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HEAT TRANSFER INVOLVING THE LAMINAR-TURBULENT TRANSITION AND THE ENHANCED TURBULENCE OF AN EXTERNAL FLOW

E. P. Dyban[*] and É. Ya. Épik

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Experimental data on heat transfer and friction in the presence of a bypass laminar-turbulent transition in a flow with an increased degree of turbulence $Tu_e = 3.2-7\%$ are reported. It is shown that several types of bypass transition can occur depending on the turbulence scale: from laminar to turbulent, from pseudolaminar to quasiturbulent, and combination. It is established that the mechanism of the transition is related to the selective properties of the wall boundary layers developed in its presence. A tendency toward the development of an upper thermal transition in turbulized flows is established.

Introduction. Investigations of the laminar-turbulent transition (LTT) have long been stimulated by the needs of aviation. Experimenters and theorists have concentrated primarily on investigations of the LTT mechanism in a dynamic boundary layer with a low degree of turbulence ($Tu_e \to 0$). The works along this line are surveyed in [1].

Investigators have pointed out that an increase in Tu_e within 0.1–2% causes only displacement of the LTT region upstream without changing the friction and heat transfer coefficients in the laminar and turbulent boundary layers (LBL and TBL). Here, doing, they have postulated the following two basic propositions: 1) the existence of a classical LBL with a Blasius profile up to the onset of the LTT; 2) independence of the LTT mechanism of Tu_e in the above-mentioned range of it (occurrence of two-dimensional Tollmien–Schlichting waves, their destruction followed by formation of so-called Emmons spots and coalescence of the latter).

In the second half of the 1960s a number of researchers (see, e.g., [2]) detected pronounced (up to 50–70%) enhancement of heat transfer on the frontal surface of a cylinder placed in a turbulized flow as well as along the profile of a turbine blade [3] in the region of LBL development. At the beginning of the 1970s investigations performed at the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine (ITTP NASU) revealed the occurrence of a layer radically differing from the LBL that was called a pseudolaminar boundary layer (PLBL). This type of layer is characterized by the following features:

- departure from a Blasius profile and enhancement of the velocity gradient on the wall;
- an increase in the thickness of the dynamic boundary layer δ, a decrease in the form parameter $H = \delta^*/\delta^{**}$, primatily due to an increase in the thickness of momentum displacement δ^{**};
- an increase in the friction and heat transfer coefficients;
- the presence of velocity and temperature fluctuations in the layer with a maximum at $\eta \approx 2-2.3$ independently of Tu_e;
- a continuous spectrum of velocity and temperature fluctuations without energy peaks at individual frequencies.

Quantitatively similar changes were detected in the TBL, called the quasiturbulent boundary layer (QTBL) in these works.

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[*] Deceased.

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A spectral analysis of velocity fluctuations in the PLTL at $\mathrm{Tu_e} \approx 1.2\%$ did not establish the presence of traditional Tollmien–Schlichting waves or formation of turbulent Emmons spots [5-7]. This has given grounds to believe that the LTT mechanism in a turbulized flow will be different from that in the case of a "classical" LBL preceding the LTB.

This nontraditional type of LTT, called a bypass LTT (BLTT) in [8], has been investigated extensively in various countries by scientists engaged in development of refined methods of calculating transfer processes in, first of all, the flow-through section of turbomachinery (see, e.g., the review [9] and [10, 11]).

The majority of the experimental and theoretical works are devoted, as a rule, to a dynamic LTT. However, under complicated external conditions a thermal LTT can develop in a different way. This is shown convincingly in [12], where with $\mathrm{Tu_e}$ changing from 5 to 3.2% along a surface in a flow and weak closed separation being present an "upper" thermal LTT, characterized by a monotonic change in the heat transfer coefficients, developed at its leading edge. Formation of an upper thermal LTT has not been observed by other researchers (see, e.g., [13-19]), which, in our opinion, is attributable, as shown below, to both the $\mathrm{Tu_e}$ and the characteristic scale of turbulence.

