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BYPASS LAMINAR-TURBULENT TRANSITION IN A THERMAL BOUNDARY LAYER

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We present results of four series of experimental investigations of the bypass laminar-turbulent transition (BLTT) initiated by actions of different nature (higher than usual degree of turbulence of the external flow, closed laminar separation at the leading edge, and their combination) on a flat surface in gradient-free flow. Our findings have supported the idea that strongly disturbed flows have a tendency toward the formation of an upper thermal bypass laminar-turbulent transition whose heat-transfer coefficient changes monotonically because of the formation of a pseudolaminar boundary layer before it. The influence of the scale of turbulence on the position of a bypass laminar-turbulent transition and the intensification of the transfer processes in the boundary layers formed before and after the bypass laminar-turbulent transition has been evaluated. We have developed a complex method for diagnostics of a bypass laminar-turbulent transition, which allows one to establish the fact of formation of the bypass laminar-turbulent transition and determine its starting and end points.

Introduction. A bypass laminar-turbulent transition arising as a result of disturbances of different nature in the external flow frequently occurs in various technical applications, especially in the flow part of turbomachines. This explains the great interest that arose in the last decade in these investigations, which is evidenced by the fact that a number of scientific-research groups whose activities are directed toward the development of improved methods for prediction and calculation of a bypass laminar-turbulent transition have been organized within the framework of large joint projects in Europe.

Unlike a laminar-turbulent transition (LTT) arising in flows with a low degree of external turbulence ($Tu_e = 0$), a bypass laminar-turbulent transition has a number of particular features that make it difficult to predict and calculate this transition. A detailed analysis of the literature devoted to the bypass laminar-turbulent transition leads to the conclusion that the first purposeful experimental investigation of this unusual type of laminar-turbulent transition was performed in the early 1970s at the Institute of Technical Thermal Physics of the National Academy of Sciences of Ukraine (ITTP NASU) [1].

The results of this investigation were found to be unexpected from two viewpoints. First, the mechanism itself of the bypass laminar-turbulent transition was distinguished by the absence of Tollmien–Schlichting waves, i.e., the linear stage in formation and development of initial disturbances. Second, before the bypass laminar-turbulent transition, the so-called (according to the ITTP NASU terminology widely used at present in analogous investigations) pseudolaminar boundary layer (PLBL) was formed. Unlike the laminar boundary layer (LBL) arising at $Tu_e = 0$, the pseudolaminar boundary layer was characterized first of all by the pressure of velocity pulsations in the layer itself; these pulsations had a continuous spectrum without discrete peaks. Independently of Tu_e, the kinetic energy of the pulsations was maximum for constant values of the Blasius parameter $\eta \sim 2–2.3$, i.e., at a fairly long distance from the wall. Scientific circles expressed great interest in the results obtained by us, and they were published practically immediately in the USA.

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TABLE 1. Experimental Data for $U_e \sim 5$ m/sec and $x = 50$–600 mm

Notation	Series 1 169–60	Series 2 81–60	Series 3 0–25	Series 4 169–35
x_r, mm	–	–	~ 25	~ 17
u'_e/U_e, %	5.0–3.1	7.0–4.3	0.2	3.6–2.6
L_e, mm	18.6–25.0	25.7–34.6	–	23.0–29.0
L_e/δ	9.8–1.0	11.2–1.2	–	5.8–1.1
u'_δ/U_e, %	5.7–3.5	7.9–4.5	4.0–1.2	5.1–2.9
$t'_{\delta_t}/\Delta t$, %	1.4–1.0	–	–	1.5–1.0
Re^{**}	76–675	82–620	114–628	155–867
Re^{**}_{st}	178	182	240	180
Re^{**}_{end}	463	482	~ 620	488

Just as in [1], in the majority of subsequent investigations performed at the ITTP NASU, the increase in the heat-transfer and momentum-transfer coefficients in the pseudolaminar boundary layer was accompanied by a decrease in the form factors of the hydrodynamic and thermal boundary layers and an increase in all the characteristic thicknesses. The so-called quasiturbulent boundary layer (QTBL) had similar distinctions from the turbulent boundary layer developing at $\mathrm{Tu}_e = 0$ [2].

