TURBULENT FLOW ON A PERMEABLE PLATE UNDER STRONG BLOWING

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Results are elucidated of an analysis of turbulent flow on a permeable plate under strong blowing, and computational dependences are proposed for the velocity distribution.

The uniform injection of nitrogen into an air stream was investigated. The flow is isothermal, and the free-stream velocity is 13 m/sec. The experiments were performed on a gas-dynamic installation equipped with interferometric and thermoanemometric apparatus [1]. Porous nickel plates (132 × 40 mm²) were mounted in the lower wall of a channel of 40 × 40 mm² section. The upper flexible wall of the channel permitted elimination of the longitudinal pressure gradients that occur with injection.

As experimental investigations [2-4] indicate, under definite injection intensities $F = \rho_w V_w / \rho_e U_e$, the parameter governing the flow is not the complex $2F/C_{f_0}$ but F. Independence of the flow from the free-stream number $Re_x = U_e x/\nu$ results in similarity of the velocity profiles represented in the coordinates

$$U/U_e = f(y/\delta_0), \tag{1}$$

where δ_0 is a measure of the flow width (δ, δ^*, or δ^{**}). It is noted that the similarity can be disturbed at the beginning and ending of the permeable plate due to the influence of the previously included section and the stream broadening in the neighborhood of blowing cutoff [3]. The flow property noted is observed when the boundary layer is separated from the wall. The absence of solid boundaries for the stream here, and, therefore, of a laminar sublayer as well, results in the reconstruction of the boundary layer from a near-wall to a free type, which means independence of the flow from Re_x also. Experimental investigations [3-5] show that the minimal blowing intensity $F = F_{cr}$ for which the flow is independent of Re_x corresponds to a linear velocity distribution over almost the whole boundary-layer thickness. Such a profile agrees with the velocity profile in the domain of turbulent-boundary-layer separation from a wall [6] obtained on impermeable surfaces under different conditions, particularly on wing profile models, in diffusors, etc. Values of F for which a free boundary layer is realized are referred to strong blowing in this paper. The minimal value of F corresponding to strong blowing was taken equal to F_{cr}. Analysis of the experimental papers [2-4, 7, 8] showed that a linear velocity profile occurs for the value $F_{cr} \approx 2\%$. This corresponds to the data of the present investigations. An exception is [9], in which $F_{cr} \approx 1\%$, which is apparently associated with the nonisothermy of the flow.

The authors' test data on the mean velocity distribution in the boundary layer are presented in Fig. 1 for strong blowing for two sections. As F increases, the velocity profiles are reconstructed from linear to S-shaped characteristics for the main section of jet flow. It is seen that the velocity profiles in the section x/L = 0.38 agree for blowing intensities of $F \approx 3\%$ and higher. The similarity noted is not conserved for the section x/L = 0.72 since cessation of the blowing is felt upstream. The velocity profiles in the section x/L = 0.38 agree with the data of other investigations of boundary layers with blowing as well as with experimental data for a half-jet [10]. Comparison with the results of a computation for a half-jet [11] also permits an assessment of the good enough agreement between the velocity profiles for the two kinds of flows (Fig. 2).

The minimal value of the blowing intensity for which the velocity profile with blowing agrees with the jet profile ($F \approx 3\%$) is close to the ratio between the gas suction velocity from the environment into the half-jet and the main stream velocity (3.2%).

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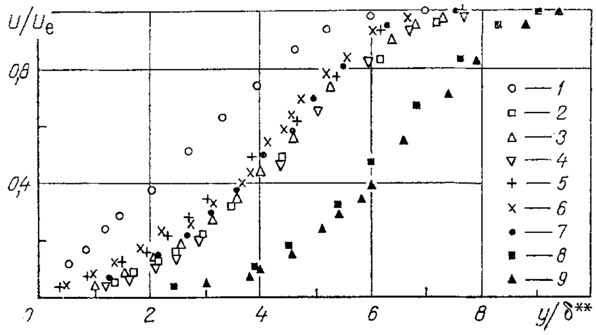

Fig. 1. Average velocity profiles on a permeable plate under strong blowing: $x/L = 0.38$: 1) $F \cdot 10^2 = 2.1$; 2) 3.1; 3) 4.0; 4) 5.1; 5) $F \cdot 10^2 = 3.1$ [8]; 6) $F \cdot 10^2 = 2.9$ [3]; 7) [10] (jet); $x/L = 0.72$: 8) $F \cdot 10^2 = 4.0$; 9) 5.1.

