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DATA ON THE STRUCTURE OF THE WALL REGION OF A TURBULENT BOUNDARY LAYER ON AN IMPERMEABLE SURFACE WITH INJECTION

V. T. Kiril'tsev, V. P. Motulevich, and É. D. Sergeivskii

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Methodological aspects are examined in regard to measurements of the components of longitudinal velocity in the wall region of a turbulent boundary layer, and measurements are presented in the case of simultaneous injection and acceleration and turbulence of the main flow.

As is well known, the structure of a flow near the adjacent wall directly determines heat and mass transfer processes and momentum transfer through the turbulent boundary layer. However, for most cases of practical importance, the structure of the flow has been adequately studied only in its external part. The experimental data available for the internal part near the wall is insufficient and often conflicting. This stems from the difficulty of obtaining measurements near the wall (for example, in measurements with a hot-wire anemometer, the difficulty includes allowing for the effect of the proximity of the wall and the high level of turbulence in the wall region on measurements of mean velocity, the spatial resolution of the transducer and the orientation of its tip relative to the wall, and the strict requirement of parallelism of the transducer wire and the wall in measurements of longitudinal-velocity components). Obtaining such measurements is made even more complicated in the presence of mass transfer and acceleration. The velocity field near a permeable wall with injection in a nongradient flow was examined in detail in [1-3], while the same near a nonpermeable wall in the presence of a substantial ($K = (-1.5\text{-}4.0)\cdot 10^{-6}$) pressure gradient was studied in [4].

In experimental study of characteristics of a turbulent boundary layer, the central problem is measuring the skin friction coefficient on the wall C_f. The result obtained in [4] is extremely important in this regard. This study made a comparison of eight common methods of determining C_f: when measuring C_f on a nonpermeable wall in the presence of a pressure gradient, preference should be given to the methods based on the assumption of a linear distribution of the mean component of longitudinal velocity $\overline{U}$ next to the wall. It was found experimentally in [1, 2] that the measurements of $\overline{U}$ next to a porous wall in a nongradient flow with injection agree well with the linear relation $\overline{U}$ = const y. In [3], the authors interpreted their test data in the wall region, obtained by the method of flow visualization in a channel in the presence of injection, as agreeing satisfactorily with the

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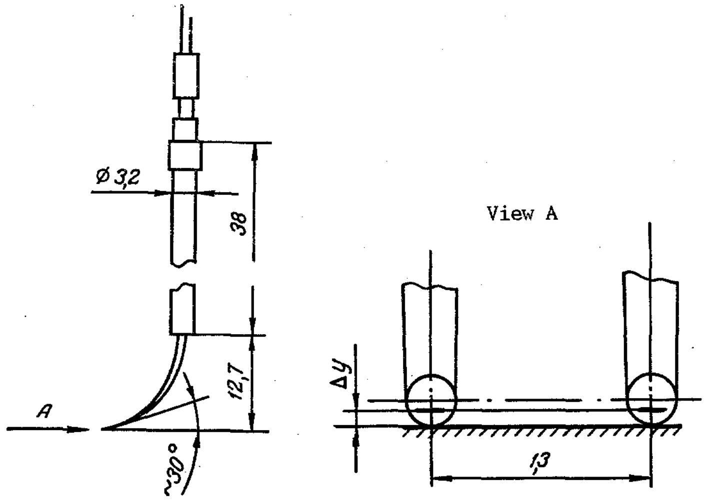

Fig. 1. Design of thermoanemometric transducer 1218-T1.5.

exponential relation $U_+ = [\exp(V_w^+ y_+) - 1]/V_w^+$. However, this data can also be represented as agreeing satisfactorily with the relation $U_+ = y_+$.

In the present article, we report on an experimental study of the field of the longituinal-velocity components in the wall region of a turbulent boundary layer developed on a porous wall of a short rectangular channel with the simultaneous action of uniform isothermal injection ($V_W(x)$ = const), a negative pressure gradient, and turbulence in the main flow (the negative pressure gradient was regulated by changint the position of the flexible upper wall, while the level of turbulence of the main flow was regulated by replacing the honeycomb grids installed in the inlet main of the wind tunnel in [5] with a grid having a geometry such that there was not significant change in the transverse scale of turbulence at the channel inlet).