It is quite obvious that if a bypass laminar-turbulent transition is preceded by a pseudolaminar boundary layer and followed by a quasiturbulent boundary layer, we have an extended chain of transition consisting of five links (laminar boundary layer – pseudolaminar boundary layer – bypass laminar-turbulent layer – quasiturbulent boundary layer – turbulent boundary layer) or of their combinations. In such situations, which are of extreme importance in engineering practice, monotone distributions of the heat-transfer coefficients can occur despite the presence of a bypass laminar-turbulent transition. In this case, the coefficients of friction remain nonmonotone and have a more smoothed form than in the case of a laminar-turbulent transition. Therefore, because of the possibility of appearance of the so-called *upper* thermal bypass laminar-turbulent transition [3–5], in investigations performed at the ITTP NASU, the hydrodynamic and thermal bypass laminar-turbulent transitions were considered separately. When the upper bypass laminar-turbulent transition is formed, the distribution of the heat-transfer coefficients in it approaches that in the quasiturbulent boundary layer or in the turbulent boundary layer *from above*, i.e., there is no nonmonotony of change in the basic parameters determining the process, which is a characteristic of the majority of transient processes. It should be noted that the upper thermal bypass laminar-turbulent transition can easily be confused with the quasiturbulent boundary layer. For identification of a bypass laminar-turbulent transition it is necessary to develop special diagnostic techniques, since many known methods used for diagnostics of a laminar-turbulent transition are found to be unsuitable for these purposes.

The powerful upsurge of computer technology opened up unlimited possibilities for the development of more refined methods of calculation of combined flows, which, however, did not spare researchers the difficulties concerning the diagnostics of a bypass laminar-turbulent transition and the assignment of its coordinates as well as the selection of the controlling factors responsible for the transfer processes in the bypass laminar-turbulent transition itself and in the boundary layers that arise before and after the bypass laminar-turbulent transition. The initial conditions playing an important part in the formation of a bypass laminar-turbulent layer are also entirely uncertain, since there are no general principles developed for their description yet. The foregoing is readily illustrated by the data (Table 1) of four series of experiments on the heat exchange on a flat surface in gradient-free flow in the presence a bypass laminar-turbulent transition which is initiated by disturbances that are different in nature: higher than usual values of Tu_e (series 1 and 2), laminar separation (series 3), and their combination (series 4).

The results obtained have been considered in two aspects. On the one hand, on the basis of an analysis of the characteristics of transfer processes (distributions of the heat-transfer coefficients and coefficients of friction, velocity and temperature profiles, changes in the characteristic thicknesses of the thermal and hydrodynamic boundary layers, transformations of the kinetic energies of the velocity and the temperature turbulence in wide and narrow frequency ranges), we made an attempt to appreciate the complex mechanism of the bypass laminar-turbulent transition. On the other hand, we developed new methods of diagnostics of a bypass laminar-turbulent transition and modified the available ones and also determined the coordinates of the starting and the end points of the bypass laminar-turbulent transition for the considered cases.

Brief Description of Experiments. We performed experiments in a T-5 low-velocity wind tunnel with a working area 120 × 120 × 800 mm in cross section, which was developed at the ITTP NASU. The tested plate 10 mm in thickness with a rounded tip 1.5 mm in radius was positioned in the working area asymmetrically. Since the cross section of the tunnel was comparatively small, all the experiments were performed with the plate inserted into it.

A comparatively low "natural" level of turbulence ($Tu_e \sim 0.2\%$) in the working area was provided by installation of a honeycomb with deturbulizing grids in the prechamber and subsequent constriction of the flow in the convergent channel (confuser). Turbulence was generated using perforated washers 10 mm in thickness and 13.5 mm in perforation diameter with perforation numbers 169 and 81, which were positioned in the prechamber ahead of the convergent channel.

The angle of attack at the tip of the plate was set using an interceptor attached to the top wall on the end of the working area. A change in the height of the interceptor caused a marked redistribution of the pressure at the tip of the plate and thereby made it possible to realize a nearly nonseparating flow (for an interceptor height of 60 mm) or flow with separation (for an interceptor height of 25 and 35 mm) past the leading edge.

In four series of experiments denoted as 169–60, 81–60, 0–25, and 169–35, the first figure corresponded to the number of perforations of the turbulence generator and the second to the interceptor height expressed in millimeters.

