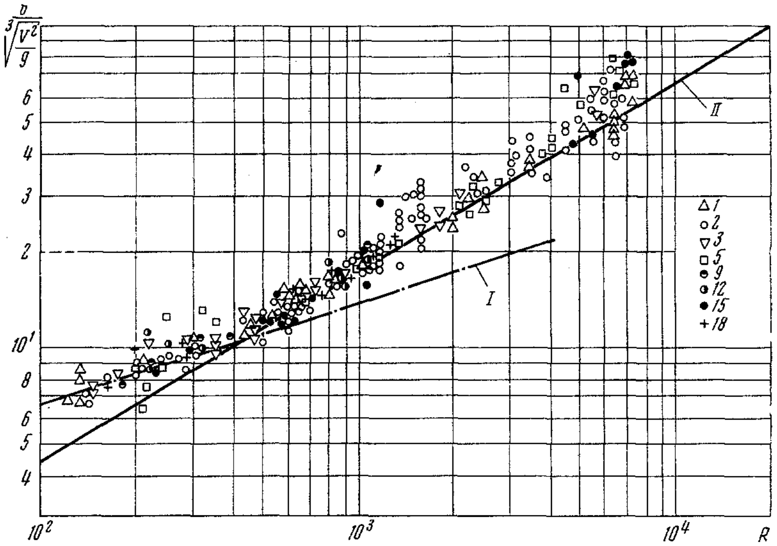

Fig. 3

permits determining the values of the mean local thickness at practically any given irrigation densities, makes it possible to record the form of three-dimensional waves and their length, and permits recording the breakaway of the liquid from the surface of the film.

The instantaneous mass flow rates in a given cross section of the working section were measured using a cylindrical measuring tank, embracing the working section, and provided with a lagless electrical pickup for the level with continuous recording of the signal on an oscillograph, and with displacement inserts for regulating the sensitivity of the device and with a quieting device for the liquid level.

With the flow of a liquid film along the walls of a vertical channel, there develops on its surface an unordered wavy motion, which exists at all practically important irrigation densities. In the initial section there arise waves of small amplitude, ripples of different length. Their length is less the lower the forward speed of the liquid. The surface waves have a clearly expressed three-dimensional character; the length of the waves is considerably greater than their height. At distances of 0.5 to 3 m from the inlet, on the surface of the film annular waves form with a wedge-shaped frontal surface and a sharply expressed steep leading slope. The limit of the appearance of annular wedge moves away from the inlet with an increase in the irrigation density. The length of the wedge increases with the irrigation density from 20-30 mm at $R = 200\text{-}400$, and to 100-200 mm with $R = 1500\text{-}2000$. At low irrigation densities ($R \sim 200$) the distance between the annular waves is on the order of 1 m over practically the whole length of the working channel. With an increase in the irrigation density, the distance is shortened to 200-300 mm in the upper part of the working section, and to 300-500 mm below. The surface of the film between the large waves is covered with small ripples.

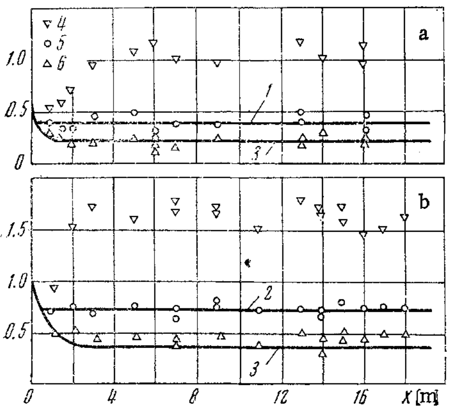

Fig. 4

An increase in the intensity of the irrigation leads not only to an increase in the height of the waves, but to a change in their form itself. It can be postulated that, with an increase in the irrigation density, and in particular the length of the path, the character of the flow of the film changes radically. In the initial sections of the channel, with any given irrigation densities and with small irrigation densities, a wavy surface motion exists over the whole length of the channel; annular waves are not formed, or their height and frequency are small. With the origin and development of annular waves, the perturbations extend themselves over the whole thickness of the liquid film, and there arises a motion similar to the motion of gravitational waves in shallow water; under these circumstances, a considerable part of the mass flow is carried by precisely these waves, i.e., "mass-flow waves."

