INVESTIGATION OF ORGANIZED STRUCTURES IN THE NEAR-WALL TURBULENT BOUNDARY LAYER ZONE ON A PLASTICALLY DEFORMABLE SURFACE

O. A. Likhachev

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At this time there is no doubt about the exceptional role of the "explosion" phenomenon: a nonstationary quasiperiodic process in whose concluding stage an abrupt ejection of delayed vortical fluid from the wall occurs in the domain of the turbulent boundary layer core, in the generation of near-wall turbulence. On the whole, this process has been studied well in definite stages of development. Its most important element is organized structures in the form of counter-rotating longitudinal vortices located in the viscous sublayer zone and their accompanying "streaks" — small retarded fluid jets [1]. The connection between the streaks observed during flow visualization and the above-mentioned coherent structures is displayed in [2]. A mean transverse scale of the coherent viscous sublayer structures, which was $\lambda_+ \sim 100$ in near-wall scale units, is obtained as a result of numerous experiments [3-6]. It is assumed that the "explosion" phenomenon is associated with an unstable mode of mean velocity profile in the streak zone. Unstable perturbations with a large growth increment result in streak separation from the wall and its subsequent intensive destruction, which is indeed recorded as the "explosion" phenomenon. Up to certain times no reliable model existed for the mechanism for the origination of pairs of counter-rotating longitudinal vortices of the scale being recorded although hypotheses were expressed about the relation of these vortices to the nature of Goertler vortices on a curvilinear surface [7] where the appropriate streamline curvature is produced by large-scale vortices located at the turbulent boundary layer core. However, this hypothesis has still not been developed further. The question is apparently resolved in [8], where a mechanism is proposed for which the idea of direct resonance realized [9] for a broad class of laminar flows is underlying.

A change in the mean scale of the coherent structures is observed when using different control factors in order to reduce the surface friction of the turbulent boundary layer. As a rule, an increase in the mean scale of the structures [10, 11] accompanies diminution of viscous friction. However, there are data of another nature. Thus, elastic surface deformation under the action of a turbulent boundary layer were studied in [12]. The longitudinal surface deformations were associated with the presence of the vortex system considered above in the near-wall boundary layer zone. An increase in surface friction was recorded in addition to growth of the characteristic scale of the structures. In general, the question of the influence of a deformable surface on the viscous friction of a turbulent boundary layer has remained open up to now. There is information about both the substantial reduction in viscous friction and about its increase [12-14].

Coherent structures existing in the near-wall turbulent boundary layer zone are studied in this paper by their "imprint" left on a plastically deformable surface. The method of visualizing the streamlines of near-wall turbulent flow was used by Prandtl [15] by using a liquid oil dye superposed on a streamlined surface. After several minutes a system of alternating bands of dye and dyeless solid substrate occurs on such a surface (Fig. 1). Prandtl gave no explanation of this phenomenon while representations existing at that time about coherent structures in a viscous sublayer permit finding the explanation of such an effect by connecting these two phenomena.

As investigations showed, the above-mentioned method of studying the near-wall structure of the turbulent boundary layer permitted disclosure of a number of interesting phenomena accompanying the flow above a plastically deformable surface. In particular, the question occurs of the possible diminution of viscous friction on such a surface since the results obtained indirectly yield a foundation for this hypothesis.

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1. EXPERIMENTAL INVESTIGATIONS

The action of a turbulent boundary layer on a plastically deformable surface was studied in an open flume with a 5 × 17 cm rectangular nozzle section for a U = 5.62 m/sec water flow velocity. A 17 × 50 cm rectangular plate of H = 3 mm thick organic glass with rounded-off leading edge was placed at a distance L = 5 cm from the nozzle in the middle section of the flow to eliminate boundary layer separation. Before starting the installation, the plate was colored with a natural oil dye. After build-up to the working mode, fine-scale wave motion accompanied by a slow dye flow under the action of the tangential stress of the free stream could be observed on the color surface. After 2-3 min a longitudinal structure of alternating strips of slowly flowing color and color-free substrate starts to appear on the streamlined surface. Then the surface pattern is stabilized and exists a sufficiently long time until a considerable part of the dye is removed by the stream. Represented in Fig. 1 is a photograph of the surface at the stage of stabilization of the structure formation process. The distance from the plate leading edge is x = 0.32-0.38 m.