In the experiments, the parameters of the velocity and the temperature turbulence were measured by a DISA-55M thermoanemometric two-channel system using sensors of diameters 5 and 1 μm, respectively. The coefficients of friction were determined from the velocity distributions near the wall as well as by a modified Clauser method. The length of the separation zone x_r was estimated by the change in the signal from a hot-wire anemometer based on a method developed at the ITTP NASU. The heat exchange on the plate was investigated by the electrocalorimetry method using six band heaters pasted on its surface and controlled autonomously. Additional heating of the tip part of the plate provided simultaneous development of a hydrodynamic and a thermal boundary layer. The boundary conditions on the largest part of the heated surface ($x > 30$ mm) were close to $q_w \sim$ const. The experiments whose characteristics in the range of x = 50–600 mm are presented in Table 1 were performed for a velocity of the external flow $U_e \sim 5$ m/sec and a longitudinal pressure gradient close to the zero gradient. It is seen from the table that the degree of turbulence estimated by the longitudinal component of pulsations (ratio u'_e/U_e) and its characteristic scale L_e changed within the ranges 0.2–7% and 18–35 mm, respectively. We will revert to the role of the latter in the process of bypass laminar-turbulent transition below.

Local Heat Exchange in the Presence of a Bypass Transition. Preparatory to describing the results obtained, it makes sense to remember that when a bypass laminar-turbulent transition develops under the conditions $Tu_e > 0$, the linear stage of a natural laminar-turbulent transition is entirely "bypassed," so that the mechanism of the bypass laminar-turbulent transition becomes *nonlinear*. Practically all modern concepts con-

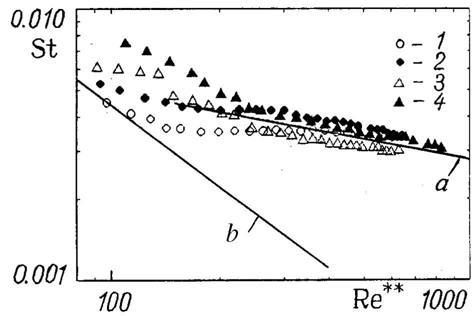

Fig. 1. Local heat exchange in the presence of a bypass laminar-turbulent transition (the numbering corresponds to the series presented in Table 1): a) $St_0 = 0.0157Re^{**^{-25}}$; b) $0.365Re^{**^{-1}}$.

cerned with the mechanism of the bypass laminar-turbulent transition are based on the model of the final (nonlinear) stage of the laminar-turbulent transition: formation of turbulent spots and their coalescence. The main distinctions are reduced to the dimensions of turbulent spots and the velocity of their propagation downstream; this velocity is exponentially dependent on the intermittency coefficient [6]. Since the linear stability theory is unsuitable in the case where a bypass laminar-turbulent transition arises, for the majority of practically important applications, experiment remains the *unique* method of prediction of both the *location* of the bypass laminar-turbulent transition and the *course* of the transfer process.

It is apparent that additional difficulties arise in calculations of the heat exchange in the flow part of turbomachines when a local separation arises near the leading edge of the blades on the pressure side or the rarefaction side (sometimes, on both sides). In the classification presented in [7], even special terminology is used for these cases: "transition in a separating flow." However, in the present investigations we consider such a type of transition as a variety of the bypass laminar-turbulent transition initiated by a "pure" separation (series 3) or a combination of a separation and Tu_e (series 4).

The distributions of local heat-transfer coefficients over the length of the surface in flow are presented as dependences $St = f(Re^{**})$ in Fig. 1. An analysis of these dependences allows the following conclusions of the features of heat exchange in the thermal boundary layer in the presence of a bypass laminar-turbulent transition:

(1) In all the investigated series 1–4, before the bypass laminar-turbulent transition, a pseudolaminar boundary layer with a heat-transfer intensity higher than that in a laminar boundary layer was formed, which determined the more smoothed character of the bypass laminar-turbulent transition as compared to the laminar-turbulent transition.

(2) As Tu_e increased (compare series 1 and 2), the thermal bypass laminar-turbulent transition process had a clear tendency toward the disappearance of the nonmonotony in the distributions $St = f(Re^{**})$; after the bypass laminar-turbulent transition, a quasiturbulent boundary layer with a higher intensity of heat transfer than in a turbulent boundary layer was formed.