Role of the Turbulence Scale. In works conducted by the ITTP NASU, as in [20], the dissipative scale L of the longitudinal fluctuation component u':

$$L = (\overline{u_e'^2})^{3/2} / U_e (d\overline{u_e'^2}/dx).$$

is used as the characteristic turbulence scale. Depending on the relative value of this scale $\bar{L} = L/\delta$ an intermediate region can develop between a turbulized external flow and a wall boundary layer, independently of the type of the latter, which is called an "overlayer" in the ITTP NASU works (see, e.g., [6, 21]). An overlayer is formed at $\bar{L} > 1.25$, and it causes more intense weakening of the transport properties of the turbulized external flow, the higher $\bar{L}$ is. This occurs only due to weakening of the energy of the velocity fluctuation component normal to the surface and it leads to strong anisotropy not only in the overlayer but also at the outer boundary of the dynamic boundary layer determined, as adopted, by the condition $U_\delta = 0.99U_e$. As a result, the eddy viscosity at the outer boundary of the dynamic layer $\nu_{t\delta}$ becomes lower than that in the external flow ν_{te}. Therefore at the same $\mathrm{Tu_e}$ values, depending on the $\bar{L}$ value, two different types of pretransition boundary layer with its corresponding BLTT can be formed.

At comparatively small $\bar{L}$ values the isotropy of the turbulence is preserved at the outer boundary of the dynamic layer and $\nu_{te} \approx \nu_{t\delta}$. In this case, deformation of the velocity and temperature fields and, above all, an increase in the friction C_f and convective heat transfer St coefficients occur. Therefore, both the dynamic and thermal BLTTs start at C_f and St that are higher than in the classical LBL, which has been observed in the present study and in [10] at $\mathrm{Tu_e} \approx 3\%$.

The second type of BLTT is observed at comparatively high $\bar{L}$ values, when the isotropy of the turbulence at the outer boundary of the dynamic layer is disturbed, which slightly affects the coordinate of the beginning of the BLTT, which depends, first of all, on the longitudinal fluctuation of the velocity in the initial cross section of the plate, but due to weakening of the transport properties of the turbulized flow $\nu_{t\delta} < \nu_{te}$. Despite the high level of the kinetic energy of the longitudinal component of fluctuations inside the layer, the near-wall velocity and temperature profiles do not undergo considerable deformations, i.e., C_f and St do not increase. As has been mentioned in some of our experimental works [7] and in [19], a BLTT begins when the C_f and St values correspond to the "classical" LBL. In just such a situation it is believed that $\mathrm{Tu_e}$ exerts no influence on the rate of the transfer processes, which is, in fact, masked by the manifestation of the strong effect of $\bar{L}$.

Selective Properties of Dynamic Wall Boundary Layers. Specific features of the mechanism of interaction of a boundary layer with an external turbulized flow can be described using our suggested distributions of "filtration coefficients" k_e: ratios of the spectral power at a given point of the boundary layer E(n) to its value in the external flow $\mathrm{E(n)_e}$ at the same frequency n.

Data on the filtration coefficients for longitudinal and transverse velocity fluctuations are given for a PLBL and a QTBL in [5-7] and our other published works. As is seen in Fig. 1, two opposing fluxes of the kinetic energy of turbulence exist in a PLBL: at $n < 300$ Hz the energy of pulsations generated in the wall region is transferred

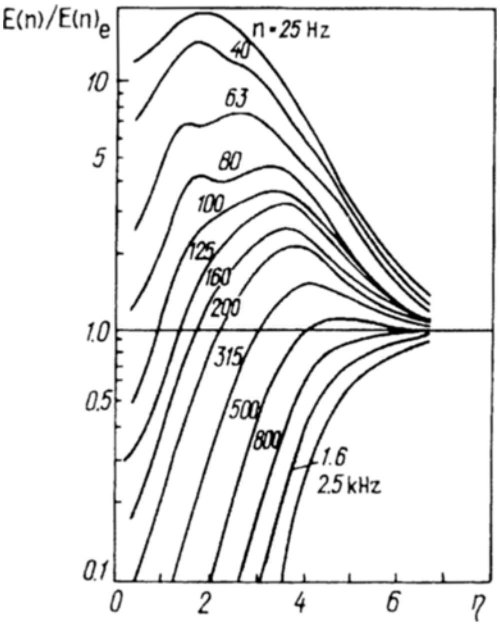

Fig. 1. Filtration coefficients of the longitudinal velocity fluctuations in a pseudolaminar boundary layer [7]. $Re_x = 25{,}300$; $Tu_e = 1.4\%$.