In order to obtain information about the general nature of the flow in the boundary layer, measurements are performed of the mean velocity profile on the plate without dye (Fig. 2) by using a Pitot tube with D = 0.4 mm outer and d = 0.2 mm inner diameters. The mean velocity profile was measured at a distance of x = 0.475 m from the plate leading edge. The velocity is referred to the dynamic velocity $u_+ = 0.287$ m/sec, which was determined by the wall law by the Clauser method [16] with Karman constant $\varkappa = 0.41$. The Reynolds number over the momentum loss thickness is $Re_\theta = 6070$. It is seen from the measurement results that under given free stream conditions a developed turbulent boundary layer is realized on a smooth plate.

For the surface pattern represented in Fig. 1 to be realized, the fluid motion in the intervals between the dye strips should have a velocity component transversal to the main flow. A flow produced by a pair of counter-rotating vortices located between these strips can correspond fully to such a motion, i.e., coherent structures whose presence in the near-wall turbulent boundary layer zone on a smooth place is detected in the papers mentioned above. In this case it is impossible to make a deduction about the lifetime of these vortices and their stability; however a statistical investigation of the transverse scales can be performed for such pairs if their dimensions are related to the distance between the dye strips. This analysis permitted indirect information to be obtained about the dynamics of coherent structure interaction.

A statistical treatment of the transverse scales of coherent structures that were identified by the distance between adjacent streaks was performed in [6]. It would be desirable to note here that in our case the dye strips correspond to the streaks. A normal logarithmic distribution function

$$P(\lambda) = \frac{1}{(2\pi)^{1/2}\psi_0\lambda}\exp\left[-\frac{1}{2}\left(\frac{1}{\psi_0}\ln\lambda/\lambda_0\right)^2\right], \tag{1.1}$$

$$\lambda_0 = \langle\lambda\rangle(1+\psi_\lambda^2)^{-1/2}, \quad \psi_0 = [\ln(1+\psi_\lambda^2)]^{1/2}, \quad \psi_\lambda = \sigma_\lambda/\langle\lambda\rangle,$$

$$\sigma_\lambda = \left[\frac{1}{n-1}\sum_{i=1}^{n}(\lambda_i - \langle\lambda\rangle)^2\right]^{1/2}$$

was taken for the coherent structure scale distribution in [6], where $\langle\lambda\rangle$ is the arithmetic mean of the structure scale for a fixed distance from the beginning of the boundary layer. The magnitude of the relative dispersion of structures for different Reynolds number values is obtained in the range $0.3 < \psi_\lambda < 0.4$.

In our case the statistical ensemble of the dimensions being investigated was chosen from 14 experimental realizations and was n = 1200 on the average for each transvese section. The statistical treatment was realized in 11 sections. The scales were measured on the stereo-comparator of "STEKO" equipped with an automatic perforation unit for the results with subsequent processing on an M-4030 electronic computer. The accuracy of measuring the strip scales was 10 μm. Displayed in Figs. 3a-c are scale distribution histograms for three different sections (x = 0.25, 0.36, 0.47 m). The data are superposed in absolute dimensions since the characteristic scale in wall units is unknown for the deformable surface. The approximation by the logarithmically normal distribution (1.1) is shown by the smooth line. It is seen that the distribution function is self-similar along the flow.