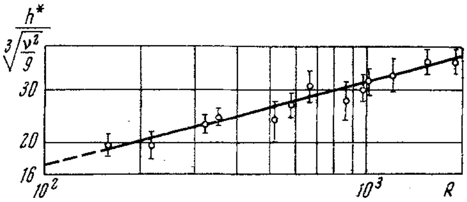

Fig. 5

The change in the instantaneous mass-flow rate with respect to the mean level is shown on Fig. 1 (for R = 800, 400, i.e., curves 1, 2, respectively) for a cross section at a distance of 5 m from the inlet. If, with a low irrigation density, the fluctuations of the mass-flow rate are relatively small (up to 30%) and the rate of change of the mass-flow rate is small (approximately with a frequency of 2-4 $\sec^{-1}$), then, with a large irrigation density (curve 2) the change in the mass-flow rate is 50-100% and takes place with a frequency of 6-9 $\sec^{-1}$. Figure 2 shows the mean-square deviation of the mass-flow rate σ with respect to its mean value $\sigma/\bar{G}$, as a function of the Reynolds number. With an increase in the Re number the value of the deviations rises, attaining $\sigma/\bar{G}$ = 0.45-0.50 with R = 3000; at large irrigation densities it subsequently remains practically unchanged.

With irrigation densities corresponding to R = 1300-1500, there can be noted the infrequent breakaway of individual drops from the crests of the large waves, at distances $x \geq 15$ m. With an increase in the irrigation density the zone of the start of breakaway moves up to the inlet device. At distances x = 13 m, with intensities Γ = 1.5-1.7 kg/(m · sec) corresponding to R = 1800-2200, at temperatures t = 20-28°C, regular breakaway of the liquid from the surface of the large waves is recorded. Here there is no frothing at the front of the large waves. An increase in the irrigation density up to R = 3500 advances the breakaway zone up to x = 5-6 m. The displacement of the breakaway zone toward the inlet device slows down gradually with an increase in the value of R. With current densities corresponding to R = 4500-5000, breakaway starts at a distance of 4.5-5 m from the inlet. With a further increase in the intensity of the irrigation, the position of the start of breakaway remains approximately constant. The connection between the Reynolds number, which corresponds to the irrigation density leading to breakaway and the length of the path at which it starts is expressed by the empirical dependence

$$R = [(1.25x - 0.96) / (x - 3.8)] \cdot 10^3 \qquad (1)$$

As follows from expression (1), with $x \leq$ 4-4.5 m there is no breakaway at any value of the irrigation density, and with $R \leq 1300$ the flow takes place without breakaway over the whole length of the experimental section.

The use of direct photography followed by analysis of the photos obtained has permitted a considerable broadening of the range of investigation of the mean thickness. Figure 3 gives experimental values of the mean thickness in the dimensionless form

$$\bar{\delta} g^{1/3} \nu^{-2/3} = f(R)$$

where ν is the kinematic viscosity for cross sections at distances from the inlet x = 1, 2, 3, 5, 9, 13, 15, 18 m, with a change in the R number of R = 120-7200. In the region R = 120-2500, the experimental points were obtained by both the capacitance and photographic methods. The solid lines are plots of values of $\bar{\delta}$ calculated for laminar flow conditions using the well-known Nusselt dependence (curve 1)

