GENERATION OF LONGITUDINAL EDDIES IN A BOUNDARY LAYER IN THE PRESENCE OF BODY FORCES

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A combined analysis is made of measurements of the kinematic and thermal characteristics of a boundary layer disturbed by the introduction of regular three-dimensional perturbations.

The current interest in the study of boundary layers in the form of systems of longitudinal eddies can be attributed to the range of flow conditions under which such layers develop, as well as to the need to control processes involving the transfer and generation of turbulence and heat and mass transfer. These disturbances are characterized in particular by one main type of boundary-layer instability on concave surfaces and surfaces heated from below. The close connection between the effects of longitudinal curvature and thermal stratification makes it possible to jointly analyze results obtained in the study of such flows.

The interest in longitudinal-vortical flows is directly connected with the possibility of their use to increase heat exchange with the surfaces in contact with the flow. It was shown in [1] that the development of longitudinal eddies during the laminar-turbulent transition in a boundary layer on a heated plate leads to an increase in the mean temperature gradient. Moreover, experimental determination of the hydrodynamic stability of a boundary layer on concave surfaces has led to the development of a method of artificially generating longitudinal eddies of a given scale and has established the character of their development as a function of the parameters of the flow [2]. Here, we experimentally study hydrodynamic and thermal features of a boundary layer when a system of longitudinal eddies is generated within it.

The experiments were conducted on a hydrodynamic stand [3] with $Re = (0.3\text{-}6.0)\cdot 10^5$ and in a wind tunnel [4] with $Re = 10^5\text{-}10^6$. In the presence of body (centrifugal) forces, the hydrodynamic boundary layer formed on the replaceable bottom walls of the stand. These walls had concave sections with radii of curvature R = 1, 4, and 12 m. The maximum depth of the concavity was 0.05 m. The kinematic characteristics (profiles of the mean and fluctuation velocities in the lengthwise direction) were measured with a laser anemometer. The velocity distributions in the transverse direction z were determined by visualization of the flow by the Teller method [2, 3]. The thermal boundary layer was created on the foil bottom wall of the working section of the wind tunnel and was somewhat thicker than the dynamic boundary layer (Pr = 0.7) [5]. Heating the foil to 40 C by passing a direct current through it ensured the boundary condition q_w = const on the surface and a temperature drop $\Delta T \approx 20$ C between the flow of air and the surface. Heat transfer was determined from the readings of thermocouples that had been soldered to the bottom surface of the foil.

Hydrodynamic studies of the transitional boundary layer were conducted with a change in the degree of turbulence ε from 0.1 to 10%. These studies were conducted in order to model the conditions that exist in actual heat exchangers. The specifics of flow over surfaces with a concave section [6] consists of the flow overcoming a positive pressure gradient at the beginning of the concavity, acceleration on the section with a negative pressure gradient, and preservation and development of the accumulated features along the plane section that follows the concave section. The visualization showed that the natural perturbations here are three-dimensional. Meanwhile, the flow is very unsteady in character (Fig. 1a). Whereas the instantaneous profiles U(z) on the flat plate retain their form over time in a fairly large range of Reynolds numbers (nearly up to the stage where turbulent spots are formed), on the concave surface the profile U(z) is independent of time only near the region where loss of stability occurs. The flow pattern was altered by the generation in the bound-

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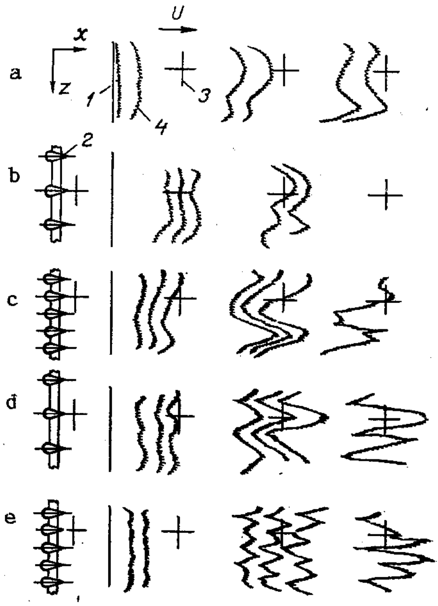