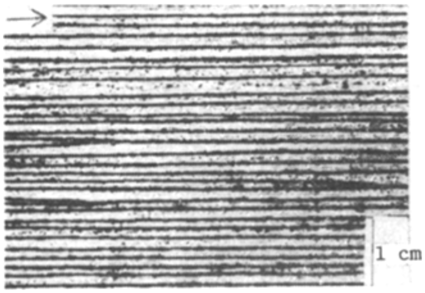

Fig. 1

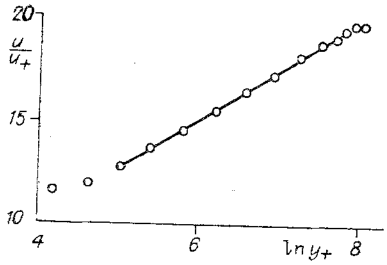

Fig. 2

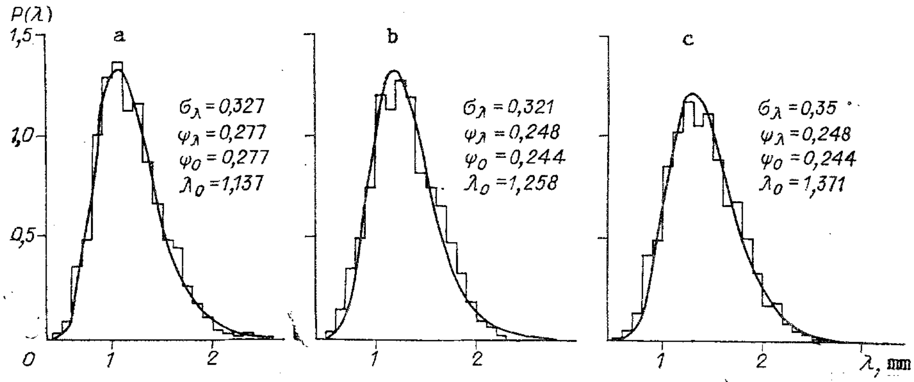

Fig. 3

Presented in Fig. 4 is a verification of the statistical hypothesis [17]. The argument of the normalized function $\alpha(y) = \int_{-\infty}^{y} P(z)\,dz$, $y = \ln(\lambda/\langle\lambda\rangle)$, is plotted along the ordinate axis. The integral is taken over the experimental step distribution function; the line corresponds to the logarithmically normal distribution. It is easy to see the good the degree of approximation of the experimental data by the logarithmically normal distribution (1.1).

The dynamic velocity governs the characteristic scale of the coherent structures on a smooth surface since, as has already been mentioned above, a universal value is obtained for the dimensionless scale $\langle\lambda_+\rangle = \langle\lambda\rangle u_+/\nu \sim 100$ in numerous experiments. As yet there is no foundation for rejecting similar representations for coherent structures on a deformable surface, with the exception of the fact that the corresponding value $\langle\lambda_+\rangle$ will depend on the properties of this surface. If it is assumed that the mean scale of structures on the plastically deformable surface is independent of Re in near-wall scale units, and is governed just by the properties of the surface, then the nature of the change in viscous friction of the boundary layer being investigated along the flow can be found from the functional dependence of the absolute value of the mean dimension of the structure on the longitudinal coordinate. In the range $Re_x \sim 10^7$ under consideration, the viscous friction of a turbulent boundary layer on a smooth plate is proportional to $\tau_w \sim Re_x^{-0.2}$ (see [18], say), which means $\langle\lambda\rangle \sim x^{0.1}$. However, as follows from Fig. 5, in the case of a deformable surface $\langle\lambda\rangle \sim x^{0.25}$, from which according to the elucidation above, $\tau_w \sim Re_x^{-0.5}$, i.e., friction varies with the longitudinal coordinate analogously to laminar boundary layer friction. It is not yet clear whether boundary layer laminarization actually occurs on a plastically deformable surface. Both direct measurements of the friction on such a surface and a study of the detailed structure of near-wall turbulence are necessary to clarify this question. An increase in the characteristic scale of the coherent structures is still another fact in favor of friction diminution. The correlation between these two circumstances was remarked in [10, 11]. The characteristic scale of coherent structures in this case exceeds by 3-4 times that being realized on a smooth plate under the same conditions.