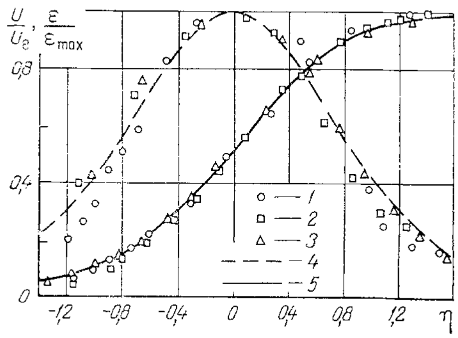

Fig. 2. Distribution of turbulent velocity fluctuations and comparison of the average velocity in a boundary layer with blowing with velocity profiles for the half-jet: $x/L = 0.72$: 1) $F \cdot 10^2 = 3.1$; $x/L = 0.38$: 2) $F \cdot 10^2 = 4.0$; 3) 5.1; 5) U/U_e computation [11]; 4) $\varepsilon/\varepsilon_{max}$ computation (2).

Profiles of the turbulent velocity fluctuations with strong blowing are represented in Fig. 2. For $F \geqslant 3\%$ the profiles agree for different F and x and are described satisfactorily by the approximation formula

$$\varepsilon/\varepsilon_{max} = \mathrm{ch}^{-2}\eta. \tag{2}$$

Here ε_{max} is the maximal value of the rms fluctuation in the velocity vector in the boundary layer; the reduced coordinate is $\eta = [(y_i - y_{max})/x]\sigma$ for the velocity fluctuation distribution, and $\eta = [(y_i - y_c)/x]\sigma$ for the mean velocity distribution; y_i is the running coordinate; and y_{max} is the coordinate at which $\varepsilon = \varepsilon_{max}$. The coordinate y_c corresponds to the distance from the wall where $U = 0.5U_e$; $\sigma = (db/dx)^{-1} = 13.5$ is a growth parameter, and b is the displacement layer width between $(U/U_e)^2 = 0.1$ and 0.9 [12].

Agreement between the velocity profiles for strong blowing and a jet permits utilization of formulas to compute the velocity distribution in a half-jet [11] for flows with blowing for $F \geqslant 3\%$. Here, the distance from the wall y_c where $U/U_e = 0.5$ can be used as the characteristic point permitting assessment of the location of the separated boundary layer relative to the wall. Because the boundary layer is free under strong blowing, then as already noted, F and not $2F/C_{f_0}$ will be the parameter governing the flow. It hence follows that thickness y_c should grow linearly downstream and be independent of Re_x, which is also verified by the formula

$$y_c = kFx, \tag{3}$$

obtained on the basis of a generalization of the experimental data. It follows from the results of the present tests that

$$\begin{aligned} k &= F \cdot 10^2 + 1 \quad \text{at} \quad 2\% \lesssim F \lesssim 3\%, \\ k &= 4 \quad \text{at} \quad F > 3\%. \end{aligned} \tag{4}$$

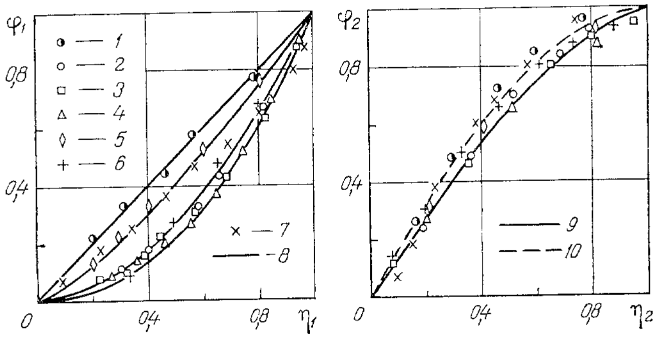

Fig. 3. Influence of strong blowing on the mean velocity distribution in the inner and outer boundary-layer domains: x/L = 0.38: 1) $F \cdot 10^2 = 2.1$; 2) 3.1; 3) 4.0; 4) 5.1; 5) $F \cdot 10^2 = 2.43$ [7]; 6) $F \cdot 10^2 = 2.93$ [2]; 7) $F \cdot 10^2 = 2.9$ [3]; 8) computation (8); 9) computation (10); 10) computation (11).

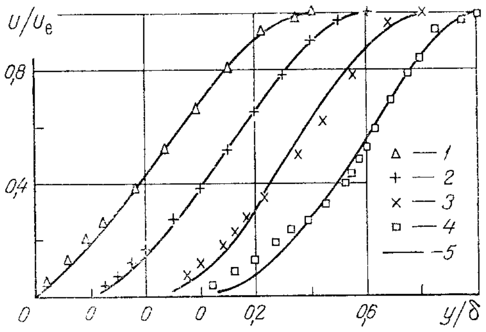

Fig. 4. Comparison of the velocity distributions in the boundary layer, computed by (8) and (10), with the experimental data: 1) $F \cdot 10^2 = 2.12$; 2) 2.43 [7]; 3) $F \cdot 10^2 = 3.1$ [9]; 4) $F \cdot 10^2 = 2.9$ [3]; 5) computation using (8) and (10).