to the external flow, while at $n > 500$ Hz pulsations from the external flow penetrate into the boundary layer and attenuate there. Thus, energy is transferred from higher to lower frequencies. Enhancement of the energy of low-frequency pulsations favors the onset of a BLTT; however, in this case the eddy viscosity increases in the layer, thus stabilizing the latter and retarding the onset of the BLTT. At the same time only drainage of the turbulence energy to the external flow is characteristic for a QTBL (just as for a TBL).

The reported data on the selective properties of dynamic PLBL and QTBL made it possible to elucidate the mechanism of the effect of Tu_e on intensification of the heat and momentum transfer processes. Earlier we related this mechanism only to deep penetration of pulsations into the layer from the outside. However, this fact is a one-sided and quite inadequate representation of the mechanism of the process. Here, it is also of importance that at $Tu_e > 0$ a distinctive "protective barrier" is formed at the outer boundary of the dynamic boundary layer that decreases drainage of the energy generated in the layer to the external flow, thus retaining the energy in the layer itself and, as a consequence, enhancing its transport properties.

The described mechanism based on the selective properties of the dynamic wall layer is not adequately reflected in the present mathematical models of a PLBL and a BLTT, and therefore the comparatively low accuracy of these models in some cases is not surprising.

Experimental Technique. For experiments, conventional open-type wind tunnels with a controllable turbulence level were used at the ITTP NASU. At velocities $U_e = 1-20$ m/sec the natural level was ~0.2%. The turbulence was varied using perforated disks (PD) with a hole diameter of 13.5 mm installed at the inlet to the convergent channel. In the experiments whose results are given below, disks with 169 (PD-169) and 81 (PD-81) holes were used

These disks ensured almost uniform velocity and pulsation fields at the outlet from the convergent channel. The anisotropy of the flow in the initial cross sections did not exceed 6%. Therefore, the characteristics of the external flow were determined on the basis of the attenuation of the longitudinal velocity pulsations:

$$U_e^2/\overline{u_e'^2} = A\,(X + X_0)^{1.25},$$

where $A = 1027$ and 537, $X_0 = 0.41$ m and 0.406 m for the PD-169 and PD-81. The indicated generators provided the following characteristics of the turbulized external flow at $X = 0.05$ and 0.6 m: $u_e'/U_e = 5-3.2$ and $7-4.6\%$; $L = 18-25$ and $26-34$ mm; $\nu_{te}/\nu = 54-43$ and $93-76$, respectively.

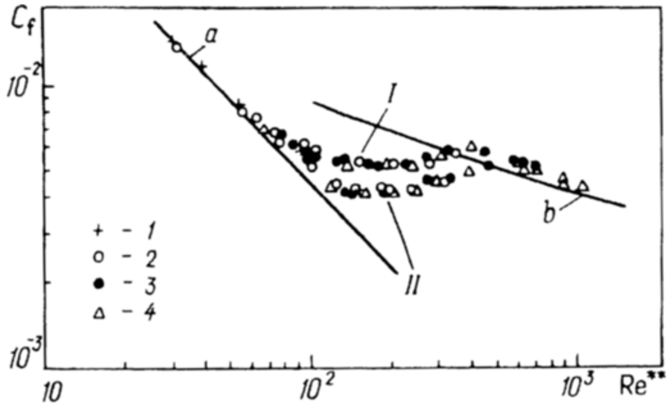

Fig. 2. Distribution of friction coefficients in the presence of a bypass laminar-turbulent transition (a, Eq. (1); b, Eq. (2)): 1) $U_e = 1$ m/sec, 2) 3, 3) 5, 4) 10; I) PD-81, II) PD-169.

