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VELOCITY FIELD IN THE INITIAL SECTION OF A FILM FLOW

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The velocity field in the initial section of gravitational film flows has been investigated analytically and experimentally, and a relationship has been obtained for calculating the length of this section.

The increasingly wide use of gravity flows of thin liquid layers in technological plants has led to an increased interest in recent years in the structure of the flows in films, particularly under the conditions of stabilization of the film [1-10]. In the initial or entry section hydrodynamic stabilization leads to a transformation of the velocity profile from the initial profile which is determined by the conditions for the distribution of the liquid into the film to the fully developed velocity profile, which takes the form of a semiparabola for the single-phase flow of the liquid in the laminar or pseudolaminar regimes. The initial velocity profile depends on many factors: the type of the distributing device and the features of its construction, the inclination and shape of the wetted surface of the wall, the form and dimensions of the wall roughness elements, the properties of the liquid, etc. [7, 10]. In making calculations, it is necessary to isolate the initial section when its length is greater than or commensurate with the total length of the wetted surface. In theoretical investigations the accuracy of the determination of the length of this section is determined by the degree of approximation of the velocity pattern which is undergoing transformation to the fully developed, stabilized profile.

Analytical relationships are known which are either somewhat simplified, and do not take into account the features of the initial liquid distribution into the film, and are unsuitable for small path lengths (for example, the functions of N. A. Gasan or R. Khagen [9]), and which therefore give results which are in poor agreement with the experimental data [3-7], or which have a complicated and inconvenient form and imply only numerical methods of solution [8, 9].

A simplified analytical method of calculating the velocity profile in the initial section was proposed earlier [1, 2, 7] for laminar flow of a wetting film along a vertical surface. A solution of the nonlinear equations of motion in dimensionless form

$$\frac{\partial^2 w}{\partial y^{*2}} - w\frac{\partial w}{\partial x^*} = -g^* \tag{1}$$

for the velocity w was sought in the form of an exponential polynomial. The dimensionless parameters appearing in Eq. (1) are:

$$w = \frac{w_x}{\bar{w}_s};\quad y^* = \left(\frac{\bar{w}_s}{\nu S}\right)^{0,5} y;\quad x^* = \frac{x}{S};\quad g^* = \frac{gS}{\bar{w}_s^2}. \tag{2}$$

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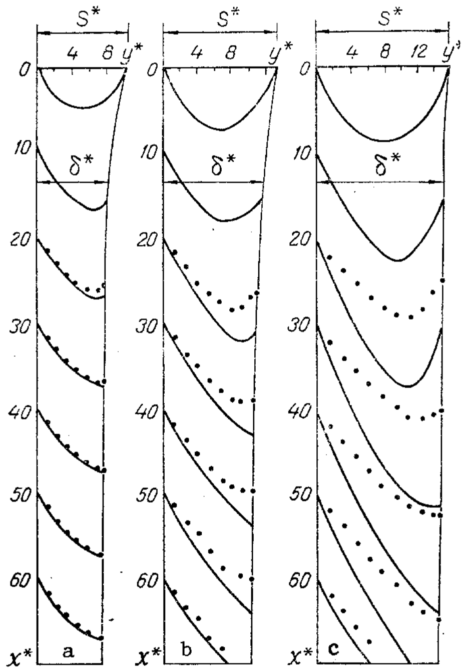

Fig. 1. Dimensionless representation of the local velocities as functions of x* and y* at various values of Re: curve a): Re = 440; curve b): Re = 760; curve c): Re = 988.

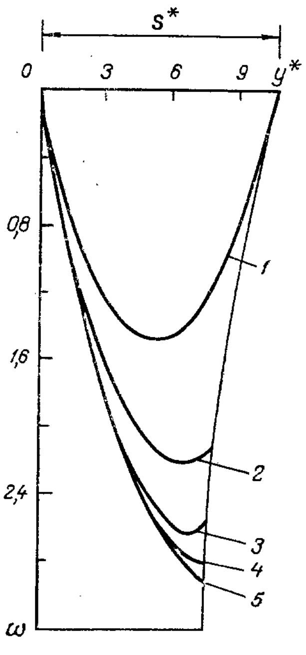

Fig. 2. The dynamics of change of w = f(y*) at Re = 440 and various values of x: 1) x = 0; 2) x = $5\cdot10^{-3}$ m; 3) x = $1\cdot10^{-2}$ m; 4) x = $15\cdot10^{-3}$ m; 5) $3\cdot10^{-2}$ m.