(3) In the development of the bypass laminar-turbulent transition, after the "pure" separation (series 3), the distribution of the heat-transfer coefficients was close to a monotone distribution, and after the bypass laminar-turbulent transition, a turbulent boundary layer was formed: the latter was approached from below. The absence of a quasiturbulent boundary layer in this series can easily be explained, since the separation decreases along the length of the plate and the Tu_e values remain fairly low.

(4) In the case of the joint influence of the separation and the external turbulence (series 4), the distribution of the heat-transfer coefficients became monotone, i.e., the quasiturbulent boundary layer was approached from above. It is precisely this thermal bypass laminar-turbulent transition that was called the *upper* bypass laminar-turbulent transition in the investigations performed at the ITTP NASU.

(5) The influence of the separation (i.e., initial disturbances) on the pseudolaminar boundary layer was stronger than the influence of Tu_e, which was evidenced by higher values of the heat-transfer coefficients before the bypass laminar-turbulent transition in series 3 and 4 as compared to those in series 1 and 2. By contrast, the intensity of longitudinal velocity pulsations in the external flow (u'_e/U_e) and at the outer boundary of the dynamic boundary layer (u'_δ/U_e) was higher in series 1 and 2. This is explained by the fact that the separation itself is a powerful source of the internal turbulence near the tip of the plate and thereby significantly influences the initial conditions under which a dynamic boundary layer is formed (certain aspects of the problem under consideration are contained in [8, 9]). It is shown in [2] that both Tu_e and the initial disturbances developed along the length of the surface in flow are responsible for the appearance of a pseudolaminar boundary layer, whereas the position of a bypass laminar-turbulent transition depends first of all on Tu_e.

It is apparent that the above-described changes in the heat-transfer coefficients cannot be predicted within the framework of the most perfect models of turbulence, i.e., in practice, experiment remains a *unique* tool that allows one to obtain a reliable idea of the distributions of the transfer coefficients in the bypass laminar-turbulent transition region as well as in the boundary layers formed before and after it.

Some Information on the Role of the Degree and Scale of Turbulence in the Mechanism of the Bypass Laminar-Turbulent Transition. Because of the formation of a pseudolaminar boundary layer characterized by high-power velocity pulsations and increased transfer coefficients, to gain access to the mechanism of the bypass laminar-turbulent transition it is necessary to perform a complex analysis of a number of characteristics of the thermal and hydrodynamic boundary layers, which would allow us, first of all, to identify fairly reliably the type of boundary layer. Because of this, preparatory to describing the diagnostic techniques used at the ITTP NASU, we will briefly discuss the role of Tu_e and the characteristic scale in the development of near-wall boundary layers.

In the experimental investigations performed at the ITTP NASU, the dissipative scale of longitudinal pulsations of the external-flow velocity L_e was selected as the characteristic scale of turbulence [2, 3, 5, 8, and others]. These investigations have shown that as the relative scale of turbulence L_e/δ reaches certain values, an intervening region called the *superlayer* arises between the outer boundary of the dynamic boundary layer and the turbulent flow independently of the type of boundary layer. The superlayer arises for $L_e/\delta > 1.25$ and causes a decrease in the energy of normal velocity pulsations (and, consequently, in the turbulent viscosity) at the outer boundary of the dynamic boundary layer as compared to the external flow. Hence, the appearance of the superlayer prevents the transfer coefficients in the boundary layer from being increased, i.e., it slows down the formation of a pseudolaminar boundary layer and a quasiturbulent boundary layer before and after the bypass laminar-turbulent transition.

It seems likely that the degree and scale of turbulence completely determine the appearance of a turbulent boundary layer or a quasiturbulent boundary layer after the bypass laminar-turbulent transition where the influence of the initial conditions decreases significantly. At the same time, a significant influence on the development of a laminar boundary layer or a pseudolaminar boundary layer before the bypass laminar-turbulent transition is exerted, in addition to the degree and scale of turbulence (i.e., ambient conditions), by the initial conditions (first of all, by disturbances arising as a result of the flow around the leading edge, including the separation). There are still no unified approaches for taking into account the initial conditions, which hampers further development of universal methods of prediction and calculation of both the pseudolaminar boundary layer and the bypass laminar-turbulent transition. The use of intermittency functions for calculation of a bypass laminar-turbulent transition is also made difficult for the above reasons despite the promising nature of such approaches, since to do this it is necessary to know exactly the type and characteristics of the boundary layers formed before and after the bypass laminar-turbulent transition.