The investigated plate had a rounded leading edge with a radius of 3 mm. The angle of overflowing was regulated by an interceptor located in the outlet cross section of the setup. Heat transfer was investigated by an electrocalorimetric method accomplished with the aid of belt-type heaters, which provided the boundary conditions $q_w = \text{const}$. Additional heating of the nose of the plate favored simultaneous development of the thermal and dynamic boundary layers.

The parameters of the velocity and temperature fluctuations were measured by a thermoanemometric method using a DISA-55M device equipped with analog analyzers of random signals. IBM PC 386 computers were used for processing the measurements results. The measurement procedure is described in detail in [6].

Friction and Heat-Transfer Coefficients. To compare the results obtained, we used the following similarity equations as the initial relations for $\mathrm{Tu_e} = 0$:

for the LBL

$$C_{f0} = 0.44\mathrm{Re}^{**-1}\ (\mathrm{Re}^{**} = U_e\delta^{**}/\nu)\,, \tag{1}$$

$$\mathrm{St}_0 = 0.365\mathrm{Re}^{**-0.25}\,; \tag{2}$$

for the TBL

$$C_{f0} = 0.027\ [1 + 0.05\,(\log \mathrm{Re}^{**} - 3.3) + 0.1\,(\log \mathrm{Re}^{**} - 3.3)^2]\,\mathrm{Re}^{**-0.268}\,, \tag{3}$$

$$\mathrm{St}_0 = 0.0157\,\mathrm{Re}^{**-0.25}\,. \tag{4}$$

As is seen from Fig. 2, the distributions of the friction coefficients are nonmonotic, which is one of the main features of an LTT, although the process itself becomes smoother. Thus, the character of the distributions $C_f = f(\mathrm{Re}^{**})$ for the investigated $\mathrm{Tu_e}$ values could at least be forecast qualitatively. At the same time the distributions of the heat transfer coefficients $\mathrm{St} = f(\mathrm{Re}^{**})$ (Fig. 3) show that with an increase in $\mathrm{Tu_e}$ the BLTT becomes a smoothed process that approaches a monotonic one. Thus, in the case of the PD-81 the nonmonotonic behavior of the plot $\mathrm{St} = f(\mathrm{Re}^{**})$ can be detected visually. However, with a scatter of the experimental points of ±10% in the regions where an LBL, PLBL, and BLTT are formed, the entire process can be approximated by a single straight line.

Thus, with an increase in $\mathrm{Tu_e}$ the BLTT shows a distinct tendency toward attenuation of the nonmonotonic change in $\mathrm{St} = f(\mathrm{Re}^{**})$ until it disappears completely. This type of BLTT was observed in [12] and was called an

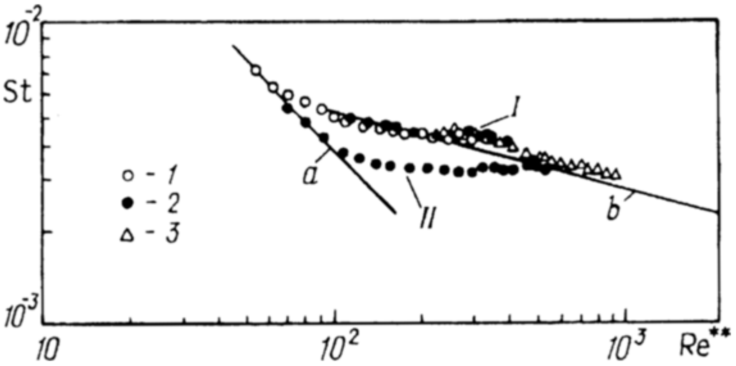

Fig. 3. Distribution of heat transfer coefficients in the presence of a bypass laminar-turbulent transition (a, Eq. (3); b, Eq. (4)): 1) U_e = 3 m/sec, 2) 5, 3) 10; I) PD-81, II) PD-169.

"upper" BLTT. It is impossible to predict the latter even qualitatively since a priori an LTT is always related to a nonmonotonic change in the transfer coefficients (those of friction and heat transfer).

In addition to a tendency toward development of an upper BLTT in the thermal boundary layer, the present experiments have also revealed development of a PLBL before the BLTT. The observed sequence of development of the wall boundary layers was as follows: LBL-PLBL-BLTT-QTBL-TBL.