The following relationship was obtained for the velocity profile in the initial section for hydrodynamic stabilization

$$w_x = \overline{w}_s\left[C\left(\frac{\overline{w}_s}{\nu S}\right)^{0.5} y - \frac{g}{2\nu\overline{w}_s}y^2\right] + \overline{w}_s\sum_{i=1}^{5}\frac{f_i(y)}{\left(\frac{x}{S}+\varepsilon\right)^i}. \tag{3}$$

The special feature of function (3) is that it takes into account the initial distribution of the velocity in the flow (at the exit from the slot distribution device in the present case). The validity of using the simplified equation of motion (1) is based on the insignificant change in the local film thickness δ in the entry section. If the optimum conditions for distributing the liquid into the film are chosen [7, 10], then no clearly marked concavity or bulge is formed in the inlet section and the change in the film thickness occurs gradually and approximates asymptotically to the steady-state value δ_{st}, so that the model which has been assumed appears to be quite suitable for small irrigation densities.

In the experimental investigation of the velocity fields in the initial sections use was made of a method based on sequential photography by a camera with a short-focus lens of the paths of spherical particles of aluminum powder of diameter $d \leq 5$ μm introduced into the liquid flow. With powerful illumination, the particles give lines on the photographic film during the exposure period such that the lengths of the lines are equal to the paths of the particles, which makes it possible to determine the vector of the longitudinal velocity component. The mean value of the longitudinal velocity component is determined from a group of eight to ten frames. This method does not make it possible to take into account the transverse velocity component which is about two orders of magnitude smaller than the longitudinal component [3], i.e., the error introduced is less than 1%. The range of velocities to be investigated governed the duration of the exposure which was selected

$$\frac{2d}{w_x m} < \tau_e < \frac{l}{w_x m},$$

which varied in the experiments over the range $\tau_e = 1 \cdot 10^{-2} - 5 \cdot 10^{-4}$ sec.

The optical system consisted of a lamp of power 1.5 kW, a large-aperture lens with a special attachment which made it possible to obtain a twentyfold magnification, and the surface of the working section. The definition was adjusted by a ground-glass and microgrid on the tube surface, and then the camera was moved by means of a micrometer screw in a plane perpendicular to the irrigated surface. The system made it possible to produce photographs at any point over the thickness of the films. The particles which were present within the limits of the depth of field of the lens

$$H = 2AK\frac{m+1}{m^2},$$

gave sharp images in contrast to the particles which were not passing in this zone. In the experiments with a magnification of twenty times, H = 8 μm. The paths were measured directly without printing positives by projecting the images at a known magnification. The experiments were carried out with external irrigation of a stainless steel tube of outside diameter 0.038 m using distilled water at a temperature of 20°C; S = 0.5 mm; $\Gamma_v = (29.4 - 242.3) \cdot 10^{-6}$ m^2/sec; Re = 120-988.

For each series of experiments a definite volumetric irrigation density Γ_v (or Reynolds number Re) was established, and the velocity profiles were measured by the method described above at fixed distances in the direction of flow of the film, x. For the same values of Γ_v and x the theoretical velocity profiles were calculated on a BÉSM-6 computer according to the expression (3) given in [1, 7].

In Fig. 1 the solid lines show the calculated dimensionless film velocity profiles in the hydrodynamic stabilization zone given by the analytical method of [1], and the points represent the results of the corresponding measurements. According to Eq. (2), the dimensionless width of the distribution slot is equal to

$$S^* = \left(\frac{\overline{w}_s}{\nu S}\right)^{0.5} S = \left(\frac{\overline{w}_s S}{\nu}\right)^{0.5} = \mathrm{Re}_s^{0.5}.$$

As the distance from the slot of the distribution device increases, there is a transformation of the velocity profile from the initial parabolic velocity profile at $y^* = S^*$ to the semi-parabolic profile which occurs in the stabilized flow. The film velocity at the outer surface increases correspondingly from zero to a maximum value $w_{fs} = 1.5\bar{w}_{st}$. The experimental data are in good agreement with the proposed relationship (1) in the region of small Reynolds numbers (Re < 320), and even with well-developed two-dimensional wave formation (Re ≤ 450) their deviation is comparable to the experimental accuracy (Fig. 1a). With increasing irrigation density the mixing effect of the waves increases, annular waves appear (closed around the tube) as well as fine capillary waves, and the measured values of the local velocity become considerably smaller than the theoretical values. Thus, the maximum discrepancy between these values is 11% at Re = 684, 32% at Re = 760 (Fig. 1b), and as much as 92% at Re = 988 (Fig. 1c).