$$\bar{\delta} = (3g^{-1}\nu^2 R)^{1/3} \qquad (2)$$

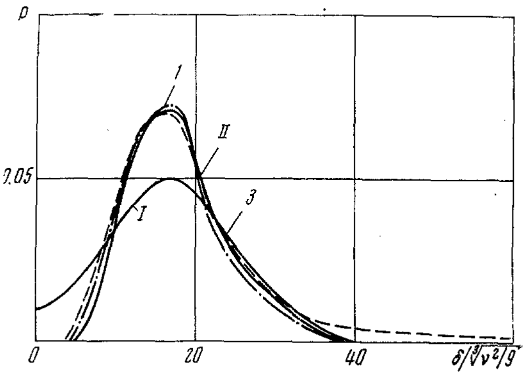

Fig. 6

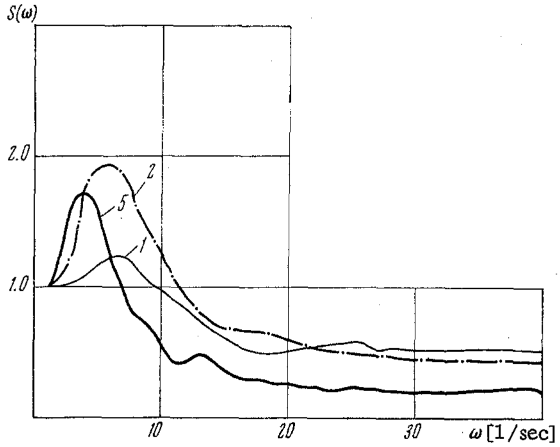

Fig. 7

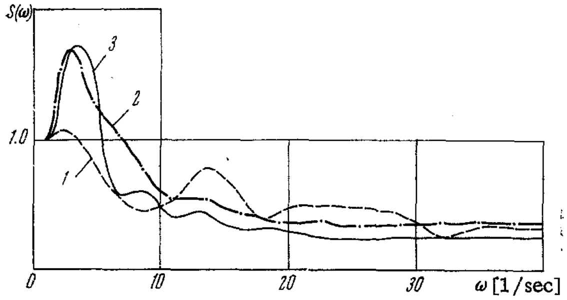

Fig. 8

and for turbulent flow of a film with a smooth surface 1 (curve 2)

$$\bar{\delta} = (0.0292 g^{-1} \nu^2 R^{7/4})^{1/3} \tag{3}$$

The satisfactory agreement between the experimental data and the theoretical dependences over the whole range of change of the R number and the length of the path must be noted. With large irrigation densities and large lengths of the path of the film, a certain regular increase in the mean thickness of the film may be attributed to the breakdown of the continuity of the flow with frothing in the wave. The increased scatter of the experimental points with an increase in the length of the path and of the irrigation density must be explained in the same way.

The capacitance method of measurement makes it possible to determine the local characteristics of the wavy motion along the length of the channel. Figure 4 shows the change in the values of $\bar{\delta}$, δ_*, and δ^* along the length of the working section for irrigation densities corresponding to R = 200 (Fig. 4a), and R = 1000 (Fig. 4b). The solid lines 1, 2 are plots of the value of the mean thickness for laminar and turbulent flow conditions, and line 3 is the mean thickness of the layer near the wall, δ_*, calculated using an empirical dependence [1]. The experimental points 4, 5, 6 correspond to δ^*, $\bar{\delta}$, δ_*.

The experimental data presented on Fig. 4 show that, for all the irrigation densities considered, the mean thickness of the film remains practically unchanged along the whole working section. The divergence of the experimental points from the calculated values lies within the limits of the accuracy of the experiment. Here, the inlet section, with a length up to 1 m, is not taken into consideration. Precisely in the section 200-500 mm from the inlet there is stabilization of the mean thickness of the film [1]. As shown by the investigation, a considerable increase in the length of the path of the film, at the measured irrigation densities, does not lead to any appreciable change in the mean thickness. The mean thickness obtained is in good agreement with the thickness calculated in terms of the profile of the mean velocity in the film [2].

The mean thickness of the continuous layer near the wall δ_* decreases appreciably with an increase in the length of the path of the film, approaching a definite constant value. The stabilization section for δ_* is considerably greater than for $\bar{\delta}$ and reaches 2-4 mm. A distinct tendency toward stabilization appears also for the mean height of the protuberances of the waves. The value of δ^* rises with an increase in the length of the path. The rate of increase of the height δ^* slows down gradually. The length of the stabilization section of the mean height of the protuberances is 3.5-5 m, and therefore could not be reliably determined in any previous investigation.

Figure 5 shows the change in the mean limiting height of the waves $h^* = (\delta^* - \delta_*)^*$ as a function of the irrigation density. The value of h^* rises with an increase of the irrigation density. The change in the limiting height of the waves can be approximated with a sufficient degree of accuracy by the dependence

$$h^* g^{1/3} \nu^{-2/3} = 5.44 R^{0.247} \tag{4}$$

An amplitude-frequency analysis was made of the wavy motion of the liquid film. The experimental values of the instantaneous thickness were analyzed in an electronic computer to obtain the densities of the distribution of the characteristic curve of the physical process and to establish the probability laws for its instantaneous values.

Figure 6 shows the density distribution of the value of $\delta g^{1/3} \nu^{-2/3}$ for the conditions R = 940 and various distances from the inlet: 1.0, 3 m. Curve I corresponds to the curve of a normal distribution with a variance and a mathematical expectation obtained experimentally. Curve II corresponds to the distribution

$$\varphi = \frac{1}{2^{m'/2}\,\Gamma(m'/2)}\, m^{(m'-2)/2} \exp\left(-\frac{m}{2}\right) \tag{5}$$

$$m' = \delta' g^{1/3} \nu^{-2/3}, \qquad m = \delta g^{1/3} \nu^{-2/3} \tag{6}$$

As can be seen from Fig. 6, a considerable change in the amplitude structure of the process takes place at a distance of up to 3 m from the inlet. At small distances from the inlet, the fraction of values close to the mean value is extremely great. With an increase in the distance from the inlet, waves of ever greater height appear and the thickness of the continuous layer decreases. This leads to stratification of the probability characteristic. Under these circumstances, while for minimal values of the thickness the stratification is insignificant and differs appreciably from the remaining distributions only with small distances from the inlet, for maximal values ($\delta < \bar{\delta}$) this stratification can be overlooked up to 3 m inclusive; i.e., saturation of the wavy motion sets in after 3 m of path length.