Experiments were conducted with a thermoanemometric apparatus (without a linearizer) operating in the regime in which the temperature (resistance) of the transducer wire was constant. The apparatus was designed and made at Kazakh State University, while the model 1218-T1.5 transducer was made by the "TSI" company. The transducer had a platinum wire 0.005 mm in diameter (wire length 1.3 mm). A diagram of the transducer is shown in Fig. 1. This transducer design was chosen on the basis of the following considerations: first, perturbations created by the transducer in the case of free flow about it may reduce the measured values of the $\sqrt{\overline{U'^2}}$ component of velocity by about 8% when the transducer is positioned coaxially with the flow and increase these values by about 11% when it is positioned normal to the flow, the exact magnitude of the change depending on the configuration of the transducer [6]; second, the studies [7-9] showed that measurments of both the mean and fluctuation components of longitudinal velocity in the wall region of a turbulent boundary layer are significantly affected by the angle of location of the legs of the transducer relative to the wall. Thus, it follows from [7, 8] that values of mean velocity measured at $y_+ < 10$ may be twice as great when the legs are normal to the wall as when they are at an angle of about 1°. This difference is smaller, the greater the ratio of the length of the wire l to its diameter d [7]. Tests conducted in a plane channel with a transducer with $l/d = 240$ [7] showed that mean velocity approaches zero no worse when the legs are located at a 45° angle than when they are positioned at a 1° angle relative to the wall. However, only profiles obtained with the transducer legs at an angle no greater than 5° coincided in [8].

As concerns the measurements of the $\sqrt{\overline{U'^2}}$ velocity component in the wall region of the turbulent boundary layer, the following can be concluded on the basis of the available empirical data: a more reliable result is again obtained when the legs of the transducer are located at an angle $0 \ll \alpha \ll 90°$ relative to the wall.

The need to accurately determine the distance of the wire from the wall places more stringent requirements on the process of welding the wire to the transducer legs. After the wire was welded, we measured the distance Δy (Fig. 1) with a KM-6 cathetometer to within ±0.005 mm: a transducer having a wire free of sag was considered suitable for measurements

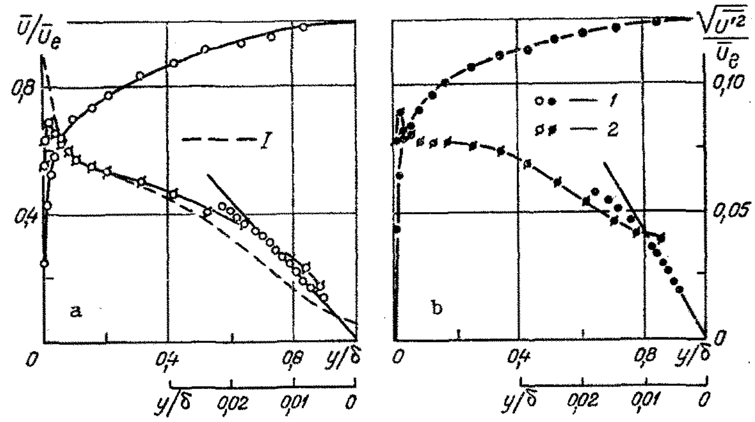

Fig. 2. Distribution of the components of longitudinal velocity at F = 0; a) $\bar{U}_e$ = 20.21 m/sec, K = 0, ε_e = 0.50%, δ = 9.50 mm, Re_{**} = 1284, H = 1.37, I — Klebanov's data [13]; b) $\bar{U}_e$ = 21.17 m/sec, K = $0.21 \cdot 10^{-6}$, ε_e = 1.85%, δ = 11.50 mm, Re_{**} = 1283, H = 1.34; 1 and 2 — $\bar{U}/\bar{U}_e$ = $\sqrt{\overline{u'^2}}/\bar{U}_e$ respectively.

