STUDY OF THE SEPARATION OF LIQUID FROM THE SURFACE OF A FILM DURING GRAVITATIONAL FLOW IN A CHANNEL

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Studies are made of the separation of liquid from the surface of a film flowing in a vertical channel. Empirical dependences are obtained which permit the quantitative description of this process.

Film flow is realized in various heat- and mass-exchange apparatus as well as in a number of instruments especially designed both for purposes of heat transfer and for their regulation. It is known [1-3] that at moderate washing densities $\Gamma \leq 2.5$ kg/m·sec and with short lengths of vertical channels $X \leq 3$-4 m the flow of a liquid film in the absence of a following or opposing gas stream is stable and is described by relationships uniquely connecting the film characteristics with the initial washing density and the current parameters: the physical properties, temperature, and length of travel of the film. In [4] it was noted that when $R(X-4.0) = (1.25X-0.96)\cdot 10^3$ liquid begins to separate from the surface of the film during its purely gravitational flow. This effect is described qualitatively without any quantitative relationships. A quantitative description of the process of liquid separation is necessary since its neglect during the determination of the local characteristics of the film and the coefficients of heat transfer to it can lead to considerable errors in the calculations.

In the present report we present the results of a study of the separation of liquid from the surface of a film during its gravitational flow within a vertical channel of great length and the radial distribution of the separated liquid at different cross sections along the height.

The experiments were conducted on an instrument described in [4]. The working section of the instrument with a length of 19 m and a diameter of 54 mm is made of 1Kh18N9T steel. Cylindrical samplers from 10 to 50 mm in diameter were used to determine the amount of separated liquid and its radial distribution over the channel.

The samplers were mounted at a distance of 2-3 mm below the cut of the cross section in which the measurements were made, which kept them from influencing the hydrodynamic environment within the channel. The separated liquid passed through the sampler to an analytical balance, while the liquid flowing in the form of a film was returned to the entrance of the working section. The total flow rate of liquid was measured with a calibrated standard diaphragm.

The studies were conducted in the range of variation in the washing density of $0.327 \text{ kg/m}\cdot\text{sec} \leq \Gamma \leq 8.64 \text{ kg/m}\cdot\text{sec}$, which at the washing temperature of 15-30° C corresponds to a variation in the Reynolds numbers of from 400 to 11,000. The measurements were conducted in three cross sections along the channel length located at distances of 3, 6, and 16 m from the entrance of the liquid to the working section.

Visual observations and oscillographic recording of the flow of the film (Fig. 1) showed that at a given washing density waves are formed at its surface whose height increases with an increase in the length of travel of the film [3]. Oscillograms of the film surface when $\Gamma = 0.814$ kg/m·sec are presented in Fig. 1. Curves 1-10 pertain to the values $X = 100$, 400, 600, 1000, 1200, 1400, 1800, 2200, 2600, 3000 mm, respectively. The conversion of the potential energy of the liquid into kinetic energy takes place in proportion to the flow down, the rate of movement and surface area of the waves increase, and consequently, the resistance provided by the stationary air core to the wave surface increases. This in turn leads to a further increase in the height of the waves and to deformation of their leading front, which becomes steep (Fig. 1). Separation of liquid from the film surface sets in when the force acting on the surface of the wave

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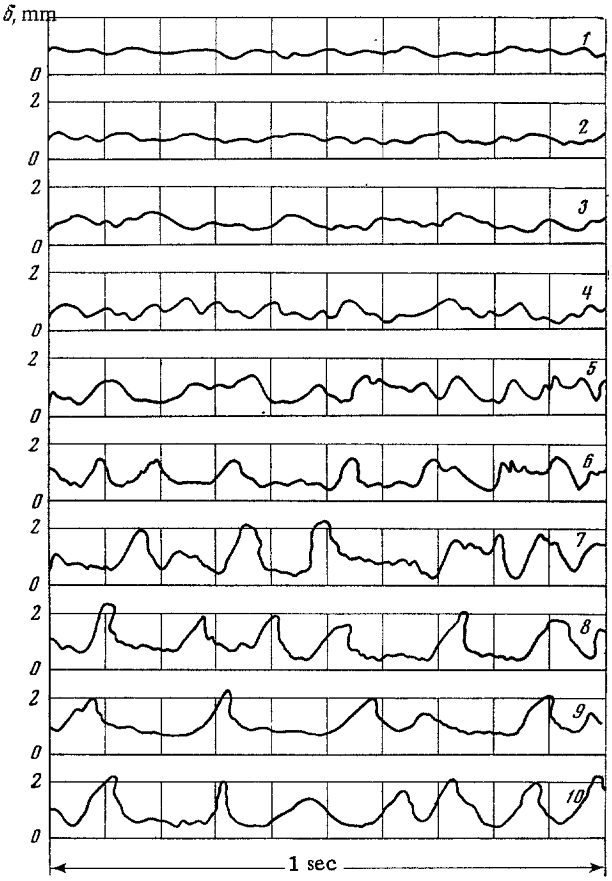

Fig. 1

exceeds the force of adhesion of the base of the wave with the continuous undisturbed layer of liquid. The separated liquid moves under the effect of the force of gravity within the vertical channel and is distributed over the radius of the latter.