Fig. 1. Visualization of the flow in the presence of centrifugal forces along a surface with a concave section R = 4 m; U_∞ = 4 cm/sec with natural development of perturbations (a − x = 1.8 m) and with the introduction of longitudinal vortices perturbations (b − x = 1.5 m, λ_z = 3.2 cm; c − x = 1.5 m, λ_z = 1.6 cm; d − x = 1.8 m, λ_z = 3.2 cm; e − x = 1.8 m, λ_z = 1.6 cm): 1) Teller wire; 2) vortex generators; 3) decimeter markings on the axis of the solid surface; 4) Teller lines reflecting the form of the profiles U(z).

ary layer of longitudinal vortical disturbances [2] by vortex generators 7 mm high and having the form of a swept wing in plan. The value of x = 1.5 m (Fig. 1, b and c) on the concave wall in the converging section on graphical copies of photographs of the boundary layer visualized in the xz plane. Downstream from this section, on the flat surface, x = 1.8 m (Fig. 1, d and e). The introduction of perturbations with λ_z = 3.2 cm produced adequate bending of the Teller line directly behind the Teller gage positioned 5 cm downstream from the grid of vortex generators (Fig. 1b). A wire Teller gage 1 was positioned at the level of the critical layer in each case. At λ_z = 1.6 cm, the periodicity of the velocity field along z was manifest 10-15 cm downflow from the sensor. Meanwhile, we also noted a tendency for the value of λ_z to double (Fig. 1c). The same effects (the formation of perturbation field regular with respect to z behind the grid and its preservation downflow in the case λ_z = 3.2 cm (Fig. 1d), as well as the appearance of a forced small-scale structure which undergoes some increase in size in the case λ_z = 1.6 cm (Fig. 1e)) were observed in the boundary layer on the flat wall which followed the concave section. In accordance with the diagram of the stability of the lengthwise vortical perturbations (Hertler diagram) [2], this effect can be attributed to the fact that perturbations at λ_z = 1.6 cm are close to neutral under the given conditions, i.e., they have a very low amplification factor. Thus, the bend in the Teller line can be formed only in the case of the prolonged action of a perturbation field on it. This situation is realized when it is moved downflow. The large-scale perturbations, with a large amplification factor, create a fairly intensive field in the space between the vortex generators and the Teller sensor. The latter immediately records the presence of forced regularity of the flow. In fact, the Hertler parameters $G = U_\infty \delta_2^{1,5} R^{-0.5} \nu^{-1}$ and $\alpha_z \delta_2 = 2\sigma\delta_2/\lambda_z$ calculated from this data for the cases in Fig. 1b and 1c are G = 0.84, $\alpha_z\delta_2$ = 0.25 and G = 0.84, $\alpha_z\delta_2$ = 0.5, respectively and characterize perturbations with maximal and near-zero amplification factors (here, the momentum thickness δ_2 averaged over a was determined from measured profiles U(y)).

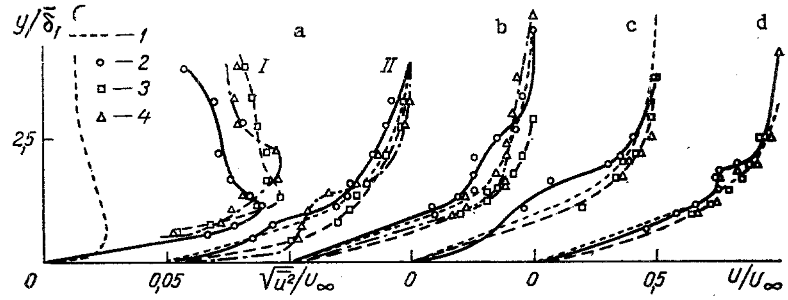

Fig. 2. Velocity profiles in the generation of longitudinal eddies in a boundary layer on a flat plate (a) and on surfaces with a concave section R = 12 (b), 4 (c), and 1 m (d): a) Re = $2.2 \cdot 10^5$, λ_z = 1.2 cm; I, II) profiles of mean and fluctuation velocities; b) Re = $1.8 \cdot 10^5$, λ_z = 2.4 cm; c) Re = $2.3 \cdot 10^5$, λ_z = 1.6 cm; d) Re = $1.2 \cdot 10^5$, λ_z = 1.2 cm; 1) reference profiles (measured without the introduction of perturbations); 2, 3, 4) profiles behind the grid of the vortex generators at z = 0 (in the wake of the generator), z = $\lambda_z/2$ (half way between adjacent generators), and z = $\lambda_z/4$.