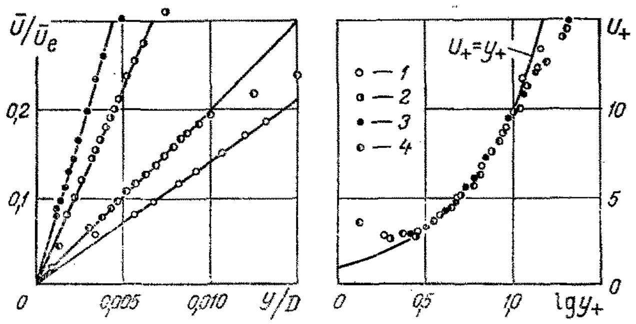

Fig. 3. Profile of mean component of longitudinal velocity in the wall region: 1) K = 0, F = 0.01, ε_e = 0.50%, Re_{**} = 4412; 2) K = $0.25 \cdot 10^{-6}$, F = 0.0072, ε_e = 0.35%, Re_{**} = 3024; 3) K = $1.38 \cdot 10^{-6}$, F = 0.0076, ε_e = 1.30%, Re_{**} = 2455; 4) K = 0, F = 0.01, ε_e = 2.50%, Re_{**} = 4137, D = 40 mm is the width of the channel.

(i.e., a transducer with a wire which did not go beyond the limits of the viewing line of the cathetometer). To be judged suitable, however, the transducer also had to produce values of Δy for both legs not differing by more than 0.02 mm. The mean value of Δy was usually located within the range 0.03-0.05 mm.

As the "zero" reading we took the point of contact of the legs with the surface of the wall, which was determined by closing the electrical circuit (the porous plate was made of nickel, with the mean height of the roughness elements equal to about 0.02 mm, pore size about 0.008 mm, and a porosity of 65-70%). The parallelism of the wire relative to the surface of the wall was checked visually through an optical lens with fourfold magnification and "obliquely" focused illumination of the transducer: the wire was considered to be parallel to the surface of the wall when no light was seen under either leg of the transducer at the moment of contact (at the moment of closure of the electrical circuit).

The minimum distance with which the experiments were begun was 0.06 mm. The transducer was moved laterally by a coordinate device with graduations of 0.01 mm.

Stability of the calibration curve over at least 200 h of continuous operation under the conditions of the experiments was assured by the method devised to prepare the transducers for measurements and by the purity of the air in the channel. Air purity was improved by installing an FP-100U filter-absorber at the inlet of the tunnel.

