# HEAT TRANSFER IN THE PRESENCE OF BYPASS LAMINAR-TURBULENT TRANSITION INITIATED BY FREE-STREAM TURBULENCE AND SEPARATION

Eleonora Epik

Institute of Engineering Thermophysics of National Academy of Sciences of Ukraine (IET NASU),
2a Zhelyabov Str., Kyiv, 03057, UKRAINE

## INTRODUCTION

During the last decade the bypass laminar-turbulent transition (BLTT), widely spread in different technical application (first of all in flow path of turbomachines), became an object of increased attention of experimenters and theorists. For solving problems of BLTT the leading scientific centers in Europe began an intensive collaboration in the frameworks of joined projects, mainly dealing with the numerical modeling of hydrodynamic characteristics of a boundary layer (BL) in the presence of BLTT.

The limited information about heat transfer features in the presence of BLTT under conditions of different disturbed factors interaction stimulated continuation of experimental investigations of this untraditional phenomenon in IET NASU [1]. The some aspects of thermal BLTT are below presented for two series of experiments at $Tu_e > 0$ : without separation and with laminar separation near the leading edge of the streamlined when longitudinal pressure gradient is close to zero.

## BRIEF DESCRIPTION OF EXPERIMENTS

The technique of measurements was traditional for the IET NASU and included combination of electrocalorimetry with thermoanemometry [2].

The experiments were carried out in aerodynamic tube T-5 IET NASU (120x120x800 mm$^3$). The working surface was heated flat plate with the leading edge rounded off by radius of 1.5 mm. The external turbulence $Tu_e$ was generated by perforated plate (169 holes) installed before an inlet confusor with contraction 9.

The separation was controlled by interceptor located in an outlet section of the working part. At velocity of an external flow $U_e$ ~.5.1-5.6 m/s near the leading edge of the plate the laminar separation with an extent of 17 mm took place when the interceptor length was 35 mm (series 169-35). The separation completely disappeared when interceptor length was 60 mm (series 169-60). In series 169-35 and 169-60 in the range of $\mathrm{Re}_x = U_e x / \nu \sim 1.7.10^4$-$2.3.10^5$ the $Tu_e$ values decreased from 3.6 to 2.6% and from 5 to 3% respectively when $x$ changed from 50 to 600 mm.

## ANALYSIS OF EXPERIMENTAL DATA

### Coordinates of the BLTT region

The diagnostics of the BLTT existence as well as determination of its start $x_s$ and end $x_e$ was realized by means of special approach developed in IET NASU [3]. This approach based on the complex analysis of global changes of integral and local characteristics of hydrodynamic and thermal BLs in the presence of BLTT.

In both series the BLTT start coincided with the point of stability loss ($Re_{\theta s} = U_e \delta_{\theta s} / \nu \sim 180$) and the relative length ($Re_{\theta e}/ Re_{\theta s} \sim 2.6 - 2.7$) remained constant. However the fact of universality, confirmed, for example, in [1, 4], is virtual and does not remove difficulties in finding the BLTT start due to uncertain correlation between momentum thickness $\delta_\theta$ and current length $x$ in disturbed flows as it will be shown below in next point.

## The features of BL development before and after BLTT

It is obviously that in the great extent the formation of BLTT depends on the type of BLs preceding to BLTT and following after it.

In both series under study pretransitional BL was pseudolaminar (PLBL) and characterized by considerable increase of local heat transfer coefficients. For example, at $Re_x < Re_{xs}$ intensification of heat transfer reached to ~ 30 and 70% and friction only to ~ 17% at $Re_x = 2.10^4$ in series 169-60 and 169-35 convincingly. The intensive heat transfer growth in PLBL, substantially outstripping friction, resulted in arising so called (due to IET NASU terminology) "upper" thermal BLTT with monotonous changes of local coefficients of heat transfer along the plate [5].

In quasiturbulent BL (QTBL) following after BLTT the intensification of heat transfer did not exceed~ 6-8%.

The deep analysis of such integral parameters of BLs as velocity and temperature profiles, characteristic thicknesses, shape parameters and wake functions, etc. permitted to discover some important aspects of thermal BLTT. In the first turn it refers to the different rates of growth of the enthalpy $\theta_t$ and momentum $\theta$ thicknesses which are responsible for intensity of heat transfer and impulse. The attempt to present the changes of characteristic thicknesses (including $\theta$ or $\theta_t$) by similarity equations, using as parameters at the outer edge of BLs [1,2] as intermittency factors [5], was unsuccessful. This circumstance is evidence of uncertainty of connection between thicknesses and $x$ under complex conditions.

## Correlation between velocity and temperature fluctuations

The remarkable feature of PLBL is an existence of powerful fluctuations of longitudinal velocity and correlated with them temperature ones [1,2]. In both series maxima of fluctuations reached to $u'_m / U_e$~13.5-14% and $t'_m / (t_w - t_e)$~12.6-13.2% In series 169-60 and 169-35 in the BLTT region the correlation coefficients of fluctuations maxima were ~0.94 and 0.86; in PLPL otherwise coefficients were higher in series 169-35 (~0.81 and 0.69). Near the wall in QTBL following after BLTT the fluctuations of velocity and temperature were the same as in turbulent BL at $Tu_e = 0$ .

Comparison of fluctuations maxima locations indicated that in thermal BL the they were situated substantially closer to the wall than in hydrodynamic one. This fact can be considered as one of the reasons of outstripping growth of heat transfer in comparison with friction in PLBL.

In contrast to [6] where in region of BLTT the increase of turbulent Prandtl number $Pr_t$ reached to 3-4, in both series the values of $Pr_t$, determined on the basis of temperature profiles, did not exceed 1-1.2.

### Selective properties of boundary layers

On the basis of spectral analysis it was showed that hydrodynamic PLBL fully absorbed from the external flow energy of longitudinal velocity fluctuation at moderate and high frequencies (n>300 Hz) meanwhile at .low frequencies (n<300 Hz) energy was generated in PLBL and partly transferred to the external flow. The strongest correlations between longitudinal velocity and temperature fluctuations existed at low frequencies $n$. With growth of $n$ the correlations became weaker and radical distinctions appeared in the shape of spectra and location of maxima of velocity and temperature fluctuations This data indicate a frequency selectivity of interaction of disturbances of external ( $Tu_e > 0$ ) and internal (separation) nature with pretransitional BL.

## CONCLUSION

The comparative analysis of characteristics of hydrodynamic and thermal BLs in the presence of BLTT was made for two cases: $Tu_e > 0$ (series 169-60) and combination of $Tu_e > 0$ with separation (series 169-35). In both cases the substantial intensification of heat transfer took place in PLBL preceding to BLTT. Due to our opinion namely this fact was the main reason of arising "upper" thermal BLTT in series 169-35.

The mechanism of outstripping growth of heat transfer in PLBL in comparison with friction was partly explained by such experimental facts as:

- the higher rates of growth of all the thicknesses (in the first turn of enthalpy) in thermal BL;
- the strong correlation between longitudinal velocity and temperature fluctuations near the wall;
- the closer location of temperature fluctuations maxima to the wall.

The attempt of penetration into the mechanism of BLTT on the basis of spectral analysis confirmed the frequency selectivity of interaction between BL and external flow, i.e. an important role of turbulence scale in the BLTT process.

It is obvious that the accurate prediction of complex transport processes characteristics needs in experimental data which have to find an adequate reflection in numerical modeling of BLTT.

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