The variation in the flow-rate concentration of liquid $(g_i - g_{i-1})/(F_i - F_{i-1})$ over the channel radius in three cross sections along its height is shown in Fig. 2 a) X = 3 m; b) X = 6 m; c) X = 16 m. The difference in the values in the numerator of this expression is the difference between the amount of separated liquid g_i in kg/sec determined by the i-th sampler and the amount of liquid g_{i-1} in kg/sec through sampler i-1, i.e., the weight flow rate of liquid through the area of the annulus formed by samplers i and i-1, equal to $F_i - F_{i-1}$ in m^2. The points designed in Fig. 2 by numbers 1-10 correspond to the values $\Gamma = 8.64$, 6.5, 4.86, 3.1, 2.25, 1.632, 1.308, 0.981, 0.654, and 0.327.

An analysis of the results presented in Fig. 2 indicates that there is a certain amount of liquid at the center of the channel at Reynolds numbers less than the Reynolds numbers characterizing the start of separation during the flow down along the outer surface of a vertical channel and determined in [4]. However, this value does not exceed a fraction of a percent and can be attributed to random separation. In the center of the cylindrical channel there is an almost uniform distribution of separated liquid along the radius with a sharp increase in the flow rate in the region near the wall with a width of 2-5 mm, which is caused by the capture of wave crests by the collecting samplers. An increase in the washing density leads to an increase in the amount of separated liquid at the center of the channel in all three of its cross sections, with the region of largest gradients being shifted somewhat toward the center in accordance with the increase in mean film thickness and in the height of the wave projection. This is especially noticeable in Fig. 2c, pertaining to the cross section located at a distance X = 16 m from the entrance of the liquid to the working section, where the wave height is greatest, the other conditions being equal.

The amount of separated liquid in the central part of the channel, as follows from Fig. 2, increases with the length of travel X of the film. At the highest washing densities $\Gamma = 6.5$-8.64 kg/m · sec studied from 15 to 25% of the liquid supplied to the entrance of the working section belongs to the portion of the central part of the channel bounded by a sampler 40 mm in diameter (Figs. 3 and 4). The notation is the same as in Fig. 2 and X = 6 and 16 m, respectively. This must be taken into account in calculating the mean film thickness, the height of the wave projections, the thickness of the continuous layer, the frequency of the wave motion, and other characteristics through the introduction of the appropriate corrections to the washing density along the length of the channel.

It follows from Figs. 3 and 4 that the total amount of separated liquid with respect to the initial flow rate increases with an increase in the washing density and along the radius of the channel, which in these figures is represented in the dimensionless form $\xi = r/r_0$, where r in mm is the current value of the radial coordinate; r_0 is the inner radius of the channel. The curves generalizing the experimental points on these figures are described up to values $\xi \leq 0.84$ by a general dependence of the form

$$g_i / G = f(\xi^n; \Gamma) \qquad (1)$$

where g_i in kg/sec is the flow rate of liquid through the sampler and G in kg/sec is the total initial flow rate.

The exponent n on the section 6 m $\leq X \leq$ 16 m of flow of the liquid depends linearly on the length of travel of the film