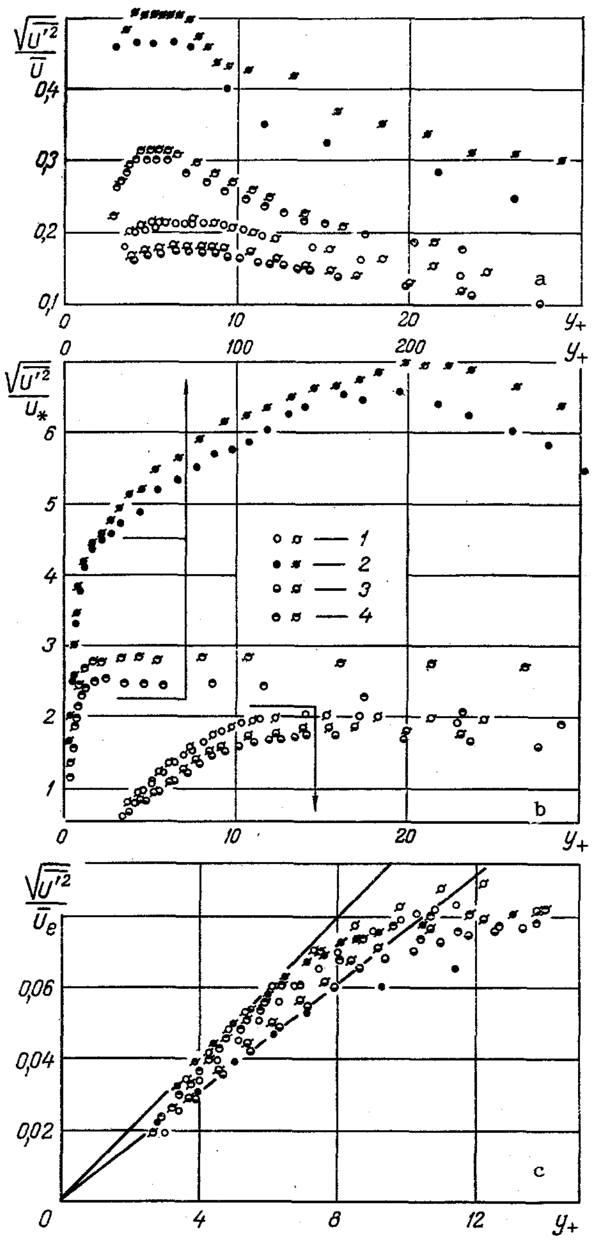

Fig. 4. Profiles of the dimensionless fluctuation component of longitudinal velocity in the wall region: 1) $K = 0$, $F = 0$ at $\varepsilon_e = 0.50$ and 2.50%, $Re_{**} = 1284$ and 1332 respectively; 2) $K = 0$, $F = 0.01$ at $\varepsilon_e = 0.50$ and 2.50%, $Re_{**} = 4412$ and 4137 respectively; 3) $K = 1.20 \cdot 10^{-6}$, $F = 0$ at $\varepsilon_e = 0.35$ and 1.60%, $Re_{**} = 800$ and 846 respectively; 4) $K = 1.38 \cdot 10^{-6}$, $F = 0.0076$ at $\varepsilon_e = 0.35$ and 1.30%, $Re_{**} = 2215$ and 2455 respectively.

The difference in the temperatures of the air flow during calibration and direct measurement, which nearly always exists, was taken into account by the method proposed in [10]. The measurements of the longitudinal velocity components were corrected for the effect of the turbulence level by the method in [11]. The method proposed in [12] was used to allow for the effect of the closeness of the wall on the mean-velocity measurements. As regards the effect of the proximity of the wall on measurements of the fluctuation component of velocity, there are no quantitative estimates for this case. However, it is quite reasonable to assume that the wall introduces only an additive component to the measurement error, i.e., that the level of the measured anemometer signal is simply shifted along the calibration curve into the high-velocity region. Thus, despite the fact that the output voltage of the anemometer is higher near the wall than its initial value, the turbulence intensity corresponds to the measured values of the voltage components, while the fluctuation velocity was determined only after a correction was introduced for the effect of the proximity of the wall.

It was not possible to study the effect of the material of the wall on the size of the correction (all of the results in [12] were obtained for a steel wall). This was because the longitudinal-velocity components shown in Fig. 2 (all results in Figs. 2-4 were obtained in a section located 337 mm from the beginning of the channel) and obtained in the absence of injection and with a zero or small negative pressure gradient indicate that the mean component of longitudinal velocity $\bar{U}$ changes almost in accordance with a linear law $\bar{U}$ = const y near the wall under the given conditions. This well-known experimental fact is evidence of the reliability of the measurements of $\bar{U}$ near the wall.

Comparison of the measured profile of $\sqrt{\overline{U'^2}}$ at $dP/dx = 0$, $V_W = 0$ and with turbulence in the main flow $\varepsilon_e = 0.5\%$ versus the data obtained by Klebanov [13] (Fig. 2a) for a fully developed turbulent boundary layer at $dP/dx = 0$, $V_W = 0$ and $\varepsilon_e = 0.02\%$ shows a marked difference in the wall region in terms of both the magnitude of the maximum and its position. However, the profiles of mean velocity turnout to be nearly the same. This result can be attributed to the presence of a convergent duct (convergence factor 5.37, length 80 mm) at the channel inlet (inlet cross section 40 × 78 mm, length 430 mm). The length of the channel is clearly inadequate for the formation of a fully developed turbulent boundary layer on the wall and a fully formed fluctuation structure. At the same time, the fact that the mean-velocity profile is fuller than would normally be expected for an undeveloped turbulent boundary layer can be attributed to the effect of the convergent duct — the insufficient time that the flow is in the channel (in all of the measurements, the velocity at the channel inlet was about 20 m/sec) for complete restructuring of the velocity profile from the fuller profile typical of flow in a convergent duct to the less full profile typical of a developed turbulent boundary layer on an impermeable plate with $dP/dx = 0$, i.e., this is nothing more than the manifestation of the history of development of a turbulent boundary layer. This conclusion is supported by the following:

