METHODS OF BYPASS TRANSITION DIAGNOSTICS

E.Ya. Epik and T.T. Suprun

Institute of Engineering Thermophysics of National Academy of Sciences of Ukraine
03057 Kiev, Ukraine

Introduction

Bypass laminar-turbulent transition (BLTT) taking place in flows with disturbances of different nature is widely spread in various technical applications. However only during the last decade the intensive investigations of BLTT were begun in reference to needs of turbomachinery, thermal power installations and internal flows in technological equipment. On the basis of detailed analysis of literature devoted to BLTT we can confidently say that the earliest experimental investigations on this problem were started in IET NASU in the beginning of the seventies [1] and their results were broadly used for understanding the BLTT mechanism aspects by a number of researchers including [2].

In investigation of IET NASU it was firstly shown that the mechanism of BLTT has a different character from that when external turbulence Tu_e~0. In particular Tollmien-Schlichting waves promoting LTT at low Tu_e were not observed in boundary layer (BL) preceding to BLTT, however strong turbulent fluctuations with a continuous frequency spectrum and a maximum of kinetic energy at constant values of Blasius parameter $\eta \sim 2\text{-}2.3$ were present. This type of BL combining the features of a laminar and a turbulent BL (LBL and TBL) was called by us «pseudolaminar» BL (PLBL). PLBL can exhibit a number of specific features, first of all, increase in friction and heat transfer coefficients. The similar changes can take place in turbulent BL, named in the same studies «quasiturbulent» (QTBL) [3].

If the development of BLTT is preceded by PLBL and followed by QTBL, the broadened chain of BLTT takes place. In comparison with the traditional chain (LBL-LTT-TBL) this chain consists of 5 links (LBL-PLBL-BLTT-QTBL-TBL) or their combinations. In such situations, which are very important for engineering practice, BLTT exhibits the tendency to disappearance of nonmonotonicity of the transport coefficients variation (first of all heat transfer) along the streamlined surface. The case of BLTT with monotonic changes of heat transfer was firstly observed in [4,5] and named «upper». It cannot be predicted even qualitatively, since BLTT as well as LTT is always a priori associated with nonmonotonic changes of transport coefficients.

It is obvious that both diagnostics of BLTT (as a whole and upper BLTT in particular) and correct definition of start and end of BLTT are not easy procedures. That is why below there are presented the results of experimental investigation in the presence of BLTT which are used for development of modified and new methods of the BLTT diagnostics and definition of its start and end.

Brief description of experiments

The experiments were conducted at velocity U_e~5 m/s in aerodynamic tunnel T-5 IET NASU with the test section 120x120x800 mm. The inlet confuser was designed by Lespinar's curve with a contraction of 9. The external turbulence Tu_e was varied by changing the number of perforations of turbulizer installed at the inlet of confuser. Without generators the natural turbulence was ~ 0.2%. The plate under study was placed in the test section asymmetrically at a height of 20 mm above bottom wall. The incidence was controlled by an interceptor located in

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the end of test section on top wall. The changes of height of interceptor caused the essential redistribution of pressure near the leading edge of the plate and thus allowed to realize flows without (at height of 60 mm) and with (at height of 25 and 35 mm) separation of laminar type. In 4 series of experiments, designated as 169-60 (case 1, Tu_e =3-5%, without separation), 81-60 (case 2, Tu_e =7-5%, without separation), 0-25 (case 3, Tu_e =0.2%, with separation) and 169-35 (case 4, Tu_e =3.6-2.6%, with separation), the figures correspond to a number of perforation and the height of interceptor in mm. The longitudinal pressure gradient was close to 0.

Parameters of velocity and temperature turbulence were measured by the DISA-55M hot-wire system with 1μ and 5μ probes; coefficients of friction were determined by modified Clauser's method (k = 0.4 and C = 5.1) or on the basis of velocity profiles near the wall. The length of the reattachment region x_r was determined by method developed in IET NASU and based on changing hot wire signal. Heat transfer was explored by electrocalorimetry. The thermal and aerodynamic measurements were carried out in the range of x=50-600 mm (where x is the distance along the plate from its leading edge).

Some features of transport processes in the presence of BLTT

Before the description of experimental data we would like to remind that in BLTT the linear stage of natural LTT is completely «bypassed», providing the non-linear transition mechanism. Most of the modern conceptions about the BLTT mechanism are based on production of turbulent spots and their propagation downstream, as it was accepted for non-linear stage of LTT. Thus in our opinion the mechanism of final stage of LTT and BLTT is factually similar and differs by spot production rate. The latter is exponentially connected with intermittency coefficient [6,7]. Because in case of BLTT the linear instability theory is irrelevant, it is difficult to predict the location of the BLTT region as well as the process course and its intensity in many important practical applications. The problem becomes more complicated when BLTT develops after a separation. In our experiments when longitudinal pressure gradient is close to 0 we observed the specified type of BLTT initiated by «pure» laminar separation and its combination with Tu_e.