$$n = 2.14 + 0.01\,X \qquad (2)$$

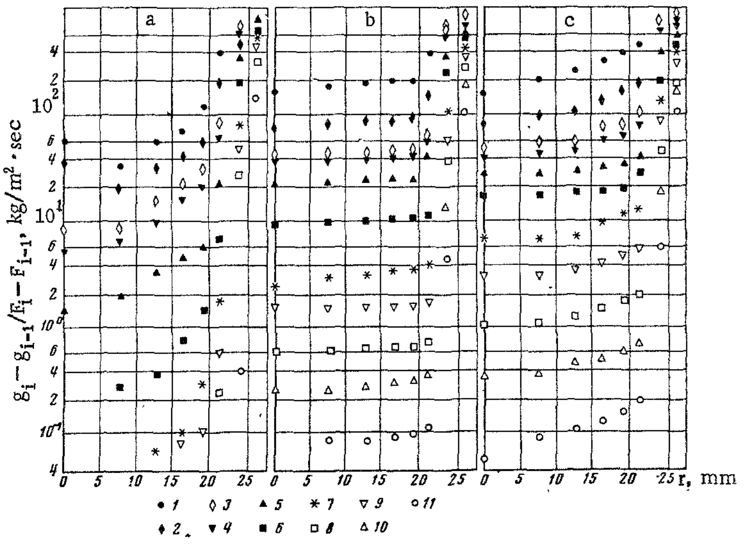

Fig. 2

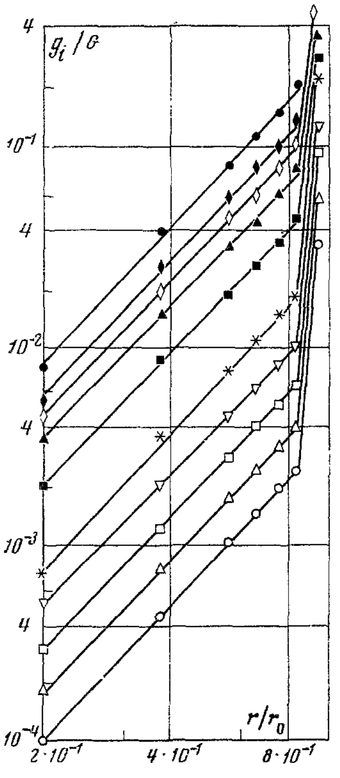

Fig. 3

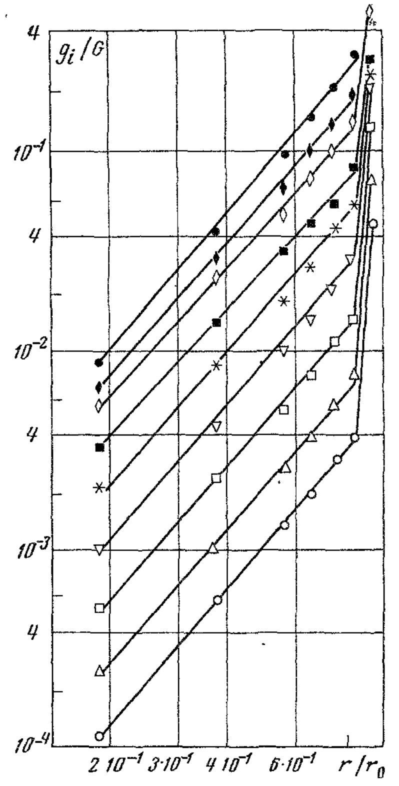

Fig. 4

The dependences (1) and (2) are valid in the region of $\xi < 0.84$, corresponding to free fall of the separated liquid. For $\xi > 0.84$ the liquid moves in a film for the majority of modes studied and a sampler 50 mm in diameter enters the wave crests, which leads to an increase in the flow rate of liquid through it and corresponds to a sharp increase in the slope of the curves in Figs. 2 and 4.

The amount of liquid g_i/G, with respect to the total initial flow rate, entering samplers of different diameters as a function of the washing density Γ is shown in Fig. 5 on a semilogarithmic scale. The points marked by numbers 1-7 are obtained by samplers with diameters of 10, 20, 30, 35, 40, 45, and 50 mm; a, b, and c pertain to X = 3, 6, and 16 m.

The amount of separated liquid entering the sampler increases with an increase in the washing density Γ and can be determined with allowance for Eqs. (1) and (2) by the expression