TABLE 1. Characteristics of the Flow Conditions and the Generated Perturbations

Designation in Fig. 2	R, m	x, m	U_∞, cm/sec	λ_z, cm	δ_2, mm	G	$\alpha_z\delta_2$
б	12	2,2	8,2	2,4	1,45	1,48	0,38
в	4	1,8	12,8	1,6	1,1	2,4	1,43
г	1	1,35	8,6	1,2	1,75	6,3	0,92

Despite the stabilization of the kinematic structure of the boundary layer when longitudinal eddies are generated in it, visualization showed the presence of weak oscillatory motion of the vortex system in the xz plane (meandering). This effect intensifies with a decrease in the radius of curvature of the surface and on the flat plate is manifest only a short distance from the grid of the vortex generators. Such a pattern can be attributed to the effect of the body forces, which lead to the development of fairly intensive three-dimensional natural perturbations. These perturbations interact with the introduced perturbations to form a complex kinematic flow pattern. This circumstance is reflected in the change in the form of the vertical velocity profiles with different radii of curvature of the surface (Fig. 2). At Re ≈ 10^5, two-dimensional perturbations (Tollmien–Schlichting waves) begin to develop near the flat plate. Under these conditions, generation of the system of lengthwise eddies suppresses the generation of the natural perturbations. Thus, the measured velocity profiles are steady and correspond in form to the presence of the above-noted three-dimensional perturbations in the boundary layer (Fig. 2a): the maximum level of the fluctuations is $0.1U_\infty$, while the averaged profiles for three values of z along the wavelength λ_z provide evidence of the existence of a developed vortex system. For the curved surfaces, we chose perturbation parameters that corresponded to the regions of maximum amplification on the stability diagram (Table 1). The vertical coordinate y (Fig. 2) was normalized with respect to the transverse mean displacement thickness δ_1. It is evident from Fig. 2 that with a decrease in R, the form of the profiles measured at the three values of z loses the features characteristic of the stable system of longitudinal eddies. However, it cannot be assumed that a more intensive field of body forces (with R = 1) would preclude the formation of a forced perturbation structure in the field. The point is that the measurement of any point-to-point distribution (in the present case, the measurement of velocity profiles with a laser anemometer) gives a representation of parameters averaged over the measurement period. Visualization of vertical velocity distributions shows that, given constant test conditions, they change slowly over time. This may be connected either with meandering of the vortex system or with the development of a more complex perturbation field.

The last conclusion was confirmed by the results of measurement of the coefficient of heat transfer α along a flat heated plate in a flow of air. The change in heat transfer along

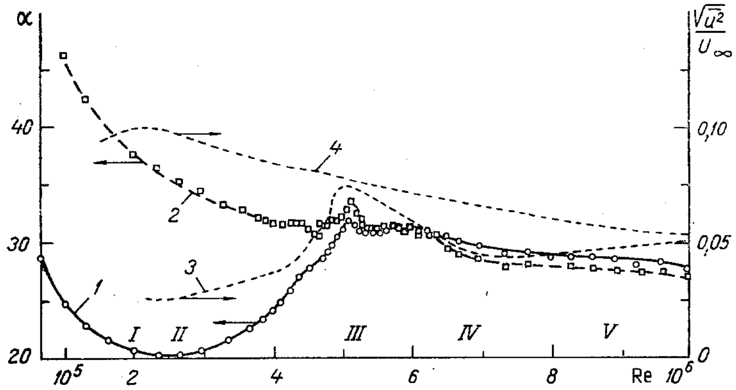

Fig. 3. Dependence, on the Reynolds number, of the heat-transfer coefficient of a heated plate and the maximum level of fluctuations u through the thickness of the boundary layer: 1, 3) $\alpha_0(Re)$ and $\sqrt{\overline{u}^2}/U_\infty(Re)$ respectively, with natural development of the transition; 2) $\alpha_0(Re)$ with the placement of an agitator on the leading edge of the plate; 4) $\sqrt{\overline{u}^2}/U_\infty(Re)$ with the generation of a system of longitudinal eddies at different stages of the transition. α, W/(m²·K).

