SOME RESULTS OBTAINED ON STUDYING THE FLOW OF LIQUID FILMS BY STROBOSCOPIC VISUALIZATION

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The characteristic features of stroboscopic visualization and the possibilities of using this method for studying the flow of thin films are considered. The velocity field and the field of turbulent pulsations are studied experimentally for the film flow of liquids with Reynolds numbers of R = 40-1770.

The experimental analysis of the kinematic characteristics of liquid films involves a number of special features. First of all, the measurements are made in a thin boundary layer; when even the smallest velocity sensors, such as the filaments of a thermoanemometer or the adapter of a Pitot tube, are introduced into this layer, there may be considerable changes in the structure of the flow, the dimensions of the velocity sensor being commensurable with the linear dimensions of the flow. The use of a thermoanomometer for studying flow in thin layers of liquid cannot be regarded as very efficient, since filaments down to one micron in size are required for measurements close to the wall and particularly inside the viscous underlayer. The manufacture of such sensors and the question of ensuring their stability are complicated problems. A further complication is the existence of a free, undulating surface of the liquid film [1, 2]. Rigorous demands are made upon the cleanness of the whole experimental set-up, since the "quality" of the filament depends very greatly on the state of its surface. Earlier attempts at using a thermoanemometer were restricted to studying simply the average values of the longitudinal velocity component, and only then within the limits of the continuous boundary (wall) layer. The diameter of the filament was in this case ten microns, which could hardly fail to affect the accuracy of the results [1]. For measurement in a thin boundary layer it is essential to allow for the effect of the wall on the readings of the instrument, this influence being very considerable and the determination of the corresponding correction frequently being difficult [3, 4].

In view of all this, visualization methods assume a particular interest [5-7].

In the present investigation we studied the flow of a descending liquid film by the stroboscopic visualization method [6], using a generator producing a train of very strong light pulses [8]. The essence of the method lies in photographing small light-scattering or reflecting particles introduced into the flow and subjected to pulses of illumination from one side. The size of the particles should be less than the scale of the phenomenon under examination, i.e., less than the dimensions of the smallest vortex which may exist in the flow. The time required for the particles to react to an instantaneous change in the character of the flow should be shorter than the shortest time scale of the flow. As "markers" in this investigation we used spherical aluminum particles 2-10 μ in size. A series of flash-lamp pulses gives a series of images of the same particles on the photographic film. The distance between two neighboring images enables us to determine the two components of the instantaneous velocity vector u_x, u_y (the x and y components are respectively reckoned along and across the flow). The measuring system consists of an electronic stroboscope [8] and an optical measuring

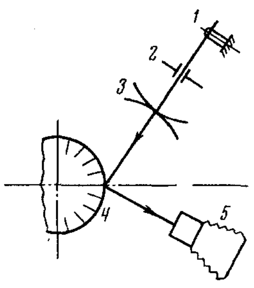

Fig. 1

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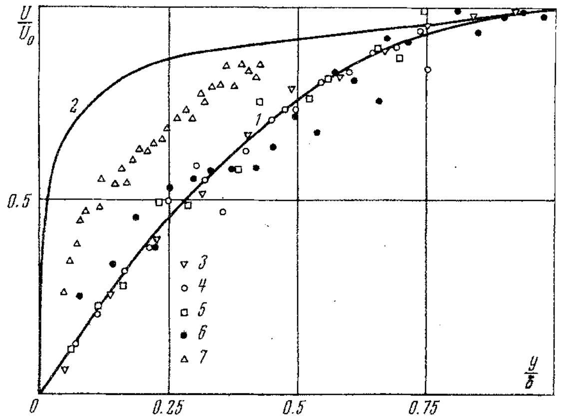

Fig. 2

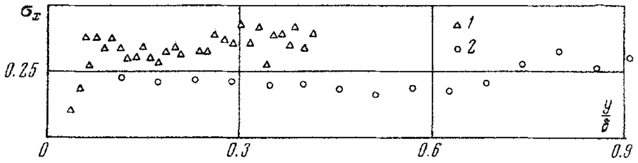

Fig. 3

device (Fig. 1) which contains the light source (a flash lamp 1), an optical slit 2, a high-transmission objective-condenser 3, and the reflecting mirror surface of the working part 4. The beam of parallel rays from the light source illuminates a region 5-8 mm in height and of the order of 3 mm around the perimeter in the liquid. The photographic camera 5 is focussed on the same region, its optical axis being inclined at a certain angle i to the normal of the mirror surface. Control experiments gave the optimum angle as i = 30-40°. The camera is supplied with an attachment giving the magnification required.

The use of visualization methods when studying film flows is complicated by difficulties of coordination (i.e., establishment of position) relative to the solid surface. In contrast to flow in a flat transparent channel [6], there is in this case no reference mark on the bottom of the channel which might be exposed on the photographic film. The problem is also complicated by the existence of a free surface, which in the overwhelming majority of cases has an undulating character [1, 2]. In a number of investigations [9, 10] no coordination was effected at all, and the resultant values of the instantaneous velocity were analyzed on the assumption that there was a uniform distribution of the particles in the liquid film and also that the velocity profile constituted a monotonic curve. However, experiment shows [11] that, even in the case of a uniform concentration of particles at the inlet, the particles distribution in the flow is far from uniform.