A comparison between the experimental distribution curves and the theoretical curve I shows that the physical process of the development of a wavy motion on the surface of a film is asymmetric in its nature, the presence of a free surface promotes the appearance of large amplitudes of the waves (an increase in the "weight" of the right-hand part of the curve of the density of the distribution), while, at the same time, the wall of the working section along which the film is flowing acts as a stabilizing factor; and minimal thicknesses ($\delta < \bar{\delta}$) are more conservative for the development of a wavy motion.

As can be seen from Fig. 6, the function φ satisfactorily describes the distribution of the principal contribution of the values of the instantaneous thickness, although it does not take into consideration the increase in the asymmetry of the process due to an increase in the contribution from waves of large height with the development of wavy motion along the length of the channel. With the given variance of the process, the curve of the normal distribution cannot be used to describe the probability character of the flow.

Determination of the characteristic frequency of the motion of the waves is the most controversial question in the hydrodynamics of the wavy motion of liquid films. First of all, there is a contradiction in the very definition of the concept of the frequency of a wavy process. Thus, in [1, 3] by frequency there is understood the number of fluctuations of the wavy surface in unit time; small-scale perturbations are discarded. In [1], with an irrigation density R = 740, the frequency varies from 50 to 20 with a change in the distance from the inlet from 0.1 to 3 m. According to [3] the most probable frequencies vary from 10 to 40 $\sec^{-1}$, depending on the irrigation density (R = 10-100) and the length of the path (x = 0.13-0.67 m). In investigations carried out using the contact method, for example [4], the frequency of the wavy motion is the number of contacts between the probe and the surface of the film. This type of measurement yields information with respect to the distribution of the maximal and minimal thicknesses of the film, while the real frequencies of the process remain undetermined.

In view of the random nature of the wavy process, the most correct is obviously a probability determination of the frequency in terms of the spectral density of the power of the wave process, which yields information on the contribution of all the frequencies existing in the process, as well as bringing out the most probable harmonic.

Figure 7 shows the spectral density of the process, normalized for 1 $\sec^{-1}$, for a fixed mass-flow rate R = 940 and different distances from the inlet. As follows from the curves of Fig. 7, the "carrier" frequency varies from 7 to 3-4 $\sec^{-1}$ with an increase in the distance from the inlet device from 1 to 3-5 m. Judging from the behavior of the spectral density with a change in the distance, saturation of the wavy motion sets in at a distance of 3-4 m. Further on, the most probable frequency remains constant and equal to 3-4 $\sec^{-1}$. The frequency structure of the process depends both on the length of the path and on the irrigation density. Figure 8 shows the development of the wavy process with a fixed distance from the inlet (x = 5 m) and different irrigation densities. Curves 1-3 correspond to R = 220, 580, 680. An increase in the irrigation density shifts the carrier frequency somewhat into the high-frequency region. However, this change is insigificant and amounts to only 1 $\sec^{-1}$. Thus, the frequency structure of the process depends strongly on the length of the path of the film. The dependence on the irrigation density is weaker.

The investigation showed that the process of the flow of a liquid film down a vertical wall is of a random character. The carrier frequencies of the process depend on the length of the path of the film and on the irrigation density. At all irrigation densities investigated, saturation of the wavy motion set in at a distance of 3-4 m from the inlet. On the surface of the film there develops an intense wavy motion which, at a definite irrigation density and path length, leads to the breakaway of part of the liquid from the crests of the waves. In the initial section of the motion of the film, right up to a distance of x = 4-5 m from the inlet, breakaway does not set in at any irrigation densities. The limits of the start of breakaway have been established as a function of the path length and the irrigation density.

Under prebreakaway conditions, the experimental data obtained on the mean thickness are in satisfactory agreement with a theoretical dependence obtained on the basis of a plane flow model with an exponential law of the velocity distribution over the cross section. The development of wavy motion leads to a situation in which a considerable part of the mass flow is carried by waves which bring about fluctuations of the mass-flow rate in a cross section. With large irrigation densities, the mean-square deviation of the instantaneous mass-flow rate with respect to the mean level reaches 50%.

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