1) the position of the maximum of $\sqrt{\overline{U'^2}}$: its relative coordinate y/δ is somewhat greater than that obtained by Klebanov, which is typical of a turbulent boundary layer in a converging channel;

2) the value of the skin friction coefficient C_f, determined from the condition of linearity of the profile of $\bar{U}$ near the wall ($3.6 \cdot 10^{-3}$), is 15-16% lower than the value calculated from the commonly used empirical relation of Ludwig and Tilman ($4.25 \cdot 10^{-3}$) for a developed turbulent boundary layer. A similar result was obtained in [4] for the flow after the convergent section of the channel.

It must be noted that, due to the inadequate spatial resolution of the hot-wire anemometer, the maximum of $\sqrt{\overline{U'^2}}$ that is obtained is always lower than the actual value. Analysis of the studies [8, 9] shows that the maximum of $\sqrt{\overline{U'^2}}$ is 15-20% lower when obtained with a transducer having a wire 0.005 mm in diameter and 1.3 mm in length than in the case of a diameter of 0.002 mm and length of 0.48 mm [9]. However, when the wire is welded to the lower half-plane of the ends of the transducer legs as it was in our case (see Fig. 1), the values of $\sqrt{\overline{U'^2}}$ component of longitudinal velocity that are obtained are overstated [8]. Based on this, the measurements of $\sqrt{\overline{U'^2}}$ will obviously not be more than 10% lower than the actual values. Thus, the most likely and principal reason for the reduced level of fluctuations near the wall is the lack of development of the turbulent boundary layer, which is related to the presence of the convergent duct.

In experimental studies of the velocity fields near a permeable wall, in the presence of injection, thermoanemometric measurements of mean velocity will be affected by transverse velocity $\bar{V}$ because in this case the readings of a single-wire transducer will correspond not to the velocity $\bar{U}$ but to a vector with the modulus $\sim\sqrt{\bar{U}^2+\bar{V}^2}$. This question was examined from a methodological point of view in [1]. The effect of the tranverse velocity $\bar{V}$ on measurements of $\bar{U}$ will obviously be substantial only when these velocities are comparable. The latter can be expected to be true, in turn, only at small distances from the wall when injection is present. In our tests, the injection velocity, with an error of 6%, was no more than 0.202 m/sec. In addition, if we take into account that measured values of velocity$\geqslant$2 m/sec were considered reliable (i.e., this is the lower limit for which the calibration relation is valid in the range up to about 30 m/sec) and that the transverse gradient $\bar{V}$ is small near the wall, it is not hard to estimate the error introduced by transverse velocity