2. THEORETICAL MODEL OF COHERENT STRUCTURE INTERACTION

A logarithmically normal distribution holds in those cases when the fluctuation of the random variable depends on its value. The mean dimension of coherent structures is

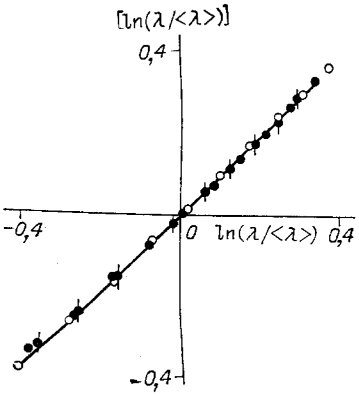

Fig. 4

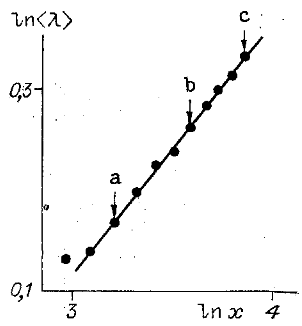

Fig. 5

increased along the stream. Growth of the scale shows that the coarser structures displace the finer ones, i.e., the structure lifetime grows as the intrinsic dimensions increase. This means that the fluctuations to which the structure dimensions are subjected depend on their magnitude. Moreover, a change in the scale of one structure results in corresponding changes for the nearest neighbors since the total vortex system pattern is practically independent of local scale changes (see Fig. 1). The above elucidation is a certain foundation for the scale distribution obtained. The circumstance that the distribution function is known can be used to construct an elementary theory of vortex structure interaction. Analogously to [19], we find the kinetic equation for the coherent structure scale distribution function. Let us recall that a pair of counter-rotating vortices in the near-wall boundary layer zone and extending along the flow is considered as the coherent structure. In the transverse direction the vortex system is the alternation of such pairs with logarithmically normal structure distribution along their dimensions λ. The intensity of the vortices united into a pair is assumed to be identical while the scale λ corresponds to their total dimension.

Let us examine the dynamics of such a vortex system in time by understanding that a change in the structure dimension in time corresponds to their variation along the flow, i.e., we introduce the transformation $t = x/U$.

Let $n(\lambda, t)d\lambda$ be the number of structures per unit length with scales between the limits $(\lambda, \lambda + d\lambda)$. Then the total number N of structures per unit length and their mean scale have the form

$$N(t) = \int_0^\infty n(\lambda, t)\, d\lambda; \tag{2.1}$$

$$\langle \lambda(t) \rangle = N^{-1}(t) \int_0^\infty \lambda n(\lambda, t)\, d\lambda. \tag{2.2}$$

By definition

$$N(t)\ \langle \lambda(t) \rangle = 1. \tag{2.3}$$

Let us introduce two functions governing the process of structure interaction: $r(\lambda, t)$ is the reciprocal structure lifetime as a function of their dimension, and $w(\lambda', \lambda, t)$ is the probability of occurrence of structures of scale $(\lambda, \lambda + d\lambda)$ because of destruction of adjacent pairs with scale λ'. The possible correlation of dimensions of adjacent structures is neglected in the construction of the present theory and the structures themselves are considered as interacting particles. It is seen from Fig. 1 that the process of destroying one scale and the occurrence of another is of the merger type, i.e., a total scale structure occurs because of the interaction of two adjacent structures. Losses of structures of scale λ are associated with two processes: destruction of a structure determined by the intrinsic lifetime and destruction of adjacent structures entailing a change in the scale under consideration. The number of structures with scale λ is enlarged because of the process of merger of two arbitrary structures of total scale λ. The probability density of the fact that on one of the sides of the structure λ there is a structure λ' is $2n(\lambda', t)N^{-1}(t)$. The probability that the destruction of an adjacent of scale λ' will cause a change of the scale λ is 1/2. In conformity with the above elucidation, we write the kinetic equation as

$$\frac{\partial n(\lambda, t)}{\partial t} = -r(\lambda, t)\, n(\lambda, t) - \left[\frac{1}{N}\int_0^\infty r(\lambda', t)\, n(\lambda', t)\, d\lambda'\right] n(\lambda, t) + \int_0^\infty r(\lambda', t)\, n(\lambda', t)\, w(\lambda', \lambda, t)\, d\lambda'. \tag{2.4}$$