The results of numerous investigations (see, for example, [10, 11] and the references cited therein) allow the conclusion that the main mechanism of the laminar-turbulent transition is determined by the amplification of a longitudinal velocity pulsation along the surface in flow. The mechanism of the bypass laminar-turbulent transition is distinguished by the absence of the linear stage characterized by the appearance and amplification of perturbations. However, the mechanism of the final nonlinear stage of the laminar-turbulent transition, which is associated with generation of turbulent spots and their growth and coalescence, is practically preserved in the case of a bypass laminar-turbulent transition, although the velocity of propagation of the spots in the longitudinal direction can be different (see [7] and the references cited therein).

The fact that the superlayer causes only a decrease in the energy of a normal velocity pulsation allows the conclusion that the scale of turbulence, which determines only the type of the boundary layers before and after the bypass laminar-turbulent transition, has practically no influence (or influences only slightly) on the position of the bypass laminar-turbulent transition region. The insignificant role of the scale of turbulence generated by the grids received primary consideration in [7].

This conclusion is supported by the fact that the results of the calculations of the coordinate of the starting point of the bypass laminar-turbulent transition, which were made according to the recommendations of different authors, including Dyban et al. [2], correspond to formula (1) in [12], which, in our opinion, has found wide application in practice for determining the position of a bypass laminar-turbulent transition:

$$\mathrm{Re}_{\mathrm{st}}^{**} = 163 + \exp\,(6.91 - \mathrm{Tu}_{\mathrm{e}}\,\%)\,. \tag{1}$$

When Eq. (1) is used, the selection of the value of $\mathrm{Tu_e}$ seems to be important. We recall that in [12] the values of $\mathrm{Tu_e}$ were determined at the center of the distance between the leading edge of the surface in flow and the starting point of the bypass laminar-turbulent transition. Thus, Eq. (1), in fact, accounts for the law of decay of the external turbulence over the length of the surface as the bypass laminar-turbulent transition is approached.

In contrast to the most of the available literature data, it has been shown in [13] that the scale of turbulence has a marked influence on the coordinates of the region of a bypass laminar-turbulent transition. For the case of the same initial values of $\mathrm{Tu_{e0}}$ = 3% set in the cross section of the plate tip in the range of L_e = 2.3–34.5 mm, Jonas et al. [13] recommend using the following dependence for determining the starting point of a bypass laminar-turbulent transition:

$$\mathrm{Log}\,\mathrm{Re}_{\mathrm{st}}^{**} = 1.426 - 0.476\,\mathrm{Log}\,L_{\mathrm{e}}\,. \tag{2}$$

An analogous dependence was recommended for determining the end point of a bypass laminar-turbulent transition.

Elementary calculations from Eq. (2) show that in the case where it is used, the start of a bypass laminar-turbulent transition is determined in fact not by $\mathrm{Tu_e}$, as follows from practically all works devoted to the same problem, but by the absolute value of L_e (in millimeters), and it is $\mathrm{Re}_{\mathrm{st}}^{**}$ = 480–133 for the above range of L_e. It should be noted that a decrease in L_e is favorable for an increase in $\mathrm{Re}_{\mathrm{st}}^{**}$, i.e., it leads to a laminar flow. Such a conclusion is contradictory to the above-described physical notions (of the ITTP NASU) of the effect of L_e, according to which a decrease in the relative value of L_e, conversely, leads to a decrease in the superlayer and to an increase in the pseudolaminar boundary layer, i.e., to a more intense penetration of disturbances from the external flow to the layer. Moreover, the above range of numerical values of $\mathrm{Re}_{\mathrm{st}}^{**}$ calculated from Eq. (2) is also in obvious discrepancy with the results of the calculation from Eq. (1), according to which $\mathrm{Re}_{\mathrm{st}}^{**}$ = 213 for $\mathrm{Tu_e}$ = 3%. If we calculate $\mathrm{Re}_{\mathrm{st}}^{**}$ from formula (1) for $\mathrm{Tu_e}$ values of ~1 and 2.5%, which have been determined, according to experimental data [13], at the center of the distance between the leading edge of the plate and the starting point of the bypass laminar-turbulent transition at L_e = 2.3 and 34.5 mm, respectively, the results of the calculation made according to the recommendations in [12] ($\mathrm{Re}_{\mathrm{st}}^{**}$ = 530

