STATISTICAL CHARACTERISTICS OF THE RIPPLE FLOW OF A LIQUID FILM

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An important factor for many processes in the heat-exchanger systems of electric power plants and chemical engineering equipment is the transfer of heat and mass between a moving or nonmoving medium and surfaces exposed to contact by liquid films, such as condensates. The character of the flow of thin liquid layers and their hydrodynamic structure largely determine the intensity of the processes involved. Numerous studies [1-6] indicate that one of the characteristic stable regimes is the ripple flow of liquid films, which occurs for certain very small Re numbers [1, 2]. In the majority of practical situations [3-6] the characteristics of the ripple surface profile experience a disordered variation. The most effective approach to the analysis of such flows under these conditions is by probabilistic techniques. The presence of harmonics of different intensities and of components of a purely random process are readily discerned through statistical analysis of the parameters of the given flows.

The present investigation is based on the fundamental principles of ripple-flow hydrodynamics [7]; disturbances on the free surface of a liquid layer give rise to longitudinal oscillations of the total layer if the wavelength λ is much greater than the average thickness δ of the liquid layer. This condition, as experiments have shown [2-6], is almost always met in the vertical gravity flow of thin liquid films over a wide range of Reynolds numbers. If a hot-wire anemometer probe is placed on the hard surface over which the film is running, it will record the corresponding velocity fluctuations $u^*(t)$ of the longitudinal oscillations of the liquid layer in the form of voltage fluctuations $e(t) = -Su^*(t)$.

The working section of the experimental apparatus was a rectangular duct with cross section 50 × 100 mm and length 1500 mm, its walls made of plastic. The surface of the duct was well wetted with a uniformly downward-flowing film of ethyl or isopropyl alcohol from a slotted distributing system. Four hot-wire anemometer probes were mounted flush with the working surface of the duct wall at distances of 70, 270, 670, and 1070 mm from the distributing system in the upper part of the apparatus. The sensing elements were nickel thin films (0.5-0.8 μ) prepared by electrochemical deposition on a special stainless steel matrix. After annealing of the samples in an inert nitrogen atmosphere at a temperature of 800°C, bars with dimensions 0.8 × 8 mm were cut out and cemented to the working surface of the plate and then soldered to electrical contacts by a hot-air jet.

The temperature of the dc-heated hot-wire probes was 40-50°C higher than the temperature of the liquid, corresponding to a working current of 0.4-0.8 A, depending on the initial resistance of the hot-wire probe. Under these conditions the time constant of the substrate material without regard for the influence of thermal conduction was about $5 \cdot 10^{-3}$ sec, resulting in approximately a 15% variation of the amplitude-frequency characteristic of the probes at a frequency of 100 Hz. On the other hand, the investigated frequency range of the surface ripple of the films was confined [4, 6] to limits of 50-60 Hz.

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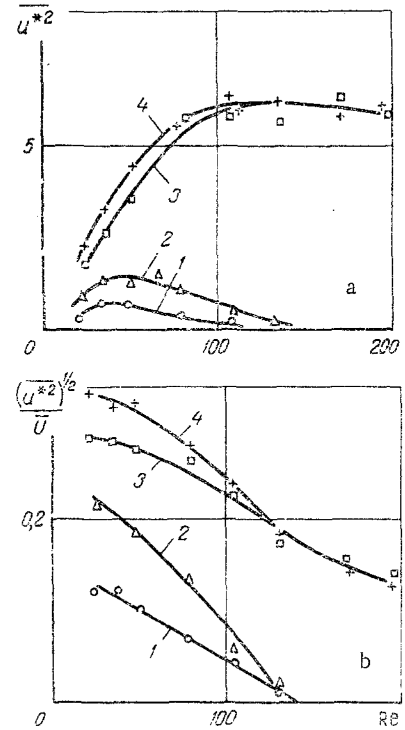

Fig. 1. Intensity of ripple flow of a liquid film. a) Fluctuation velocity squared; b) relative intensity of ripple flow. 1) x/L = 0.05; 2) 0.18; 3) 0.45; 4) 0.73. $\overline{u^{*2}}$ in cm²sec⁻².