the plate (curve 1 in Fig. 3) is alternating in character: the initial reduction is connected with an increase in the thickness of the boundary layer; the subsequent sharp increase is connected with the generation of perturbations which intensify during the transition; the moderate reduction in α toward the end of the plate is connected with a decrease in the amplitude of the perturbing motion and thickening of the pre-turbulent and turbulent boundary layers. To relate the quantity α with the level and type of perturbing motion in the transitional boundary layer, Fig. 3 shows the distributions of α and $\sqrt{\overline{u}^2}$ with respect to the Reynolds number. The Roman numerals denote stages of the transition [7] in accordance with the successive transformation of the type of perturbations. Here, I denotes the appearance of intensifying Tollmien–Schlichting waves, II denotes the origination of perturbing motion in three dimensions, III denotes the formation of a system of longitudinal eddies, IV denotes the development of perturbing motion connected with meandering of the eddies, and V denotes the appearance and growth of turbulent spots with the formation of a turbulent boundary layer. Structural-kinematic analysis of the boundary layer and correlation of the stages of the transition with certain Reynolds numbers can be done in the case of nongradient flow on a flat plate in the absence of body forces. However, as was shown above, the same physical mechanisms form the basis for the development of the transition process on low-curvature concave surfaces as well. An increase in the intensity of body forces of this type leads to a change in the Reynolds numbers corresponding to different stages of the transition and to lengthening of the stages themselves. This fact is well-illustrated by two limiting cases of the onset of instability. The first case is the absence of the influence of body forces (flow over an unheated horizontal wall). Here, the first stage of the transition is dominant: instability begins with the excitation of plane waves. This stage occurs over a wide range of values of Re, and even the occurrence of three-dimensional effects in the perturbing flow does not change the character of the average motion (the Blausius profile remains the same nearly up to the stage of development of longitudinal eddies). The second limiting case is the action of just body forces directed along a normal to the surface (free convection above a horizontal plate heated from below). Here, ordered motions develop in the form of vortex cores. Flow over the concave surfaces studied here is characterized by shortening of the first stage and acceleration of the development of three-dimensional wave disturbances. In connection with this, it can be assumed that curves 1 and 3 in Fig. 3 roughly coincide with each other. In this case, it is logical to also assert that the peaks of $\sqrt{\overline{u}^2}$ and α coincide with respect to the Reynolds number ($Re = 5 \cdot 10^5$).

The placement of a wire agitator on the leading edge of the plate increases the heat transfer of the plate on the initial section (curve 2). However, the structure of the boundary layer is quasi-turbulent in character. This is evidenced by the presence of the peak on curve 2 at $Re = 5 \cdot 10^5$. The generation of three-dimensional perturbations at different stages of the transition causes an increase in the maximum values of fluctuation velocity (curve 4),

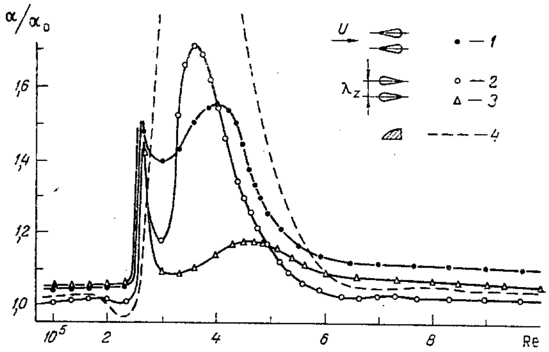

Fig. 4. Relative change in heat transfer in relation to Re in the presence of a grid of vortex generators (1-3) and a two-dimensional barrier 5.4 mm high with a rounded leading edge (4): 1) vortex generators with a sharp leading edge, $\lambda_z = 1.5$ cm; 2, 3) with a rounded leading edge ($2 - \lambda_z = 1.5$ cm; $3 - \lambda_z = 1.8$ cm).