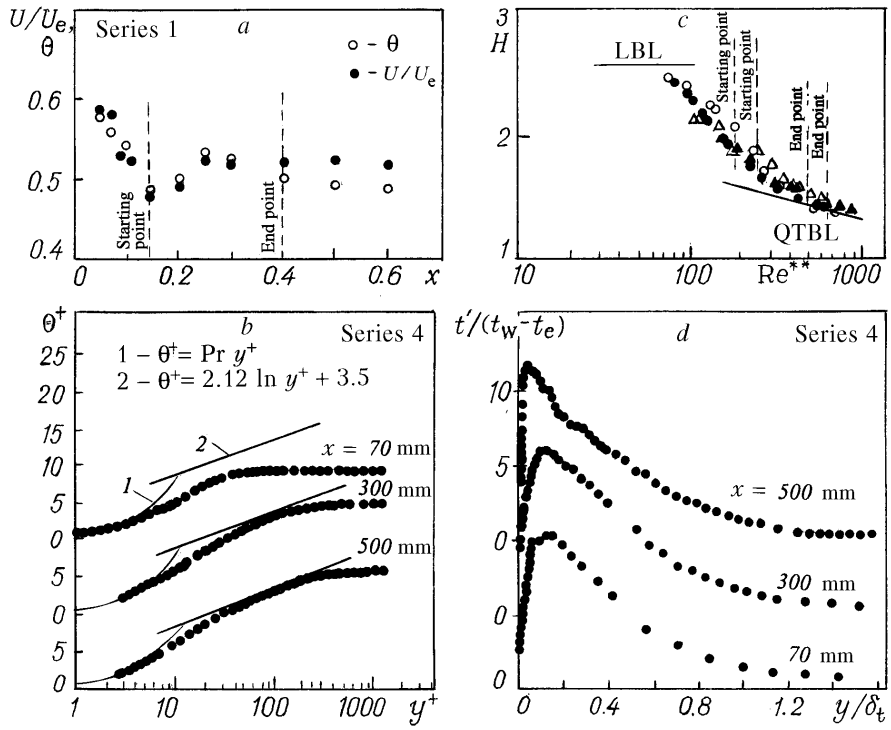

Fig. 2. Methods of diagnostics of a bypass laminar-turbulent transition which are based on an analysis of changes in the time-average (a–c) and pulsation (d) characteristics of the dynamic and thermal boundary layers.

and 245) and in [13] (Re^{**}_{st} = 480 and 133) also differ significantly. This, in our opinion, points to the necessity of additional revision of the experimental data of [13].

The analysis performed by no means casts any doubt on the physical validity of the currently popular concept (detailed above) of the comparatively weak influence of the scale of turbulence on the position of the region of a bypass laminar-turbulent transition, which, however, does not exclude the important role of the scale in the formation of a pseudolaminar boundary layer and a quasiturbulent boundary layer before and after the bypass laminar-turbulent transition, as is emphasized in the works of the ITTP NASU.

Principles of Diagnostics of a Bypass Laminar-Turbulent Transition. For diagnostics of the type of boundary layers formed before and after the bypass laminar-turbulent transition and determining the position of the region of the bypass laminar-turbulent transition, it is necessary to develop special methods, keeping in mind that the accumulated experience in investigating the laminar-turbulent transition can be insufficient in a number of cases. This problem was partially touched upon in [14]. We dwell on some methods of diagnostics of a bypass laminar-turbulent transition, which are extensively used at the ITTP NASU.

