AN EXPERIMENTAL STUDY OF THE FLOW OF A LIQUID FILM ALONG A VERTICAL WALL

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Results of a study of the friction stabilization section and thickness of a liquid film flowing along a vertical wall are presented. Spectral analysis of friction pulsations is used to study the transition from laminar to turbulent flow mode in the film.

1. Flow Stabilization. Alekseenko et al. [1] presented results of measurements of mean friction and mean liquid-film thickness over the Rayleigh number range Re = 20-2800 in the known stabilized flow region at a distance of 800 mm from the input slit. That distance was chosen on the basis of theoretical evaluation of the stabilization length of the friction and thickness values [1, 2].

Results of experimental studies of the character of liquid film thickness stabilization are few in number and contradictory. For example, in [3] a complex relationship was found between mean thickness and distances of 800-1000 mm, and the author noted the remarkable increase in mean film thickness in the wave development region. Ganchev and Kozlov [4] indicated a stabilization region in the interval 200-500 mm from the input.

The literature offers no data on stabilization of shear stress on a wall in film type flow. Also, knowledge of the stabilization length is necessary for planning of experiments on film flow and in development of methods for engineering calculations of film heat and mass exchangers using short tubes.

It is known that the character of flow stabilization is dependent on entrance conditions, i.e., on the construction of the liquid distributor and the flow regime therein.

The present study examines the flow of a film over the external surface of a vertical tube 60 mm in diameter. Measurements were performed with the use of two liquid distributors, ring-shaped channels 200 mm in length with slit widths of 0.5 and 1.0 mm, respectively. Careful preparation and centering of the channel permitted attainment of a uniform liquid discharge over the perimeter of the working portion.

Measurement of local shear stress and local liquid film thickness were made with the electrodiffusion and shadow methods described earlier in [1].

Figure 1 presents data on the mean values of shear stress and film thickness in the stabilization zone. Distances are measured from the output edge of the distribution slit. The values τ and δ are referred to their values in the stabilized flow region.

It can be concluded from the curves obtained that thickness and shear stress stabilize almost simultaneously. It is evident that stabilization commences especially rapidly in the case where the film thickness and the output slit of the distributor are equal in magnitude ($h/\delta_0 = 1$).

Figure 2 presents shear-stress stabilization length L as a function of Reynolds number Re for various values of slit width (0.5 and 1 mm). The experimentally defined stabilization length L was taken as the distance from the distributor edge at which the shear stress value differed from its value in the stabilized flow region by no more than 20%. This definition was chosen because the most significant changes in flow occur at a distance x = L, chosen by us as the stabilization length (Fig. 1). Also the

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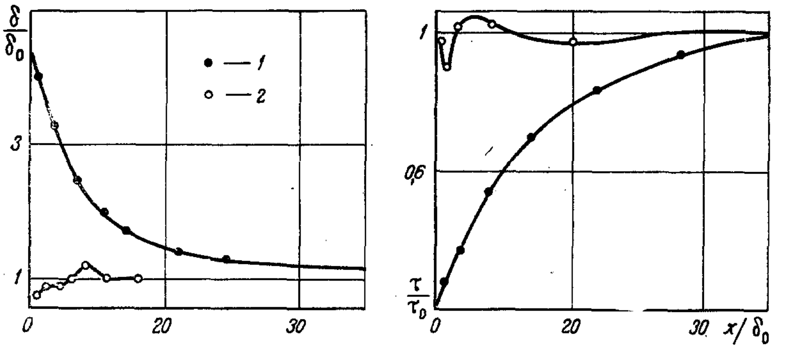

Fig. 1. Change in mean values of friction and film thickness along cylinder length: 1) Re = 75, h/δ_0 = 3.7; 2) Re = 455, h/δ_0 = 1.

further quite smooth change in friction and thickness with increase in x/δ_0 at an experimental error ≈ 7% does not permit a more accurate determination of stabilization length. Figure 2 also shows the theoretical curve calculated in [1] for the case of turbulent flow in the slit and in the film itself for a 1.0 mm slit.

2. Friction Pulsation. In the majority of studies on liquid film flow the transition from laminar to turbulent flow is determined from the inflection in the curves of such parameters as film thickness, tangent stress [1], and heat transfer coefficient [5, 6] as functions of Re. It is evident from the data of these studies that the transition occurs in the range Re = 300-800, it being difficult to determine an exact value Re*, although many authors attempt to do so.

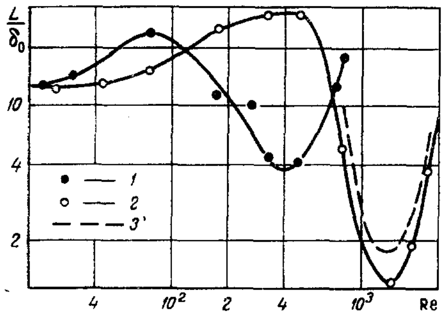

Fig. 2. Tangent shear-stress stabilization length versus Re: 1) h = 0.5 mm; 2) 1.0 mm; 3) theoretical curve of [1].

Since the characteristic peculiarity of film flow is the presence of significant pulsations in the hydrodynamic characteristics even in the laminar wave mode, it is natural to employ spectral analysis for a more detailed study of the transition region.