By definition for the function $w(\lambda', \lambda, t)$

$$\int_0^\infty w(\lambda', \lambda, t)\, d\lambda = 1. \tag{2.5}$$

The relationship (2.5) corresponds to the fact that a new structure of some scale will occur during merger. The change in the total number of structures per unit length with time can be obtained if (2.4) is integrated with respect to all the scales. Then by using the relationships (2.1), (2.3) and (2.5), we find

$$\frac{dN}{dt} = -\frac{d\langle\lambda\rangle}{dt}\frac{1}{\langle\lambda\rangle^2} = -\int_0^\infty r(\lambda, t)\, n(\lambda, t)\, d\lambda. \tag{2.6}$$

Since self-similarity of the distribution function is obtained in experiment, we introduce appropriate self-similar functions by the relationships

$$n(\lambda, t)d\lambda = N(t)P(\zeta)d\zeta = P(\zeta)\, d\lambda/\langle\lambda\rangle^2,$$
$$r(\lambda, t) = \Omega(t)R(\zeta),\ w(\lambda', \lambda, t)\, d\lambda = W(\zeta', \zeta)\, d\zeta. \tag{2.7}$$

Here $\Omega(t)$ is the vorticity scale characterizing the vortex from the vortex pair. Such a time scale is introduced because the characteristic time of vortex pair development is of the order of the period of rotation of the vortices comprising it. After substitution of (2.7) into (2.4), we obtain an equation in the self-similar functions introduced

$$\left(P + \zeta\frac{dP}{d\zeta}\right)\int_0^\infty R(\zeta')\, P(\zeta')\, d\zeta' - R(\zeta)\, P(\zeta) + \int_0^\infty R(\zeta')\, P(\zeta')\, W(\zeta', \zeta)\, d\zeta' = 0. \tag{2.8}$$

The function $W(\zeta, \zeta')$ satisfying the relationship (2.5) and reflecting the process of origination of a scale ζ as a result of merger of two scales can be represented in the form

$$W(\zeta, \zeta') = \begin{cases} P(\zeta - \zeta'), & \zeta' \leqslant \zeta, \\ 0, & \zeta' > \zeta. \end{cases} \tag{2.9}$$

For the known function $P(\zeta)$ defined by (1.1), the equation (2.8) is integral in the function $R(\zeta)$. Because of the homogeneity and linearity of (2.8) the function $R(\zeta)$ is determined by the accuracy of an arbitrary factor. Let us renormalize this function by dividing it by the constant $\alpha = \int_0^\infty R(\zeta')\, P(\zeta')d\zeta'$, and let us introduce a new $R_+(\zeta) = R(\zeta)P(\zeta)/\alpha$. The equation for the function $R_+(\zeta)$

$$\left(P + \zeta\frac{dP}{d\zeta}\right) = R_+(\zeta) - \int_0^\zeta P(\zeta - \zeta')\, R_+(\zeta')\, d\zeta' \tag{2.10}$$

is a Volterra integral equation of the second kind. The method of direct replacement of the integral by a finite sum by a generalized trapezoidal formula [20] is used to solve this equation.