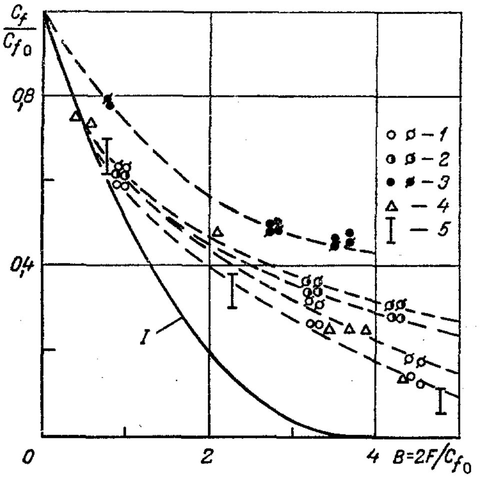

Fig. 5. Effect of injection on the skin friction coefficient (data is shown for two sections located 275 and 337 mm from the channel inlet): 1) K = 0, Re** = 986-4412 at ε_e = 0.40-0.50% and 2.40-2.50% respectively; 2) K = $(0.20\text{-}0.28)\cdot 10^{-6}$, Re** = 940-3260 at ε_e = 0.35% and 1.60-1.85% respectively; 3) K = $(1.38\text{-}1.65)\cdot 10^{-6}$, Re** = 600-2455 at ε_e = 0.35 and 1.30-1.45% respectively; Δ) data from [15]; K = 0, ε_e = 0.13%, Re** ≤ 5000; 5) scatter of empirical points for the data in [16]; K = 0, $\varepsilon_e \approx$ 1%, Re** ≤ 5000; I) Leont'ev–Kutateladze limit law.

in the measurement of $\bar{U}$. Here, we use the expression $\bar{U}_{msm} = \sqrt{\bar{U}^2 + V_W^2}$ = 2 m/sec, which is 0.51% of the actual value of $\bar{U}$. This error quickly decreases going away from the wall. Thus, no correction was made for the effect of transverse velocity V on the measurements of $\bar{U}$. The data obtained shows that the velocity $\bar{U}$ changes near the wall in accordance with a law close to the linear law $\bar{U}$ = const y. The correction for the proximity of the wall begins to "work" beginning with the coordinate $y_+ \approx 3.0\text{-}3.5$ for all the conditions investigated, which confirms the initial conclusion reached by the authors of this method. The data in Fig. 4a and b on the distribution of the $\sqrt{\overline{U'^2}}$ component of velocity shows appreciable modification of the fluctuation structure of the flow in the wall region of the turbulent boundary layer. As concerns the turbulence intensity in the main flow, its effect on the fluctuation structure increases markedly in the presence of injection. Here, it must be noted that along the channel the level of turbulence $\varepsilon_e = \sqrt{\overline{U_e'^2}}/\bar{U}_e$ of the main flow changes in relation to the flow regime (channel geometry). Thus, with $d\bar{P}/dx = 0$, ε_e increases from 0.35% in the inlet section to 0.50% in the control section when a honeycomb grid is in the inlet main of the wind tunnel. The value of ε_e increases from 2.25 to 2.50% when the substitute grid is in the main (a similar change in ε_e was noted in [1]). This evidently is connected with the deviation of the upper wall of the channel to ensure the regime with dP/dx = 0, i.e. with the certain degree of divergence of the channel; at dP/dx < 0, the value of ε_e remains nearly the same in the first case but decreases in the second case. It follows from Fig. 4b that the maximum of $\sqrt{\overline{U'^2}}/U_*$ at dP/dx $\leqslant$ 0 and F = 0 is located in the region y_+ = 14-16. A similar result was obtained in [14].

Let us turn our attention to the presence of the region with $\sqrt{\overline{U'^2}}/\bar{U} \approx$ const (Fig. 4a) near the wall ($4 \leqslant y_+ \leqslant 9$). A similar result was obtained in [14] in a flow in a channel with parallel nonpermeable walls. It follows from Fig. 4c that in the same region $4 \leqslant y_+ \leqslant 9$ the change in $\sqrt{\overline{U'^2}}$ is close to the linear relation $\sqrt{\overline{U'^2}}$ = const y under all of the conditions studied. Thus, the quantity $\sqrt{\overline{U'^2}}/\bar{U}$ may be close to a constant only when the velocity $\bar{U}$ in the same region changes according to a law close to linear $\bar{U}$ = const y. Consequently, analysis of the fluctuation characteristics of a turbulent boundary layer for the flow conditions studied here confirms that the mean velocity $\overline{U}$ changes according to a law which is close to linear $\overline{U}$ = const y near the wall. In general, the data in Fig. 4c provides evidence of the complex and ambiguous dependence of the quantity $\sqrt{\overline{U'^2}}/\overline{U}_e$ on external influences. The only feature of fluctuation structure which is common to all of the flow conditions studied is the presence of the section $\sqrt{\overline{U'^2}}/\overline{U} \approx$const in the region $4 \leqslant y_+ \leqslant 9$.