(1) *The starting and the end points* of a bypass laminar-turbulent transition can be determined as the minimum and maximum points of the change in the dynamic pressure (or in the electric signal from the measuring element of a hot-wire anemometer, which is proportional to the time-average velocity or the time-average temperature) along the length of the surface in flow at a fixed small (within the limits of the displacement thickness) distance from the wall (Fig. 2a). The method is considered as traditional for diagnostics of a laminar-turbulent transition. With it, the coordinates of the starting point of this transition are determined more exactly than the coordinates of its end point. An unambiguous advantage of this method is its suitability for all the types of bypass laminar-turbulent transition, including the upper one.

(2) *The starting and the end points* of a bypass laminar-turbulent transition can be determined as the minimum and maximum points of the transfer coefficients if these points can be determined accurately in the

corresponding distributions. As is seen from Fig. 1, the distributions St = $f(\mathrm{Re}^{**})$ give no way of determining the position of a bypass laminar-turbulent transition in series 4 when, because of the appearance of an upper thermal bypass laminar-turbulent transition, the changes in the heat-transfer coefficients become monotone and the quasiturbulent boundary layer is approached from above. An analogous problem arises in series 3 in the case where the turbulent boundary layer is approached from below. Hence, the method is appropriate in individual cases, which is explained by the particular features of the development of a bypass laminar-turbulent transition depending on the initial and ambient conditions.

(3) *The starting and the end points* of a bypass laminar-turbulent transition can be determined on the basis of an analysis of the transformation of the velocity and temperature fields along the length of the surface in flow (Fig. 2b). If a laminar boundary layer or a pseudolaminar boundary layer are formed before the bypass laminar-turbulent transition, the velocity profile in the coordinates of the wall law is characterized by the presence of only two zones: a viscous zone and a buffer zone. In this case, in the pseudolaminar boundary layer we can have an increase in the velocity and temperature gradients near the wall as well as in the thicknesses of the dynamic and the thermal boundary layers (which is clearly seen when the corresponding distributions are compared to the Blasius profile). Further deformation of the velocity and temperature profiles, which points to the fact that a bypass laminar-turbulent transition begins to form, is manifested in the first deviations from the initial profile and the appearance of a flattened region between the viscous and the buffer zones – an analog of the future region of action of the logarithmic law. Further extension of this region in both directions is completed by the end of the bypass laminar-turbulent transition: the velocity profile becomes typical of that of a quasiturbulent boundary layer with negative values of the wake parameter, which is due to the presence of external and initial disturbances as well as disturbances with low Re^{**}.

(4) *The end* of a bypass laminar-turbulent transition can accurately be determined from the distributions of the form factors of the hydrodynamic or the thermal boundary layer (Fig. 2c) from the initial point of coincidence with the straight line $H = f(\mathrm{Re}^{**})$ drawn for the quasiturbulent boundary layer or the turbulent boundary layer. We should note that it is precisely the distributions of the hydrodynamic form factor that are most frequently used by experimenters for determining the starting point of a laminar-turbulent transition, which corresponds the point of the first deviation from the value of $H = 2.59$. As follows from the presented data, this method is *entirely* unsuitable for determining the starting point of a bypass laminar-turbulent transition, especially in the cases where a pseudolaminar boundary layer is formed. The use of this method can lead to a seemingly large decrease in $\mathrm{Re}_{\mathrm{st}}^{**}$. It has been shown in the works of the ITTP NASU that the formation of a pseudolaminar boundary layer itself, as well as of a quasiturbulent boundary layer, is accompanied by a decrease in the form factors because of an increase in the momentum-loss thickness or in the enthalpy in the case of the conservatism of the displacement thickness of the hydrodynamic or thermal boundary layer.

(5) *The starting and the end points* of a bypass laminar-turbulent transition can be determined on the basis of an analysis of the distributions of the velocity and temperature pulsations (Fig. 2d). In the initial cross section of a bypass laminar-turbulent transition, as well as before the bypass laminar-turbulent transition, the profile of temperature pulsations differs from the profile of longitudinal velocity pulsations in the rounded shape in the neighborhood of the maximum positioned at $y/\delta \sim 0.3$. In the process of bypass laminar-turbulent transition, the pulsation profile acquires a pointed shape typical of a turbulent boundary layer or a quasiturbulent boundary layer with a maximum at $y^+ = 13$. Hence, the profile shape and the position of the maximum of the pulsations allow one to diagnose the position of a bypass laminar-turbulent transition. Moreover, the beginning of a bypass laminar-turbulent transition is characterized by the highest absolute values of the maximum of the pulsations for a given case, whereas at the end of the bypass laminar-turbulent transition, the values of the maximum decrease somewhat or remain constant as in a turbulent boundary layer or a quasiturbulent boundary layer.