The solution of (2.10) is represented in Fig. 6 for $\psi_0 = 0.244$, which corresponds to an experimental value. For $\zeta_1 = \lambda_0/\langle\lambda\rangle = 0{,}97$ the function $R_+(\zeta)$ changes sign the first time. This shows that the number of structures with scale $\lambda < \zeta\langle\lambda\rangle(\approx\langle\lambda\rangle)$ diminishes with time while the number of structures with scale $\lambda \geqslant \langle\lambda\rangle$ increases, i.e., a tendency to growth of the mean scale is observed. In the neighborhood of $\zeta = \zeta_1$ the function behaves as $R_+(\zeta) \simeq -(1/\psi_0^2)\ \ln(\zeta/\zeta_1)P(\zeta)$. The scales corresponding to the even roots $\zeta_n \simeq (n + 1)/2$ (n is the ordinal number of the root) of the function $R_+(\zeta)$ are stable. Unstable scales among which is indeed the mean dimension of coherent structures considered above correspond to the odd roots. Its change with time is given by (2.6), which in this case has the form

$$d\langle\lambda\rangle/\langle\lambda\rangle dt = \alpha\,\Omega(t). \tag{2.11}$$

The mean scale of the coherent structures on a plastically deformable surface varies in conformity with the law $\langle\lambda\rangle \sim t^{0{,}25}$ (see above). It follows from (2.11) that the characteristic vorticity associated with coherent structures varies according to the law

$$\Omega(x) \sim U/x. \tag{2.12}$$

Here the inverse passage is realized to the dependence on the longitudinal coordinate. According to the assumption made above, the lifetime of a vortex pair is determined by its associated characteristic vorticity. The relationship (2.12) yields the dependence of the vorticity scale on the longitudinal coordinate. Hence the characteristic lifetime of the structure is

$$T(\sim\Omega^{-1}) \sim x/U. \tag{2.13}$$

The relationship

$$\theta/x \sim u_+^2/U^2 \tag{2.14}$$

is valid for a turbulent boundary layer (θ is the thickness of the momentum loss, and u_+ is the dynamic velocity). If (2.14) is substituted into (2.13), then we will have for the dimensionless lifetime

$$T_+ (= Tu_+^2/\nu) \sim \mathrm{Re}_\theta. \tag{2.15}$$

If it is assumed that the structure lifetime determines the characteristic period between "bursts," then the relationship (2.15) expresses the dependence of this period on the inner and outer boundary layer scales. The expression $T_+ = 0.65\mathrm{Re}_\theta^{0.73}$ is obtained in [21] for the period between "bursts," but the limited number of data and their radical spread do not yield complete confidence in the exponent. The attractiveness of the exponent p = 0.73 is apparently that the relationship TU/δ = const (see [22]) is valid for it, and governs the dependence of the period between bursts only on the outer parameters. However, at this time it is considered that the period between "bursts" depends on both the outer and the inner boundary layer scales. The relationship (2.15) yields such a connection.

3. DISCUSSION

The singularity of the coherent structures considered above is that they are developed above a surface that is deformed easily under the action of tangential stresses. A wave mode of fluid film flow with different rheological properties is here realized on the surface itself. The question arises as to the manner in which such a combined flow influences the viscous free stream drag. On one hand the fluid surface can suppress the process of turbulent velocity fluctuation generation, while on the other the presence of a fine-scale film flow wave mode can influence it as additional surface roughness. Finally, when a film flow mode in the form of alternating bands occurs on the combined surface, a mechanism of turbulent energy generation suppression is possible because of the more ordered development of near-wall coherent structures. Ordering can be associated with the fact that in this case the coherent structures are separated by a barrier that takes a shape corresponding to the existence conditions for these structures. In other words, the shape and scale of such rifling are self-consistent with the boundary layer being developed on this surface. The favorable influence of longitudinal rifling on the reduction of viscous friction of a turbulent boundary layer is shown in [23], where an 8% reduction in friction is obtained by an empirical selection of the shape and scale of the rifling and the mechanism for viscous friction diminution is different since the characteristic scales of the artificial rifling by which the noticeable reduction in friction is achieved are significantly less than the characteristic scale of the near-wall vortex structures existing on a smooth plate under the same conditions. In this case the transverse roughness executes a stabilizing role, whereby the relatively small degree of viscous friction diminution is explained. The investigations performed in this paper afford a certain foundation for hoping that friction conditions can be realized on a plastically deformable surface during which turbulent energy generation will be suppressed in a more optimal manner.