Figure 5 shows measurements of the skin friction coefficient C_f found from the slope of the mean-velocity profile near the wall. Here, the value of C_{f0} was determined from the well-known Schultz–Grunov empirical relation: $C_{f_0}=0{,}37\left[\lg\left(\frac{x\overline{U}_e}{\nu}\right)\right]^{-2{,}584}$, where x = 0 at δ_{**} = 0 for the regime with F = 0 and K = 0. The value of C_{f0} was calculated separately for each level of turbulence in the channel inlet. It can be seen that the results obtained at K = 0 agree well with the data of other authors. At the same time, the experimental results are layered in regard to both the acceleration parameter K and the level of turbulence in the main flow ε_e: the greater the value of K and ε_e, the higher the location of the measured values of C_f. However, the greater K, the smaller the effect of ε_e. Thus, it can be assumed that the scatter of C_f measured by different authors with the same values of F and Re_{**} under the conditions K = 0 may be the result of different values of ε_e (especially for large values of the injection parameter B). The fact that the experimental points at K = 0 lie above the theoretical Leont'ev–Kutateladze curve can also be attributed to the effect of low Reynolds numbers Re_{**} and the presence of the turbulent external flow. The effect of the latter in the presence of injection was studied in [17].

NOTATION

$K = \frac{\nu}{\overline{U}_e^2}\frac{dU_e}{dx}$, acceleration parameter; ν, kinematic viscosity; $\overline{U}$ and $\sqrt{\overline{U'^2}}$, mean and fluctuation components of longitudinal velocity; V, transverse velocity; l and d, length and diameter of wire of hot-wire anemometer; P, static pressure in the flow; $y_+=yU_*/\nu$ and $U_+=\overline{U}/U_*$, dimensionless coordinate and velocity; $U_*=\sqrt{\tau_W/\rho_W}$, "friction" velocity (dynamic velocity); τ_W frictional stress on the wall; $F = \frac{\rho_W V_W}{\rho_e \overline{U}_e}$, intensity of injection; $B = 2F/C_{f_0}$, injection parameter; C_f and C_{f_0}, skin friction coefficient under specific flow conditions and for developed turbulent flow on an impermeable wall with dP/dx = 0 in the same section; $Re_{**}=\delta_{**}\overline{U}_e/\nu$, Reynolds number; δ_{**}, momentum thickness; $\varepsilon=\sqrt{\overline{U'^2}}/\overline{U}$, turbulence intensity. Indices: e, main flow; W, wall.

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LOSS OF A PASSIVE IMPURITY IN A TURBULENT VORTEX RING

É. I. Andriankin and P. A. Pryadkin

UDC 532.72

A diffusion boundary-layer approximation is used to obtain an analytic solution to the problem of the loss of a passive impurity by a turbulent vortex ring.

Turbulent vortex rings have long interested many investigators due to the relative ease of obtaining them, the transfer of impurities and their travel over long distances, the long-term stability of the rings, etc. Thus, here we study the possibility of making practical use of vortex rings to remove smoke and harmful gases at industrial plants, to remove contaminants from the walls of various types of containers, etc.

There are many methods of organizing vortex rings [1]: surface explosion of a large quantity of explosive [2], injection of a liquid of one density into a liquid medium of a different density [3, 4], etc. Henceforth, for the sake of definiteness we will have in mind a turbulent vortex ring (TVR) obtained in a container filled with smoke (a Wood box [5]) and having an explosive charge on its bottom. However, the theory proposed here is applicable for other methods of producing vortex rings.

There are two types of TVR's created by a vortex generator: toroidal [3, 6, 7], which loses nearly all of the impurity it transports during its motion; ellipsoidal [8]. In contrast to the former, the latter are formed by preliminary agitation of the flow, such as by the installation of a metal grid in the working part of the generator nozzle. In this case, small quantities of impurity are lost in the wake. The resulting vortex consists of a core — a toroidal vortex — surrounded by a moving shell having the form in the direction of motion of an oblate ellipsoid of revolution. Continuity of the velocity field outside and inside the vortex is maintained (similar to the motion of a drop in a liquid). The main losses of passive

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