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CALCULATION OF FRICTION AT PERMEABLE SURFACE

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The laws of friction between a stream of fluid and a permeable surface are generalized for bodies of various shapes.

The laws of friction at the surface of a permeable plate have by now been most thoroughly studied in both theory and experiments. Monograph [1], for instance, contains tabulated results of R. Iglish's solution to the problem for a laminar boundary layer with uniformly distributed suction, and in monograph [2] is demonstrated the possibility of self-adjoint solutions to the momentum equation for a laminar boundary layer with suction or injection velocity which varies as a linear function of one space coordinate ($v_0 \sim x$), while in monograph [3] a theory of a boundary layer with vanishing viscosity yields a solution to the problem for a turbulent boundary layer. In the first of these monographs [1] also are reported results of some numerical calculations by the Truckenbrodt and Poechau methods for respectively laminar and turbulent boundary layers with suction. The laws of friction during turbulent flow through a pipe with surface suction have also been studied [4]. The problem of friction during transverse flow across pipes has, however, been explored much less thoroughly.

Here will be reported results of studies made pertaining to that case.

The laws of friction in that case have been established according to the R. Eppler method [5], applicable to both laminar and turbulent boundary layers with suction or injection at bodies of arbitrary shape in an external stream. The method is based on simultaneous solution of the momentum and energy equations

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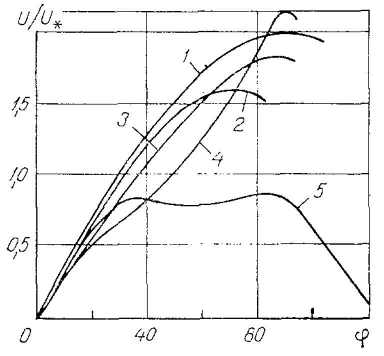

Fig. 1

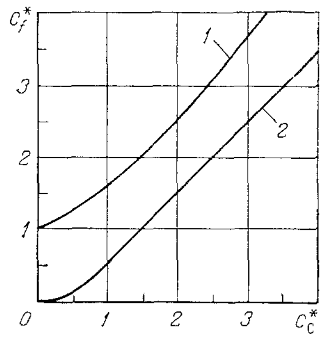

Fig. 2

Fig. 1. Velocity distribution over pipe circumference $U/U_* = f(\varphi)$: 1) pipe in stream with zero-gradient potential flow; 2) pipe in real stream; 3,4) pipe in stream with $K_q = 0.5$ and 0.8, where $U_* = U_\infty(1 - k_q)^{0.5}$; 5) pipe of criss-cross bundle.

Fig. 2. Relation $c_f^* = f(c_c^*)$: 1) suction; 2) injection.

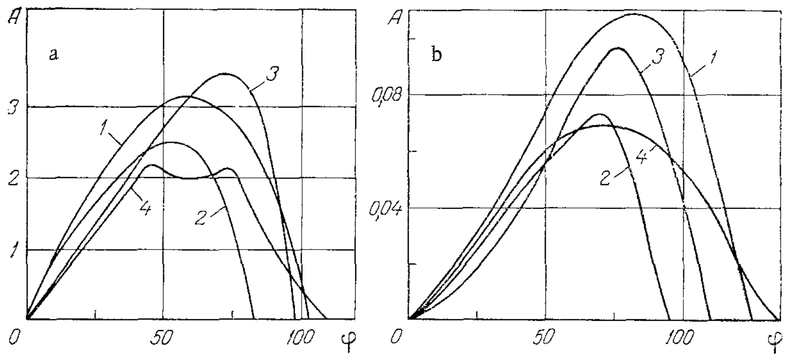

Fig. 3. Distribution of shearing stresses over circumference at $v_0 = 0$ (a — laminar boundary; b — turbulent boundary layer): 1) zero-gradient potential flow around pipe; 2) real stream flowing around pipe; 3) $k_q = 0.45$–0.85; 4) flow around criss-cross bundle; $A = \frac{\tau_c}{\rho U_*^2}\mathrm{Re}^{0.5}$ for (a) and $A = \frac{\tau_c}{\rho U_*^2}\mathrm{Re}^{0.2}$ for (b).

$$\frac{d\delta_2}{dx} = -(2 + H_{12})\frac{\delta_2}{U}\frac{dU}{dx} + \frac{\tau_f}{\rho U^2} + \frac{v_0}{U},$$

$$\frac{d\delta_3}{dx} = -3\frac{\delta_3}{U}\frac{dU}{dx} + 2\frac{(d+t)}{\rho U^3} + \frac{v_0}{U},$$

with $v_0 < 0$ for suction and $v_0 > 0$ for injection; for a laminar boundary layer

$$\frac{\tau_f}{\rho U^2} = \frac{\varepsilon^*}{\mathrm{Re}_{\delta_2}} \quad \text{and} \quad \frac{2(d+t)}{\rho U^3} = \frac{2D^*}{\mathrm{Re}_{\delta_2}},$$

and for a turbulent boundary layer

$$\frac{\tau_f}{\rho U^2} = 0.045716\,[(H_{12} - 1)\,\mathrm{Re}_{\delta_2}]^{-0.232}\exp(-1.260 H_{12}),$$

$$\frac{2(d+t)}{\rho U^3} = 0.01\,[(H_{12} - 1)\,\mathrm{Re}_{\delta_2}]^{-1/6}, \quad \mathrm{Re}_{\delta_2} = \frac{U_{\delta_2}}{\nu_p}.$$

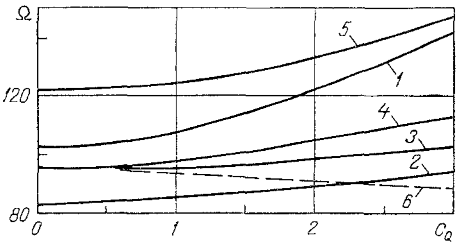

Fig. 4. Dependence of separation angle Ω on permeability c_Q for laminar boundary layer (solid line corresponding to suction, dash line corresponding to injection): 1) zero-gradient potential flow around pipe; 2) k_q = 0; 3) k_q = 0.5; 4) k_q = 0.8; 5) flow around criss-cross bundle; 6) k_q = 0.5 and flow with injection.