The sequence LBL-BLTT-QTBL is observed in [13-15] and in [19], where the PLBL is absent, which, in our opinion, is in no way related to BLTT formation but is caused by the simultaneous influence of Tu_e and $\bar{L}$ on the development of the pretransition boundary layer.

Selective Properties of Temperature Boundary Layers. Above, we analyzed the dynamic filtration coefficients, whose definition presents no difficulties in flows with a high level of Tu_e if $E(n)_e$ is used for normalization purposes. However, with low Tu_e levels the structure of the external flow is often disordered, which does not allow $E(n)_e$ to be used for normalization. All this applies in full measure to external temperature fluctuations at any Tu_e when the wall but not the external flow is subjected to heating.

Therefore, in analyzing temperature fluctuations, temperature coefficients of filtration $k_{\delta\theta}$ are employed for whose normalization a power spectrum at the outer boundary of the thermal boundary layer $E_\theta(n)_{\delta\theta}$ is used that is determined, as usual, by the condition $T_{\delta\theta} = 0.99T_e$ (where T is the temperature, $\delta\theta$ is the thickness of the thermal boundary layer).

The filtration coefficients of temperature fluctuations (Fig. 4) differ radically from those of longitudinal-velocity fluctuations by the following:

- in all types of developing temperature boundary layers there is no energy absorption at high frequencies; at all frequencies energy is generated near the heated wall and transferred to the external flow;
- the temperature coefficients of filtration are considerably greater than in the case of velocity fluctuations; for instance, at X = 70 mm in the PLBL the values of $k_{\delta\theta\max}$ reach 40–50 at $n \approx 7$ Hz, and they are retained up to the beginning of the BLTT (X = 150 mm). In the course of the BLTT they increase to ~80 and then decrease, as the QTBL develops, to ~20. Such high $k_{\delta\theta}$ values are not surprising since at the outer boundary of the thermal boundary layer the energy of temperature fluctuations is much lower than that of the velocity fluctuations;
- the maxima of the temperature coefficients of filtration in the region of low frequencies (n < 450 Hz) lie closer to a wall, while those in the region of high frequencies are, on the other hand, at a distance from the wall, as compared to the case of velocity fluctuations. This testifies to the fact that at different frequencies the velocity and temperature fluctuations are correlated to a different degree.

The described aspects of interaction of temperature boundary layers with external turbulence must be taken into consideration in developing mathematical models of a BLTT.

Coordinates of a Bypass Laminar-Turbulent Transition. The majority of the existing methods of determination of the coordinates of the beginning and end of an LTT are developed for Tu_e = 0 and do not allow for changes in the internal structure of the pre- and posttransition wall boundary layers. The methods used for

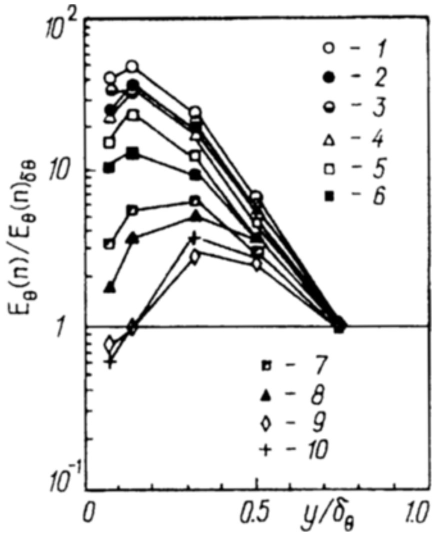

Fig. 4. Filtration coefficients of temperature fluctuations at the beginning of a bypass laminar-turbulent transition (PD-169, $X = 150$ mm; $U_e = 5$ m/sec): 1) $n = 5.5$ Hz, 2) 9, 3) 18, 4) 45, 5) 90, 6) 180, 7) 450, 8) 900, 9) 1800, 10) 4500.

LTT diagnostics can turn to be invalid or must be modified in the case of BLTT development. Thus, for instance, of the seven methods discussed in [17] only two can be used for determination of the beginning of a BLTT (points of the minimum coefficients of dynamic pressure and friction) without any modifications. Therefore, it is necessary to come to an agreement concerning the methods and criteria of measurements that could allow unambiguous interpretation of the results obtained, their comparison, and further wide use for development of calculation methods.