We will now present the results of spectral analysis of friction pulsation on the wall. Friction measurements were made by the electrodiffusion method described in [1]. Energy spectra of shear stress were calculated from the power spectra of limiting diffusion current in an electrochemical cell. In [7] the following relationship between friction pulsation spectral powers S_τ and diffusion current S_I is given:

$$S_\tau = \frac{S_I \bar{\tau}^2}{F^2 S^2 |H|^2 \bar{q}^2},$$

where $|H|^2$ is the square of the modulus of the transfer function, given with sufficient accuracy by

$$|H|^2 = [(9 + 0.54\bar{\omega}^2)^2 + (0.027\bar{\omega}^3)^2]^{-1/2},$$

where $\bar{\omega}$ is dimensionless frequency

$$\bar{\omega} = 2\pi f \left(\frac{\mu^2 l^2}{\bar{\tau}^2 D} \right)^{1/3}.$$

To measure spectral power of limiting diffusion current pulsations a spectrum analyzer constructed at the Institute of Heat Physics, Siberian Branch, Academy of Sciences of the USSR was used. The analyzer operates on the filtration principle. It consists of a set of end window bandpass filters, a squarer, low pass filter, and recording instruments. The signal studied is applied to the bandpass filter, then squared, averaged by the lowpass filter, and recorded on the paper tape of the recorder.

Spectral density of input signal power is determined from the equation

$$G = k \frac{u^2}{\Delta f_i},$$

where u^2 is the signal at the analyzer input, proportional to the square of the limiting diffusion current, Δf_i is the bandwidth of the i-th filter, k is a correction factor, equal to unity for a filter with rectangular

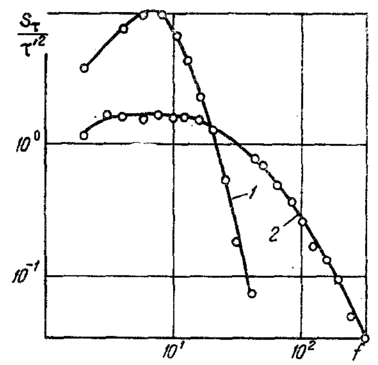

Fig.3

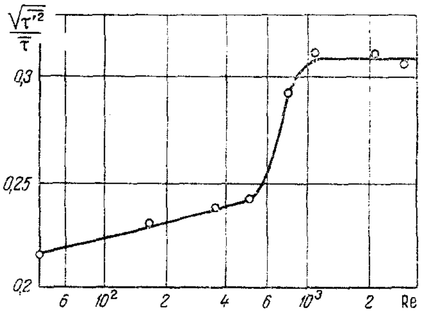

Fig.4

Fig.3. Normalized friction spectrum, 1/Hz, on wall: 1) Re = 50; 2) Re = 2800.

Fig.4. Mean-square shear-stress pulsation versus Reynolds number.

characteristics. For real filters, k is calculated from experimental curves of square of output voltage versus frequency of applied signal.

Averaging time at each of the frequencies was chosen as a function of accuracy required and frequency of the bandpass filter, and reached 20 min. Device reliability was verified with a noise generator. Moreover, the method was also checked by measuring spectral density of friction pulsations on the wall of a circular tube. Results showed satisfactory agreement with the data of a number of authors, obtained by various methods [8].

Dispersion of the shear-stress pulsation was calculated from the equation

$$\overline{\tau'^2} = \sum_i (S_\tau)_i \Delta f_i$$

with the condition that the filter passbands covered the entire frequency range with no gaps. It is also assumed that the change in spectral density over the frequency range Δf_i is small.

Figure 3 shows characteristic friction pulsation spectra for various Re. Measurements were performed at a distance of 800 mm from the entrance in the stabilized mean friction region. It is evident from the graphs that the dominating oscillation frequencies exist in the laminar wave mode. In the turbulent flow mode (Re > 1000) there is a certain relatively wide range of frequencies bearing the major portion of the pulsation energy. In this range the spectrum appears uniform, i.e., analogous to a "white noise" spectrum.

Figure 4 presents shear-stress pulsation-dispersion as a function of Reynolds number Re. The curve is divided into three regions, corresponding to laminar-wave, turbulent, and transition modes. In the case of laminar-wave flow the pulsation level increases slowly with increase in Re, attaining a value of 0.24 at Re = 500. With further growth in Re a sharp increase in pulsation level to 0.32 (Re = 1000) occurs, after which the dispersion remains at a constant value up to Re = 3000, the highest value attained in the experiment.

NOTATION

x, y, Longitudinal and transverse coordinates; δ, film thickness; m; τ, friction on wall, N/m^2; $\bar{\tau}$, mean friction on walls, N/m^2; h, slit width, m; L, stabilization length, m; Q, irrigation density, m^2/sec; Re, Reynolds number (Re = Q/ρ, where Q is equivalent to Γ); q, specific mass flow kg/m^2·sec; F, Faraday number; S, cathode area, m^2; ν, kinematic coefficient, m^2/sec; μ, dynamic coefficient; f, frequency, Hz; l, characteristic dimension; D, diffusion coefficient, m^2/sec; $\bar{\omega}$, dimensionless frequency; H, transfer function; S_τ, friction pulsation spectral density; N^2·sec/m; S_I, current pulsation spectral density, A^2/sec. Indices: 0, equilibrium value; *, critical value.

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