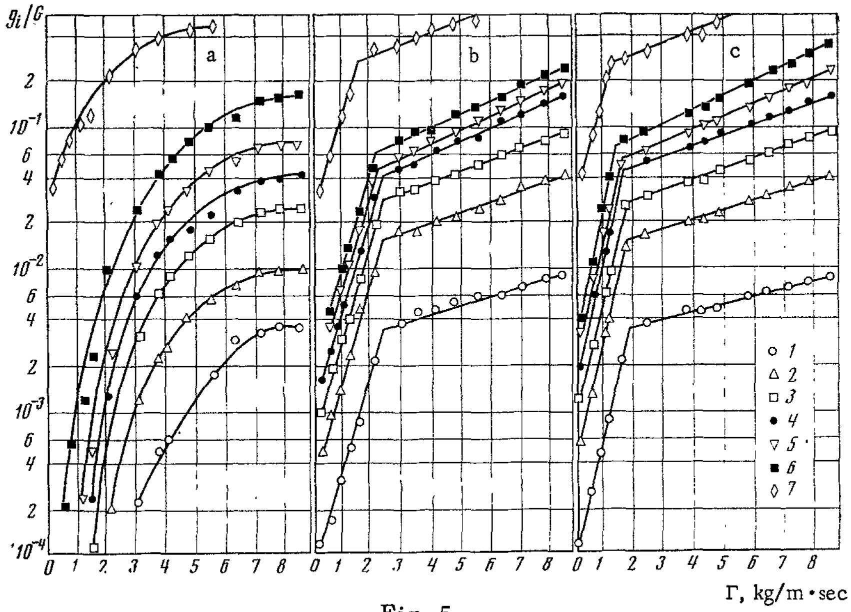

Fig. 5

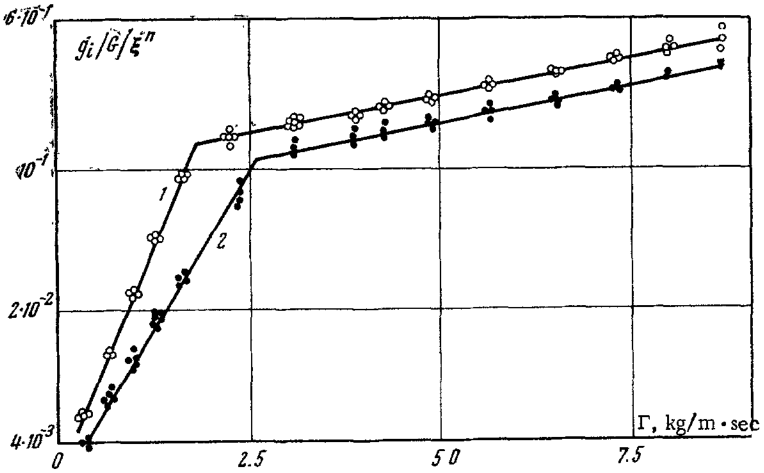

Fig. 6

$$g_i / G = \xi^n \exp (A + B\Gamma) \qquad (3)$$

where A and B are constant coefficients.

It follows from Fig. 5 that for a length of travel of the liquid film $X > 3$, which for a majority of the washing densities studied corresponds to the length of the section of stabilization of the wave motion according to the data of [2, 3], the coefficient B characterizing the slope of the lines remains constant in each of the cross sections studied and does not depend on the diameter of the sample. However, in the cross section $X = 6$ m for $\Gamma \geq (2.0\text{-}2.2)$ kg/m·sec and in the cross section $X = 16$ m for $\Gamma \geq (1.8\text{-}2.0)$ kg/m·sec a sharp drop occurs in the rate of increase in the separated liquid, which is indicated by a decrease in the slope of the curves and accordingly in the coefficient B. The effect is explained by the saturation of the process of separation from the film surface after the separation of the "excess" amount of liquid and by the increasing, starting with a certain washing density, reverse separation of liquid onto the surface of the running film. Based on this, it can be concluded that the process of separation of liquid from the surface of the film in the region of its travel lengths corresponding to $X \geq (6\text{-}16)$ m does not have a cascade nature.

In Fig. 6 the experimental data presented in Fig. 5 are adapted in the coordinates $[(g_i/G)/\xi^n; \Gamma]$. Curves 1 and 2 pertain to the values $X = 16$ and 6 m. The dependences obtained make it possible to determine the amount of liquid separated from the film surface and its distribution over the radius of a vertical cylindrical channel. For the region of washing densities $\Gamma < (1.8\text{-}2.2)$ kg/m·sec the dependence has the form

$$g_1 / G = \xi^{2.14-0.01X} \exp[\Gamma(1.14 + 0.06X) - 6] \tag{4}$$

For the region of washing densities 1.8–2.2 kg/m · sec $< \Gamma \leq$ 8.64 kg/m · sec

$$g_1 / G = \xi^{2.14+0.01X} \exp[0.177\Gamma - (2.17 + 0.03X)] \tag{5}$$

Equations (4) and (5) are valid for X > 3 m, i.e., under conditions of established film flow.

The experiments conducted indicate that because of the return of the separated liquid to the film surface in the case of flow within a vertical channel of great length, the flow of the latter is characterized by a clearly expressed tendency toward stabilization along the length of the channel; in particular, the coefficients on X in Eqs. (4) and (5)have a small value. As a result, the movement of a liquid film over the inner surface of a channel is more stable than during flow over an outer surface when natural reverse separation to the film is almost absent.

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