Without going into the details of the employed methods of diagnostics of the start ($\mathrm{Re}^{**}_{\mathrm{st}}$) and end ($\mathrm{Re}^{**}_{\mathrm{end}}$) of a BLTT, the results of the present investigation allowed us to conclude, based on a thorough analysis of the distributions $C_f = f(\mathrm{Re}^{**})$ and $\mathrm{St} = f(\mathrm{Re}^{**})$, that for the two investigated cases PD-169 and PD-81 $\mathrm{Re}^{**}_{\mathrm{st}} = 182$ and 178, while $\mathrm{Re}^{**}_{\mathrm{end}} = 482$ and 463. These figures confirm data of [22] of the constancy of the ratio $\mathrm{Re}^{**}_{\mathrm{end}}/\mathrm{Re}^{**}_{\mathrm{st}}$ for $\mathrm{Tu}_e = \mathrm{var}$ (in the present experiments this ratio is 2.65 and 2.6, respectively).

The $\mathrm{Re}^{**}_{\mathrm{st}}$ values for both cases were higher than those calculated in accordance with the recommendations made in [9] and [22]

$$\mathrm{Re}^{**}_{\mathrm{st}} = 400\mathrm{Tu}_e^{-5/8} \quad \text{and} \quad \mathrm{Re}^{**}_{\mathrm{st}} = 163 + \exp(6.91 - \mathrm{Tu}_e)$$

by a factor of 1.24 and 1.57 [9] and 1.08 and 1.12 [22], respectively, for the PD-169 and PD-81. The situation is no better in a comparison with other recommendations, including the use of $\mathrm{Re}_{x\ \mathrm{st}} = U_e X_{\mathrm{st}}/\nu$ and $\mathrm{Re}_{x\ \mathrm{end}} = U_e X_{\mathrm{end}}/\nu$, where prescribing the length X itself involves additional uncertainty due to special features inherent to the beginning of development of the layers.

Our brief analysis establishes that despite the great variety of recommendations existing in the literature, at present we cannot predict BLTT coordinates with a sufficiently high accuracy.

Conclusions. The main emphasis in the present work is given to the special features of a BLTT at $\mathrm{Tu}_e = 3.2-7\%$ and $L = 18-34$ mm. We have intentionally excluded such aggravating factors as a longitudinal pressure gradient, periodic velocity unsteadiness, roughness, etc. We have also not described the change in the turbulent Prandtl number or in many integral and local parameters. Some of these data are contained in the literature cited.

The present investigation has mainly concentrated on BLTT features that have not been discussed in the similar works of other researchers, first of all, in [13-19]. Among these features, first of all, the pronounced influence of turbulence and its characteristic scale on formation and development of a pretransition PLBL is noteworthy. The changes in the internal structure of this layer and the increase in the friction and heat transfer coefficients determine the regularities and character of the BLTT itself. The distinct tendency toward formation of an upper thermal BLTT testifies to the need to extend experimental research into the areas of higher Tu_2 and lower $\overline{L}$ values where an upper BLTT can be expected to develop in not only thermal but also dynamic boundary layers. This (still purely hypothetical) case undeniably stands in need of experimental verification.

Another important factor is the selective interaction of wall boundary layers with a turbulized external flow: generation, in particular, of energy in the pretransition dynamic PLBL at low frequencies and its absorption outside at high frequencies; high integral correlation of velocity and temperature fluctuations near a wall with a different correlation with respect to frequencies; etc. It seems worthwhile to investigate the BLTT in the case where the flow, not the wall, is heated, when the integral correlation can be lower near the wall but higher, on the other hand, at the outer boundary of the layer. Although it is very difficult to realize this case experimentally, its results can be very interesting since the behavior of thermal boundary layers in the presence of a BLTT is hard to predict.