The values of functions ε^*, D^*, and of the form factor H_{12} for a laminar boundary layer are given in tables, all depending on the form factor $H_{32} = \delta_3/\delta_2$.

The relation between form factors H_{32} and H_{12} for a turbulent boundary layer is $H_{12} = (11H_{32} + 15)/(48H_{32} - 59)$ [5].

This system of equations was solved on a BÉSM-4M high-speed computer, with $v_0 \sim x^{-m}$ ($0 < m < 0.5$) for laminar and turbulent boundary layers at a plate in a zero-gradient stream and at a pipe with outside diameter d_0 in a transverse stream.

For the plate it was assumed that $U = U_\infty$ = const and $dU/dx = 0$.

For the pipe the velocity distribution over the outside surface of the vaporous boundary layer was assumed to follow the generalized relation based on numerical analysis of experimental data on flow around pipes in channels with various obstructions [6]:

$$\frac{U}{U_\infty} = A_1^* \frac{x}{d_0} + A_2^* \left(\frac{x}{d_0}\right)^3 + A_3^* \left(\frac{x}{d_0}\right)^5, \quad A_1^* = 3.6314\left(1 + \frac{k_q}{2}\right),$$

$$A_2^* = -2.1709(1 - 12.128k_q^{2.226} + 3.7376k_q),$$

$$A_3^* = -1.5144(1 + 18.542k_q^{2.277} - 6.878k_q),$$

with the obstruction factor k_q defined as the ratio of pipe diameter to channel width.

Such a velocity distribution is also characteristic of pipes bundled into a gallery across a stream with a longitudinal pitch $S_2/d \geqslant 3$. The actual velocity distribution over a pipe in gallery bundle with $S_2/d < 3$ is more intricate than that [6], because in this case the stream makes contact with such a pipe at a point shifted from the $\varphi = 0$ location facing the stream by an angle of up to 55° depending on the longitudinal pitch of the bundle and on the Reynolds number.

The studies have revealed, moreover, that the impact point is close to the $\varphi = 0$ location when the Reynolds number is low and approaches the $\varphi \simeq 55°$ as the Reynolds number reaches ∿4000, a further increase of the Reynolds number resulting in a reversal of the shift back to the $\varphi = 0$ location. For this reason, the velocity distribution shown in that study [6] is valid only as a first approximation for a close-packed gallery bundle of pipes.

The velocity distribution characteristic of criss-cross bundles [6] is shown in Fig. 1, along with the velocity profiles used for our calculations.

The separation angle was determined from the condition that $\tau_f = 0$ for a laminar boundary layer and from the condition that $H_{32} \sim 1.58$ for a turbulent boundary layer [1, 5].

Calculations were made for the cases of laminar flow retained over the entire surface, turbulent flow sustained throughout the boundary layer, and a turbulent boundary layer over a part of the surface only (the corresponding transition point was determined according to the Eppler method [5]).

An analysis of the results of our calculations for a transverse potential flow across a pipe [7, 8] and also of the other results [1-4] indicates that the distribution of local shearing stresses within the region of nonseparation flow with either laminar or turbulent boundary layer can be generalized, accurately enough for practical purposes, by one-parameter relations covering the case of suction and the case of injection. These relations are depicted in Fig. 2, where $c_f^* = c_f/c_{ac}$; $c_c^* = c_c/c_{ac}$; $c_f = 2\tau_f/\rho U_*^2$; $c_c = 2A/Re^m$; $c_{ac} = 2v_0(U/U_*)/U_*$; and $U_* = U_\infty$ for flow around a plate or $U_* = U_m$ for flow inside a pipe.

The values of A and m in calculation of c_c for flow around a plate and for flow inside a pipe were determined in accordance with the well-known Blasius and Prandtl formulas. The values of A for various velocity profiles in a stream flowing around a pipe are given in Fig. 3, with m = 0.5 for a pipe under a laminar boundary layer and m = 0.2 for a pipe under a turbulent one. The boundary layer was in all cases found to become turbulent at $Re \approx 1.5 \cdot 10^5$.

The graph in Fig. 4 depicts the dependence of the separation angle Ω on the intensity of transverse flow for a laminar boundary layer, based on the solution to the system of equations. In the case of a turbulent boundary layer the angle Ω was not found to depend noticeably on c_Q over the c_Q = 0-3 range.

Therefore, in all said cases of transverse flow the local shearing stresses in boundary layers are determined by those in the two extreme cases: stream of nonpermeating fluid and stream with maximum intensity of transverse flow.

The results of the preceding analysis suggest that the graphical relation in Fig. 2 can be regarded as a universal one for flow through channels and around axisymmetric bodies.

NOTATION

x, longitudinal coordinate; φ, angle read from the frontal point on a cylindrical surface; v_0, transverse velocity of a fluid; δ_2, momentum thickness of a boundary layer; δ_3, energy thickness of a boundary layer; U, velocity of flow at the outer edge of a boundary layer; U_∞, velocity of the oncoming stream; d, pipe diameter; U_*, determining velocity; U_m, mean velocity over a pipe section; c_f, friction coefficient at a permeable surface; c_c, friction coefficient in the case of zero transverse flow; c_{ac}, friction coefficient in the case of intense transverse flow; $c_Q = v_0\sqrt{Re}/U_*$, permeability.

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