(6) Determination of the coordinates of a bypass laminar-turbulent transition on the basis of a spectral analysis of the velocity or temperature pulsations from the change in the spectral function in a selected narrow frequency range is not so efficient as in investigations of a laminar-turbulent transition. However, using spectral analysis, we can perform reliable diagnostics of the *type* of boundary layer, in particular, of the pseudolaminar boundary layer, since the pseudolaminar boundary layer is precisely the layer where we have the sink of the kinetic energy of longitudinal velocity pulsations at low frequencies to the external flow, and conversely, the absorption of the energy of these pulsations from the external flow by the boundary layer at high frequencies. Because of this, the selective properties of a boundary layer are extensively used in the experimental practice of the ITTP NASU for diagnostics of the type of boundary layer, and spectral analysis is not only one of the methods of diagnostics but also the key to understanding the complex mechanism of energy exchange between the boundary layer and the external flow, which gives us an idea of the directions of energy transfer (sink of energy from the boundary layer to the external flow or absorption of energy from the external flow) in accordance with frequencies.

Using a combination of the above methods, we diagnosed the development of a pseudolaminar boundary layer before the bypass laminar-turbulent transition in all the investigated series and determined the position and length of the zone of the bypass laminar-turbulent transition. The corresponding values of Re_{st}^{**} and Re_{end}^{**} are given in Table 1. The results obtained show that at $\mathrm{Tu_e}$ = 2.6–7%, including the case of the presence of laminar separation near the leading edge of the plate (series 1, 2, and 4), the values of Re_{st}^{**} are practically coincident with the values of Re^{**} for the point of stability loss ($\mathrm{Re}_{st}^{**} \sim 180$). In series 3, where a pseudolaminar boundary layer arises, after the laminar separation at $\mathrm{Tu_e} \sim 0.2\%$, the bypass laminar-turbulent transition region shifts downstream ($\mathrm{Re}_{st}^{**} \sim 240$). In all the series, the relative length of the zone of the bypass laminar-turbulent transition remains approximately constant ($\mathrm{Re}_{end}^{**}/\mathrm{Re}_{st}^{**} \sim 2.6$–$2.7$), which agrees with the data from [12].

Conclusions. We have performed four series of experimental investigations of heat exchange in the case of appearance of a bypass laminar-turbulent transition on a flat surface in gradient-free flow under the action of disturbances of different nature (higher than usual turbulence of the external flow, laminar separation at the leading edge, and their combination). The results obtained have shown that in turbulent flows at $\mathrm{Tu_e}$ = 2.6–7% (including the case of the presence of separation) the starting point of the transition is practically coincident with the point of stability loss. In all the investigated series, before the bypass laminar-turbulent transition, a pseudolaminar boundary layer was formed, which was partially caused by the influence of the scale of turbulence. The enhancement of the pseudolaminar boundary layer favors the appearance of the upper thermal bypass laminar-turbulent layer and is characterized by monotone changes in the heat-transfer coefficients. Particular emphasis has been placed on the methods of diagnostics and determination of the position of a bypass laminar-turbulent transition that were developed at the ITTP NASU. These methods are based on a complex analysis of the integral and local characteristics of the boundary layer developed before and after the bypass laminar-turbulent transition.

NOTATION

H, form factor of the dynamic boundary layer; *L*, scale of turbulence; *t*, temperature; t', temperature pulsation; *U*, velocity; u', longitudinal velocity pulsation; *q*, heat flux; *x* and *y*, longitudinal and normal coordinates; y^+, dimensionless normal coordinate; δ, thickness of the dynamic boundary layer; θ and θ^+, dimensionless temperature; Re^{**}, Reynolds number in the momentum-loss thickness; St, Stanton number. Subscripts: e, external; end, end; r, reattachment; st, start; t, thermal; w, wall; δ, outer boundary of the dynamic boundary layer; 0, at $\mathrm{Tu_e} = 0$.

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