The assumption as to the monotonic nature of the velocity profile also meets with the objection that only the profile of the average velocity may be assumed to be monotonic. An optical-mechanical method of coordination was employed in [12]; a short-focus objective with a very small depth of focus (3-5 μ) was placed in a plane perpendicular to the washed surface. All sections right up to the wall were successively illuminated and photographed. In this case the resultant information was extremely limited, since for each individual measurement only a very narrow region was illuminated and photographed, there being a high probability of finding no particle at all in this region. In the most favorable case the factual information was limited to the instantaneous values of the longitudinal velocity component. Furthermore, extremely rigorous demands were imposed upon the accuracy of manufacturing the mechanism used for moving the objective.

In the present investigation we used an optical method of coordination. If the surface of the working part along which the liquid film flows is optically specular, then each particle falling into the frame will have both a real and an imaginary image. In the photographic material we shall have a "double" track of the particle. The real and imaginary images of the particle are symmetrical with respect to the mirror plane and equidistant from it. The distance of the particle from the wall may be expressed in terms of the corresponding coordinates of the extreme images of the tract: ξ_1, ξ_3, the extreme real coordinates of the track, and η_1, η_3, the extreme imaginary coordinates, as follows:

$$y = [(\xi_1 - \eta_1) + (\xi_3 - \eta_3)] /4 \qquad (1)$$

In deciphering the tracks of the particles we must remember that the optical axis of the photographic camera is not perpendicular to the washed surface but inclined at a certain angle i. Since the object of the photograph, the "velocity sensor," lies in a medium with a refractive index n > 1 while the photographic objective lies in air with n = 1, we must take account of the refraction of the incident and reflected light

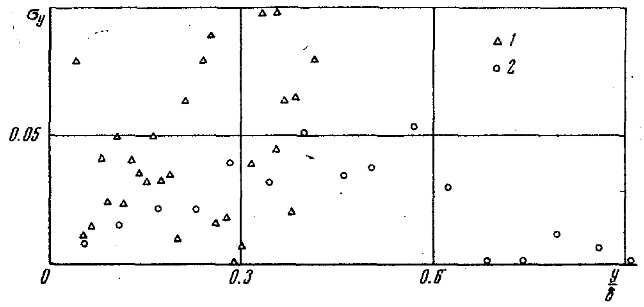

Fig. 4

rays at the boundary of the two media. Allowing for reflection and refraction and the magnification of the objective with the adapter N, the relationship between the real distance from the wall and the value recorded in the photographic material may be written

$$y = \frac{(\xi_1 - \eta_1) + (\xi_3 - \eta_3)}{4N \sin i \sqrt{1 + (1 - n_1^2/n_2^2)\,\mathrm{tg}^2 i}} \tag{2}$$

The structure of the flow was studied in an apparatus the working part of which constituted a vertical cylindrical channel 1000 mm long with a diameter of 43 mm made of Kh18N10T steel. The outer surface of the working section was carefully polished so as to give an optically specular surface. The working liquid, distilled water, was fed to the outer surface of the working section through a slot distributor from a tank with a constant free level.

We studied the velocity and turbulent pulsation fields in a cross section lying at a distance of 530 mm from the entrance, the spraying liquid having a temperature of $t = 23$-28°C and the spraying density being $\Gamma = 0.03$-1.5 kg/m · sec. In this way we studied the liquid film flow for a range of Reynolds numbers (as determined from the thickness and velocity of the film) $R = 40$-1800, i.e., both the laminar-undulatory and turbulent modes of liquid film flow [2]. Figure 2 shows the profiles of the average film velocity expressed dimensionlessly. The distance from the wall is normalized with respect to the film thickness δ, determined by the mass flow and the experimental velocity profile.

The continuous lines represent the quadratic velocity distribution for the laminar mode of flow (1) and the power distribution with a power index $^1/_7$ for the turbulent mode (2). We see from the curves that for low intensities of sprinkling ($R = 40, 60, 140$, points 3, 4, 5 in Fig. 2) there is a fairly good agreement with the parabolic velocity distribution. Thus, despite the existence of wave motion on the surface of the film, the average flow is in fact laminar. The wave phenomena on the surface may be compared with the intermittent nature of the outer boundary of the boundary layer when the average velocity profile remains monotonic. With increasing sprinkling intensity ($R > 200$, points 6, 7), lamination of the velocity profiles occurs, the velocity gradient at the wall increases, the degree of filling of the profile increases, and there is a gradual transition from the laminar-undulatory to the turbulent-undulatory mode of flow. However, even for the greatest sprinkling intensity ($R = 1770$, points 7) the velocity profile still differs considerably from the profile of well-developed turbulent flow based on the $^1/_7$ law (curve 2).

We studied two components of the intensity of the velocity pulsations u_x', u_y'. Figures 3 and 4 show the mean square values of these quantities referred to the mean flow velocity $\sigma_* = \sqrt{\overline{u'^2}}/\bar{u}_x$, $\sigma_y = \sqrt{\overline{u_y'^2}}/\bar{u}_x$ for two modes of flow, $R = 60$ and 1770 (points 2 and 1 in Figs. 3 and 4 respectively).

First of all, we should note the presence of fairly large longitudinal velocity pulsations for all modes of film flow, including low densities of sprinkling. Transverse pulsations were also recorded for all modes of flow, but their intensity was much weaker than that of the longitudinal pulsations, and only for the greatest sprinkling densities did it approach the level of the latter. For low sprinkling densities, corresponding to the quadratic distribution of the mean velocity, the transverse pulsations are an order of magnitude smaller than the longitudinal, their value increasing slightly on moving away from the wall.

For both longitudinal and transverse pulsations there is a clear tendency to increase with increasing density of the sprinkling. The transverse pulsations increase more rapidly.

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