The intensity of the downward ripple flow of the film

$$\overline{u^{*2}} = \frac{1}{T}\int_0^T u^{*2}(t)\,dt$$

was recorded by a VZ-5 square-law millivoltmeter as corresponding fluctuations of the hot-wire voltages. The lower frequency limit of the instrument was lowered to 0.5 Hz by preliminary modulation of the input voltage.

To determine the numerical values of $\overline{u^{*2}}$ the hot-wire probes were calibrated by the excitation of oscillations of the liquid mass flow by means of a membrane in the interior of a slotted duct with a cross section 0.6 × 60 mm. The plane membrane was set into transverse oscillations with a small constant amplitude of $9 \cdot 10^{-2}$ mm by a cam mounted on the axle of a miniature electric motor. The entire open-rectangular-calibration mechanism was pressed firmly to the working surface of the plate in the vicinity of the appropriate hot-wire embedding site.

Calibration curves were plotted with allowance for the variation of the system sensitivity with increasing average flow velocity of the film and supply current; the value of the latter was initially selected to make $|S|^2$ identical for all four hot-wire probes. The region of thermal disturbance of the liquid layer by the probes, because the latter were small, did not exceed 2-5% of the average thickness of the flowing film. The dimensions of that region varied only slightly in the course of the experiment, because the calibration and subsequent tests were conducted at a constant probe temperature and the parameter $|S|^2$ was taken directly into account in the calibration. The experimental points obtained in the calibration procedure were satisfactorily approximated by the relation

$$e^2 = |S|^2 \mathrm{Re}^{-1/3}\overline{u^{*2}},$$

where the variation of the fluctuation velocity was simulated by regulation of the motor rpm.

The measurements showed that the ripple flow intensity $\overline{u^{*2}}$ increases on the average with the mass flow of the irrigated liquid. The appreciable maximum of $\overline{u^{*2}}$ observed (Fig. 1a) in the interval of regular ripple flow (x = 70 and 270 mm) is attributable to the motion of the wave-formation boundary and turbulence of the liquid film near the feeding mechanism. On the other hand, in the hydrodynamically stabilized regime (x = 670 and 1070 mm) the values of $\overline{u^{*2}}$, having attained a maximum, then vary only insignificantly as the Reynolds number is increased. It is important to note that as the film runs down the plate the ripple flow intensity increases appreciably, attaining values approximately an order higher for x = 1070 mm than in the initial region x = 70 mm.

The average thickness and average velocity $\bar{U}$ of the film were also determined in the measurements by the standard contact method using a micrometer screw and a fine needle, permitting the relative intensity $(\overline{u^{*2}})^{1/2}/\bar{U}$ to be estimated. For small flow rates (Re < 40) the relative intensity (Fig. 1b) attains maximum values of 0.12-0.35, falling off rapidly with increasing flow velocity of the liquid film.

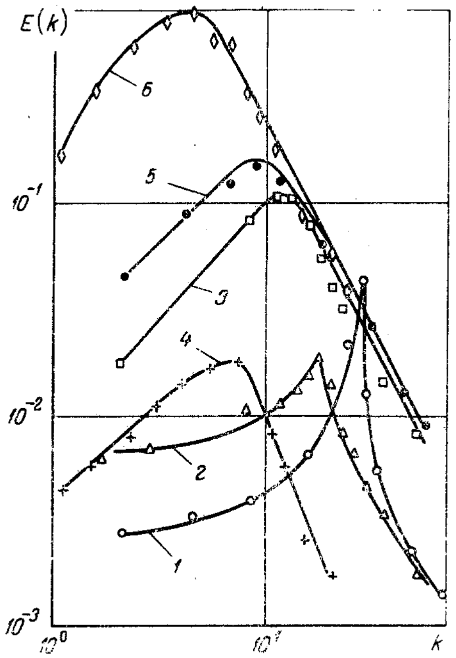

Fig. 2. Energy spectrum E(k) of the film velocity fluctuations. 1,2,3) Re = 38; 4,5,6) Re = 170; 1,4) x/L = 0.05; 5) x/L = 0.18; 3,6) x/L = 0.73. k in cm^{-1}.