In 4 series of experiments pointed above the distributions of friction coefficients were nonmonotonic. The distributions of heat transfer coefficients along the plate $\mathrm{St} = f(\mathrm{Re}^{**})$ indicated that in all cases the development of BLTT was preceded by PLBL, where heat transfer coefficients were higher than in LBL (Re^{**} was determined on momentum thickness). In cases 1-3 the BLTT process became smoother in comparison with LTT and approached to monotonic. In case 4, where BLTT was organized by combined influence of laminar separation and Tu_e, after a separation the distributions of heat transfer coefficients demonstrated monotonic changes along the plate length. In case 3 BLTT transformed directly into TBL without an appearance of QTBL meanwhile in cases 1, 2 and 4 QTBL developed after BLTT.

It is obvious that the described variations of transport coefficients don't permit to diagnose the BLTT origin correctly and to predict the location of its start and end. So the additional measures of diagnostics are required for such uncertain cases.

Diagnostics of bypass transition

Without going into discussion of advantages or drawback of BLTT diagnostics methods, below we will consider those that are most widely used in practice at IET NASU.

1. The start and end of BLTT is determined from points of minimum and maximum in the distributions of friction and heat transfer coefficients. One can distinguish these points in curves

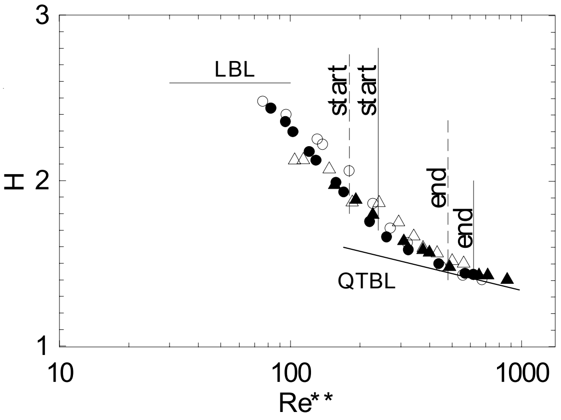

Fig. 1. Shape parameters (cases: ○ – 1, ● – 2, Δ – 3, ▲ – 4).

$C_f = f(\mathrm{Re}^{**})$ for all cases and $\mathrm{St} = f(\mathrm{Re}^{**})$ for cases 1-3, excluding case 4 when thermal «upper» transition takes place.

2. The start and end of BLTT is determined on the basis of transformations of velocity and temperature profiles in wall coordinates. In the process of BLTT a two-layer BL (a wall region + buffer zone) transforms into a three-layer one (a wall region + buffer zone + logarithmic part). The start of BLTT is determined by the first distortion of two-layer laminar-like profile, a namely: by appearance of a flattened portion (an analog of the future region of log-law validity) between the buffer zone and the external flow. The end of BLTT corresponds to the profiles of QTBL with negative values of wake parameter caused by increased Tu_e at low Re^{**}.

3. The end of BLTT is clearly determined on the basis of the distribution of hydrodynamic or thermal shape parameters as the first point of coincidence of the *H* values with those in QTBL, which can be presented by straight line (Fig. 1). It is necessary to note that in the experimental practice the variations of *H* are broadly used for determination of the LTT start. For example in [8] the LTT start is considered as the point where the shape parameter begins to deviate from value of 2.6 typical for LBL. As it followsfrom presented data, such method does not suitable for determination of BLTT start when BLTT begins after PLBL. In cases the start coordinate Re_{st}^{**} can be substantially underestimated.

4. The start and end of BLTT is determined as points of minimum and maximum of dynamic pressure as well as of hot-wire signal proportional to mean velocity or temperature in the streamwise direction at a small (~0.7 mm in given cases) fixed distance from a wall (Fig. 2). This method is traditional for LTT diagnostics.

5. The determination of the BLTT start and end is possible on the basis of profiles of velocity and temperature fluctuations. Because the principal mechanism of BLTT is associated with strengthening longitudinal fluctuations, correlated with temperature fluctuations near the wall, the profiles of the latter were chosen for illustration of method in the case 4 (Fig. 3). The BLTT start is characterized by round shape of the profiles of longitudinal velocity or temperature fluctuations in region of their maxima near the wall. Such shape also takes place in PLBL.