However, even if these deductions are not confirmed by direct measurement of the viscous friction, they demand a clarification of the results underlying the reason for such assumptions. Among them are the increase in the mean scale of the coherent structures as compared with the dimensions of structures on a free surface under the same external conditions and the law of variation of the mean scale of structures along the stream. Investigation of the boundary layer reaction on change in the boundary conditions discloses additional possibilities for the construction of a near-wall turbulence generation model.

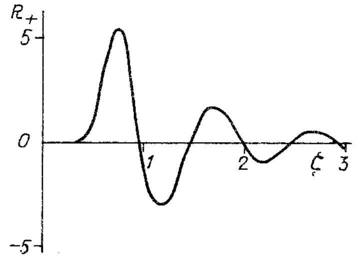

Fig. 6

The theory proposed in Section 2 is an attempt to utilize the representation of coherent structures as isolated elements lasting a long time and reproducing their shape during interactions and being an inherent part of the near-wall zone of any turbulent boundary layer. This would permit reduction of the complex wave dynamics of perturbation development in the near-wall zone to the interaction of specific structural elements. The theory is phenomenological since it relies on the visual pattern of the scale change and the experimentally obtained scale distribution function of structures. Only nearest neighbors are taken into account during structure interaction and the collective nature of their interaction is ignored. How important taking account of the long-range order is, is shown in [24] where the dynamics of pairwise merger of chains of coherent structures modeling free shear flow is examined on the basis of the conservation laws. However, an important distinction of coherent structures in the near-wall turbulent boundary layer zone is that viscosity effects are essential for them. Consequently, a priori it is difficult to estimate the role of the collective effects; in this case they are simply neglected. This difficult question requires a more detailed study. The relation obtained theoretically connecting the period between the "bursts" and the outer and inner boundary layer parameters reflects the power-law dependence of period, made dimensionless in the near-wall scales, on Re_θ correctly on the whole according to experiment.

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TURBULENT BOUNDARY LAYER ON THE ROTATING END OF A SWIRL CHAMBER

É. P. Volchkov, S. V. Semenov, and V. I. Terekhov

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Aerodynamics and heat transfer in the neighborhood of a rotating disk have been studied by many investigators. A survey of such works can be found in [1], for example. Most of these studies examined the cases of rotation of a disk located in a free volume or exposed to an axial flow [1-3], as well as the interaction of a twisted flow with a stationary surface (a bibliography on this subject can be found in [4]).

Information on the interaction of a rotating disk with a twisted flow is limited to [5, 6]. The authors of [5] theoretically examined the turbulent boundary layer formed on a disk rotating at an angular velocity Ω and interacting with a gas flow which was itself rotating as a solid. A theoretical and experimental study was made in [6] of the laminar boundary layer on the rotating end wall of a swirl chamber. The angular velocity of the end was fixed, while the gas rotated in accordance with the law governing a free vortex.

In actual swirl chambers with an outlet containing a diaphragm, the rotation of the gas takes place in accordance with a complex law. As a first approximation, the flow outside the outlet hole is assumed to be a potential flow in which the circulation $\Gamma = v_0 r = \text{const}$, where v_0 is the circumferential component of velocity in the flow core. As was shown in [4, 7], such a law of flow rotation is observed with a change in the radius from the lateral wall of the chamber R to r* (r* determines the radius value where all of the gas enters into boundary layers on the end plates and travels through them into the region of the outlet hole). The rotation of a gas in a swirl chamber or tube not provided with a diaphragm occurs in accordance with the law of quasi-solid rotation at an angular velocity $\omega = v_0/r = \text{const}$.

Rotating end plates can be used in a number of vortex-type processing units to improve their efficiency. In these cases, the circumferential velocity of the flow decreases with approach toward the end wall. The velocity decreases not to zero, but to the linear velocity of rotation of the end at the given point. This alleviates the imbalance of centrifugal forces in the end boundary layer and preserves the radial pressure gradient in it, which leads

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