this being manifest to the greatest extent in the initial stages of the transition — when the natural disturbances of the boundary layer are small. In the third stage of the transition and in the turbulent boundary layer, almost no increase is seen in the maxima of the profiles $\sqrt{\bar{u}^2}/U(y/\delta_1)$ with the introduction of longitudinal-vortical perturbations [8]. However, the maxima themselves are shifted away from the wall and are more diffuse in character than in the case of a naturally developed boundary layer. The maximum velocity gradients $\partial U/\partial y$ are also seen in this region (see Fig. 2d and [8]). Thus, the generation of longitudinal eddies intensifies the generation of turbulence $-\rho uv \partial U/\partial y$. However, since this takes place in a region away from the solid surface, the increase in shearing stresses on the surface should be insubstantial. Thus, increasing heat transfer by means of ordered vortex structures is advantageous in that it leads to smaller hydraulic losses than with the use of conventional agitators based on the use of separation phenomena [9]. Also, the site where the grid of the vortex generators is placed should be chosen so as to coincide with the initial stages of the transition.

The change in the heat-transfer coefficient α along a heated plate with vortex generators located on it near the third and second stages of the transition shows that a single generator does not affect the distribution of heat transfer along the plate. The location of a series of vortex generators near the region corresponding to the third stage of the transition also has almost no effect on the character of α(Re) in either the transitional or turbulent boundary layers. The generation of longitudinal eddies in the region of the second stage (and in the region where α_0 is minimal) leads to a marked increase in the heat-transfer coefficient α downflow of the grid of the vortex generators. Curve 1 in Fig. 4 shows the relative change in heat transfer α/α_0 under these conditions (here, the maximum of α/α_0 above the generators is not shown). The same figure shows similar results obtained using vortex generators with a different geometry (curves 2 and 3). These generators were used to increase drag and thus increase the level of the resulting perturbations and approach the conditions under which the two-dimensional barriers traditionally employed to intensify heat transfer (curve 4) are used. Comparison of the results shows that curves 2 and 4 are identical: a sharp increase in the ratio α/α_0 behind the barrier and its rapid decrease to the initial level. Since the rate at which the flow returns to equilibrium is directly connected with the magnitude of the perturbation [4], it can be assumed that similar mechanisms influence the boundary layer in cases comparable to those being considered here, i.e., a two-dimensional barrier and a series of vortex generators (discrete barrier) can be regarded as roughness elements having head resistance and resistance due to a change in the velocity distribution and, thus, the shearing stresses near these elements. In the first case (curve 1), the vortex generators introduce additional resistance mainly due to the second term. Thus, the increase seen in heat transfer here is connected not with separation phenomena but with organization of the structure of the boundary layer in the form of a system of longitudinal eddies.

The reaction of the boundary layer, under the influence of body forces, to introduced three-dimensional perturbations is selective with respect to the quantity λ_z [2]. Thus, from the viewpoint of intensifying heat transfer by the generation of longitudinal-vortical perturbations, it is first of all necessary to decide whether to choose to have large values of α/α_0 on a short section of the immersed surface or have moderate values on a longer section. In accordance with the results of kinematic studies, in the first case it is expedient to excite perturbations whose parameters are characteristic of the region of maximum amplification of the stability diagram. In this case, there is a rapid increase in the amplitude of the perturbations and turbulence in the boundary layer. In the second case, perturbations close to neutral perturbations should be generated. Due to prolongation of the respective stages of the transition and some effect on the turbulent boundary layer, conditions are created in this instance for a less intense but more long-lasting effect on the structure of the flow.

Thus, the generation of longitudinal-vortical perturbations makes it possible to order the flow structure in a boundary layer in the presence of body forces. By changing the scale and amplitude of the introduced perturbations, it is possible to regulate the degree and duration of the effects on the boundary layer. This in turn makes it possible to use the results obtained here to control heat and mass transfer near surfaces in contact with a flow.

NOTATION

x, y, z, longitudinal, normal, and transverse coordinate axes; U_∞, velocity of free-stream flow; U, u, longitudinal components of mean and fluctuation velocities in the boundary layer; R, radius of curvature of the concave section; G, Hertler parameter; Pr, Prandtl number; Re, Reynolds number; α, heat-transfer coefficient; α_z, wave number of longitudinal-vortical perturbations; δ_1 and δ_2 displacement thickness and momentum thickness, respectively; λ_z, wavelength of longitudinal-vortical perturbations along z; ν, kinematic viscosity; ρ, density.

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