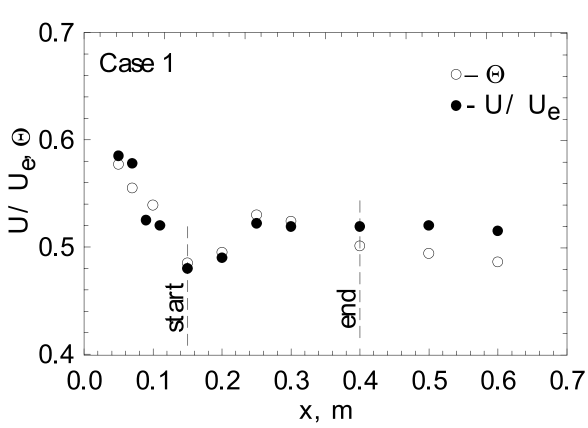

Fig. 2. Changes of temperature and velocity

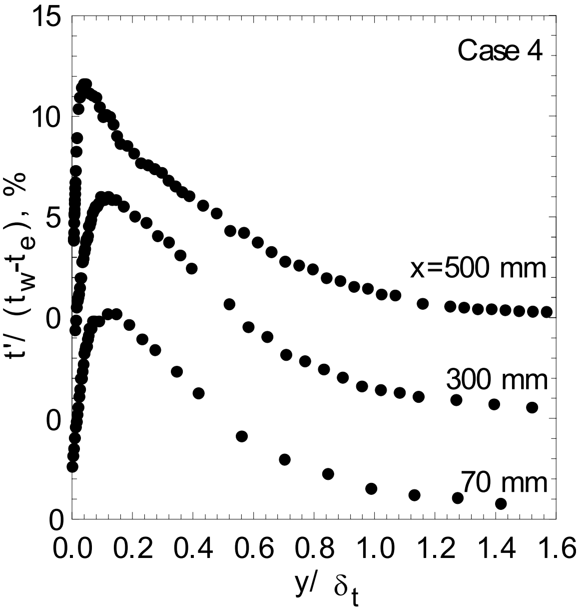

Fig. 3. Temperature fluctuations in BL.

In the BLTT process this shape transforms into sharp one typical for QTBL or TBL. The visual qualitative analysis leads to quantitative estimation of position of the BLTT start and end, however this method needs measurements in many closely located cross-sections especially in BLTT zone.

6. The changes of maxima values of longitudinal velocity or temperature fluctuations along the plate permit to fix the BLTT start as the first point with the highest value of maximum for concrete case under study. The BLTT end coincides with beginning of TBL or QTBL region where the constant or slightly decreasing values of maxima take place.

7. The changes of positions of longitudinal velocity or temperature fluctuations maxima permit to fix the BLTT start as the first point with the highest value of y_m^+ for given case.

8. The methods for determining the BLTT coordinates on the basis of spectral analysis of energy of velocity and temperature fluctuations in a full and a fixed frequency band are not so effective for BLTT as for LTT. However it is useful to note that namely spectral analysis permits to confirm the existence of PLBL before BLTT. As shown in our works (see, e.g., [3, 5]), in PLBL the energy of low-frequency longitudinal fluctuations generated near the wall drains into an external flow and simultaneously the energy of relatively high-frequency fluctuations penetrates into a BL from an external flow and decays in it. These selective properties are broadly used in our practice for identification of PLBL before BLTT.

On the basis of combination of presented methods it was shown that in turbulized flows in the range of Tu_e=7.0-2.6% the BLTT start (Re_{st}^{**}~180) practically coincided with the point of stability loss (cases 1, 2 and 4). In case of «pure» separation it shifted downstream to Re_{st}^{**}~240, however in all cases the length of BLTT was approximately constant ($\mathrm{Re}_{end}^{**}/\mathrm{Re}_{st}^{**}$ ~2.6-2.7) what is in agreement with [3, 9]. However in [7] the values of Re_{st}^{**}

with the Tu_e growth could be less than Re^{**} based on stability loss. In our opinion this fact can be connected with different experimental methods of determining the BLTT length and first of all its start.

Conclusion

The special attention was paid to the features of transport processes in the presence of BLTT and detailed description of finding its start and end. There are proposed more than 8 methods for diagnostics of BLTT. Analysis of these methods permitted to conclude that the BLTT end is determined easier and more correctly than its start.

The discrepancy of data of different authors demonstrates the necessity to come to agreement between scientists on diagnostic procedures of complex phenomena including BLTT.

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