Finally, it is desirable to clarify some technical and methodical aspects. The former include refinement of experimental conditions (which allows elimination or at least evaluation of the factors BLTT, for instance, the separation or depth of the pressure peaks at the leading edge of the plate, the presence of an unheated section, and so on); the latter include the need to develop unified approaches to determination of BLTT characteristics (coordinates of the BLTT region, intermittence coefficients, etc.).

Only concerted and agreed efforts of researchers can make it possible to approach a solution of such a complicated problem as heat transfer in the presence of a BLTT.

NOTATION

C_f, coefficient of friction; E(n), energy spectrum in frequency space; H, dynamic form parameter; L, scale; q, heat flux; n, frequency; T, temperature; U, velocity; u', longitudinal velocity fluctuations; X, y, longitudinal and normal coordinates; δ, thickness of the dynamic boundary layer; $\delta\theta$, thickness of the thermal boundary layer; δ^*, displacement thickness; δ^{**}, thickness of momentum displacement; η, universal transverse coordinate; ν, viscosity. Subscripts: e, external; end, end; f, friction; 0, $Tu_e = 0$, initial condition; t, turbulent; st, start; w, wall; δ, outer boundary of the dynamic boundary layer; $\delta\theta$, outer boundary of the thermal boundary layer; θ, thermal.

REFERENCES

1. Y. S. Kachanov, Ann. Rev. Fluid Mech., **26**, 441-481 (1994).
2. J. Kestin, Adv. Heat Transfer, 3, 1-32 (1966).
3. E. P. Dyban and V. D. Kurosh, "Comparative study of the heat transfer of a nozzle blade profile in a wind tunnel and in an air turbine," NASA TT-F-16060 (1968).
4. E. P. Dyban and É. Ya. Épik, in: Near-Wall Turbulent Flow [in Russian], Pt. 2, Kiev (1975), pp. 25-34.
5. E. P. Dyban, É. Ya. Épik, and T. T. Suprun, Teplofiz. Teplotekh., No. 30, 86-90 (1976).
6. E. P. Dyban and É. Ya. Épik, Heat-Mass Transfer and Fluid Dynamics of Turbulized Flows [in Russian], Kiev (1985).
7. V. S. Kosorygin, N. F. Polyakov, T. T. Suprun, and É. Ya. Épik, Instability of Sub- and Supersonic Flows [in Russian], Kiev (1982), pp. 85-92.
8. M. Morkovin, "Bypass transition to turbulence and research desiderate," NASA Conf. Publ. 2386 (1985).
9. R. E. Mayle, ASME J. Turbomachinery, **113**, 509-537 (1991).
10. P. E. Roach and D. H. Brierlay, Numerical Simulation of Unsteady Flows and Transition to Turbulence, Cambridge (1992), pp. 310-347.
11. M. Savill, Engineering Turbulence Modeling and Experiments (1993), pp. 310-347.
12. E. P. Dyban, E. Ya. Epik, T. T. Suprun, and S. V. Kuimov, in: Int. Symp. on Turbulence, Heat and Mass Trans., 2, 1.12.1-1.12.4 (1994).
13. M. F. Blair, Trans. ASME, J. Heat Trans., **105**, 33-47 (1983).
14. M. F. Blair, Fluids Eng., **114**, 313-332 (1992).

15. K. H. Sohn, J. F. O'Brien, and E. Reshotko, in: Proc. 7th Symp. on Turbulent Shear Flows (1989), pp. 2.4.1-2.4.6.
16. F. J. Keller and T. Wang, ASME 93-GT-67 (1993).
17. C. L. Kuan and T. Wang, Exp. Thermal Fluid Sci., **3**, 157-173 (1990).
18. T. Wang, T. W. Simon, and J. Buddhavarapu, J. Eng. Gas Turbines Power, **107**, 1007-1015 (1985).
19. D. Zhou and T. Wang, ASME 93-GT-66 (1993).
20. P. E. Hancock and P. Bradshaw, Trans. ASME, J. Fluids Eng., **105**, 284-289 (1983).
21. E. P. Dyban and E. Ya. Epik, Near-Wall Turbulence, Hemisphere Publ. Corp. (1989), pp. 139-155.
22. B. J. Abu-Ghannam and R. Shaw, J. Mech. Eng. Sci., **22**, 213-218 (1980).