It is detected that the quantity y_c differs slightly from δ^* and is connected with it by the relationship

$$y_c = \delta^*/1.044. \tag{5}$$

Since

$$\delta^{**} = Fx \tag{6}$$

for strong blowing, then it follows from (3)-(6) that the form parameter $H = \delta^*/\delta^{**}$ can be determined from the formula

$$H = (F \cdot 10^2 + 1) \cdot 1.044 \text{ at } 2\% \lesssim F \lesssim 3\%,$$
$$H = 4.176 \text{ at } F > 3\%. \tag{7}$$

Analysis of the results obtained permitted establishment of the similarity of the velocity profiles in the domain $U/U_e \leqslant 0.5$ for fixed values of F represented in the coordinates $\varphi_1 = U/U_c$ and $\eta_1 = y/y_c$ (here $U_c = 0.5U_e$). The velocity distribution can be approximated by a power-law dependence of the form

$$U/U_c = (y/y_c)^n, \tag{8}$$

where

$$n = F \cdot 10^2 - 1 \text{ at } 2\% \lesssim F \lesssim 3\%,$$
$$n = 2 \text{ at } F > 3\%. \tag{9}$$

Velocity distributions are presented in Fig. 3 for this domain as computed from (8) for $F \cdot 10^2 = 2$, 2.4, 2.9, and 3, as well as for experimental results of the authors and from [2, 3, 7]. Satisfactory agreement is observed between the experimental and the computed data.

It should be noted that a separation zone occurs for strong blowings at the wall. It is shown in [13] that fluctuations of varying sign are observed here with the identical probabilities for the positive and negative velocities, indicating "swinging" of the fluid mass around the mean position. Such "swinging" can be the result of the influence of external factors, for instance, the effect of the regular large-scale vortex structure of the separated boundary layer. The longitudinal component of the average velocity in the separation is zero in practice. Taking the velocity distribution in the form (8) down to the wall, we thereby neglect the separation zone; however, this assumption is not essential since the thickness of this domain is less than 1% of the boundary-layer thickness [13].

The velocity distribution in the outer flow domain $0.5 \leqslant U/U_e \leqslant 1$ can be determined from the approximate dependence

$$(U-U_c)/(U_e-U_c) = 1-[1-(y-y_c)/(\delta-y_c)]^{3/2} \tag{10}$$

or by using an expression obtained on the basis of the Hintze formula [14]:

$$U/U_e = 1-\cos\left\{\pi\left[0.5+\frac{y-y_c}{2(\delta-y_c)}\right]\right\}. \tag{11}$$

This is verified by the satisfactory agreement between computations using the formulas presented and the results of the present investigations, as well as with the data of other authors represented in Fig. 3 in the coordinates $\varphi_2 = (U-U_c)/(U_e-U_c)$ and $\eta_2 = (y-y_c)/(\delta-y_c)$.

The law for the growth in external zone thickness along the isotach $U/U_e = 0.5$ is close to the change in turbulent-boundary-layer thickness on an impermeable plate. The thickness of this zone $\delta_1 = \delta - y_c$, determined along the normal to the plate surface, can be computed from the formula

$$\delta_1 \approx (0.37x\mathrm{Re}_x^{-0.2})/\cos\alpha, \tag{12}$$

where $\cos\alpha$ is the angle between the plate surface and the isotach $U/U_e = 0.5$. The quantity δ_1 is determined with the previously included section in front of the permeable surface taken into account.

A comparison of the velocity profiles over the whole boundary-layer thickness, obtained by using (8) and (10), with the test data presented in Fig. 4 again confirms that these formulas describe well enough the velocity distribution in a boundary layer with strong blowing.

Therefore, by separating the boundary layer into exterior and interior domains with an interface passing through $U/U_e = 0.5$, and utilizing (8) and (10), information can be obtained about the velocity distribution in a boundary layer with strong blowing ($F \geqslant 2\%$). In conclusion, it should be noted that such a nature of the flow with strong blowing with a free boundary layer indicates a possibility of using the jet model to analyze a boundary layer with blowing.

NOTATION

x, y, coordinates along and normal to the plate surface; U, V, horizontal and vertical velocity components; H, form parameter; δ, boundary-layer thickness; δ^*, displacement thickness; δ^{**}, loss of momentum thickness; ν, kinematic viscosity coefficient; ρ, density; Re_x, Reynolds number in the longitudinal coordinate; F, blowing parameter; L, plate length; σ, growth parameter; ε, rms velocity vector fluctuation; k, constant in (3); n, constant in (8); Subscripts: e, for conditions on the boundary-layer outer boundary; w, for conditions on the wall.

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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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