Hence, the simplified flow model (1) is confirmed quite well by the experimental data in the region Re ≤ 450. Of course, this does not necessarily mean that the true kinematic structure of the flow is in complete agreement with the limitations which were made in deriving the relationship (1), especially since this did not take into account the development of wave formation on the outside surface of the film.

The dynamics of the transformation of the velocity profile from a parabola into a semi-parabola according to Eq. (1) are shown in Fig. 2. While the change in the local velocity is considerable at small path lengths of the film x over the entire right-hand developing branch of the parabola, at larger path lengths which are close in value to the length of the initial section for hydrodynamic stabilization x_h, this is more noticeable at the outside surface of the film. The length x_h was therefore determined by means of the relationship (3) for the case $y = \delta_{st}$, where the deviation of the calculated value of the velocity at the outer surface of the film from that for fully established flow was taken to be no more than ± 1% [2, 7]. In the zone Re ≤ 450, the relationship which is obtained can be described by the expression $x_h = 6.17\ \mathrm{Re}^{0.45}\ S = 67.3\ \mathrm{Re}^{0.12} \times \delta_{st}$. For the given conditions (Re = 450) the maximum value of x_h was $37.4 \cdot 10^{-3}$ m. It was not possible to determine the length x_h experimentally with sufficient accuracy, since the wave formation at the outer surface of the film (especially when shock waves occurred, Re > 150) did not make it possible to measure the local stream velocities reliably close to the outer surface, particularly since in this zone it is not possible to ignore the transverse velocity component [3-6].

NOTATION

A, value of tolerable disk of unsharpness of negative, mm; C, constant; d, particle diameter, m; $f_i(y)$, function of the transverse coordinate y; g, acceleration of gravity, m/sec^2; H, depth of focus of lens, μm; K, lens opening; l, length of long side of frame, m; m, magnification of image; $\mathrm{Re} = 4\Gamma_v/\nu$, Reynolds number for film flow; $\mathrm{Re}_s = \bar{w}_s S/\nu$, Reynolds number for flow in slot; S, width of slot of distribution device, m; w_{fs}, film velocity at outside surface, m/sec; w_x, local film velocity along x axis, m/sec; $\bar{w}_{st}$, mean film velocity in fully established flow regime, m/sec; $\bar{w}_s$, mean velocity of liquid in slot, m/sec; x, longitudinal (vertical) coordinate of stream, m; x_h, length of initial section for hydrodynamic stabilization, m; y, transverse (horizontal) coordinate of stream, m; Γ_v, volumetric irrigation density, m^2/sec; δ, local film thickness, m; δ_{st}, film thickness in the fully established flow regime, m; δ*, dimensionless film thickness in the initial section calculated by the graphical-analytical method of [2]; ε, constant; ν, kinematic viscosity of liquid, m^2/sec; τ_e, exposure time, sec.

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REFINEMENT OF WALL-TURBULENCE HYPOTHESES

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The correspondence between the hypotheses and the experimental data is examined. The distribution functions of the Prandtl mixing length near a smooth wall and the Komogorov turbulence scale in pipe flow are refined.

Present-day methods for the calculation of heat and mass transfer associated with the turbulent flow of a liquid or gas in pipes and boundary layers are based on semiempirical theories using a certain linear turbulence scale. In turn, various hypotheses are used to determine the turbulence scale, but they have not been corroborated by direct comparison of the calculated and experimental values of the scale. It is customary to test only the correspondence of the proposed hypotheses with the measured velocity profile, and this approach admits differing, occasionally mutually exclusive assumptions in the face of the scatter of the experimental points.

In the case of the mixing length l introduced by Prandtl, e.g., neither of the more precise relations of Prandtl [1]

$$l_+ = \varkappa y_+ \tag{1}$$

or Rotta [2]

$$l_+ = \varkappa (y_+ - y_{1+}) \tag{2}$$

has been determined, where y_{1+} is a quantity roughly equal to the dimensionless thickness of the viscous sublayer. The discrepancy of the results of calculations according to these relations near a wall (for $y_+ \approx 30$) attains 30-50%, which does not meet the accuracy requirements of engineering computations.

Neither has the transition from the quadratic law predicted by L. D. Landau and V. G. Levich [3] for the variation of the mixing length l near a wall to a linear function been determined. According to Sherstyuk's hypothesis [4], the quadratic function is replaced by the linear law (2) at a dimensionless distance from the wall $y_+ = 15$. According to Van Driest's hypothesis [5], this transition is a smooth exponential, which approaches the linear law (1) asymptotically as the dimensionless distance y_+ increases:

$$l_+ = \varkappa y_+ [1 - \exp(- y_+/A_+)]. \tag{3}$$

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