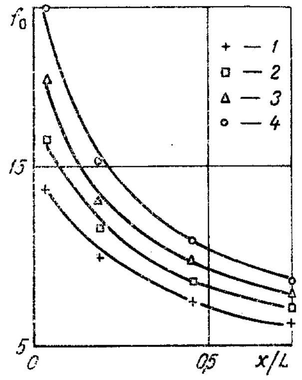

Fig. 3. Variation of frequency f_0 along the wetted surface. 1) Re = 38; 2) 60; 3) 90; 4) 140. The results are given for an isopropyl alcohol film.

The structure of the ripple flow was investigated by statistical analysis of the voltage fluctuations from the hot-wire probes. A heterodyne spectrum analyzer with a bandwidth Δf = 1 Hz was used, its output representing the average value of the amplitude squared of the oscillation components in the frequency band $f \pm {}^1/_2\Delta f$:

$$\overline{u^{*2}}(f,\ \Delta f) \approx \frac{1}{T}\int_0^T u^{*2}(t,\ f,\ \Delta f)\,dt,$$

$$E(f) \approx \frac{\overline{u^{*2}}(f,\ \Delta f)}{\Delta f}.$$

The resulting statistical spectra were normalized to unity and then reduced to the form

$$\overline{u^{*2}} \approx \int_0^\infty E(f)\,df \quad \text{or} \quad \overline{u^{*2}} \approx \int_0^\infty E(k)\,dk,$$

where $k = 2\pi f/\bar{U}$ is the wave number. The areas under the E(k) curves in the corresponding frequency interval of Fig. 2 are equal to $\overline{u^{*2}}$ and characterize the distribution of the ripple flow intensity among the corresponding harmonic frequencies.

The occurrence of a fairly distinct maximum in the E(k) spectra is observed only for the initial flow region x $\leq$ 70 mm, indicating the presence of one or more harmonic components with a distinct periodicity. The broad frequency composition of the spectra from the lower hot-wire probes attests to disruption of the regularity of the ripple profile, which becomes more like a train of solitary large waves. Besides the fundamental harmonic, which corresponds to the frequency of transmission of the crests through a fixed zone near the hot-wire probes, the spectra also include harmonic components determined by the waveform of the solitary crest itself.

The variation of the character of the wave-formation process can be clearly traced through an analysis of the spectral harmonic components at whose frequencies f_0 a large part of the ripple energy is concentrated. As we see in Fig. 3, the rearrangement of the ripple profile with downward flow of the film is accompanied by an abrupt decrease of the characteristic frequency f_0 of the free surface of the film, particularly for small liquid mass flow rates.

We note that even for Re = 300-400, i.e., for values 30 times greater than Re_{cr} (initiation of wave formation), the surface of the flowing film exhibits turbulence near the feeding mechanism. At distances of 300-350 mm or lower the surface acquires a regularly ordered profile, and the corresponding spectra $E(f)$ have a pronounced maximum corresponding to the characteristic frequency f_0.

NOTATION

δ is the average film thickness, mm; $\bar{U}$ is the average film velocity, cm/sec; x is the longitudinal coordinate, mm; L is the length of the experimental section, mm; $u^*(t)$ is the fluctuation velocity, cm/sec; f is the frequency, $\sec^{-1}$; T is the averaging interval, sec; $E(f)$ and $E(k)$ are the energy spectra (frequency, wave number); S is the hot-wire probe sensitivity; $Re = 4\bar{U}\delta/\nu$ is the Reynolds number.

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