Mechanism of turbulence generation in the logarithmic region of the boundary layer affected by the adverse pressure gradient

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Abstract. The sequence of turbulent energy production, diffusion and dissipation processes in the region of the boundary layer of $y/\delta=0.45$ under conditions of streamwise adverse pressure gradient has been described for the first time using the Smoke Image Velocimetry (SIV) technique with a good spatial and temporal measurement scale commensurate with the linear and temporal scales of the Kolmogorov vortex dissipation. Considerable increase in the third-order moments of the turbulent velocity fluctuations and their spatial gradient describing the turbulent diffusion energy transport in the region of $y/\delta=0.45$ has been observed.

1. Introduction

The presence of streamwise adverse pressure gradient (APG) has a significant effect on the development of the boundary layer. Experiments on the turbulent boundary layer (TBL) with adverse pressure gradient, studied via point measurement methods of instantaneous velocity, explained the basis physics of such flows sufficiently [1-15]. It was obtained from the results of point measurement that the streamwise adverse pressure gradient leads to an increase in the deviation of the shape of the velocity profile from the wall law. Moreover, in [4] it was revealed from the analysis of experimental data that the streamwise adverse pressure gradient breaks a number of aspects of the mixing length theory valid for a zero-gradient boundary layer. The difference of velocity profile (in wall coordinates) and the logarithmic law in the region of $y/\delta=0.45$ ($\delta$ is the boundary layer thickness) obviously leads to a change in the magnitude of velocity gradient over the boundary layer thickness, and, consequently, to a change in the intensity of generation of turbulent pulsations [16] and Reynolds stresses [6, 7, 10, 16].

The appearance of a second peak on the profiles of turbulent pulsations in the region of $y/\delta=0.45$ indicates a possible considerable rearrangement of the mechanisms of turbulent energy production, diffusion and dissipation compared to zero-gradient boundary layer. However, despite the relevance and research interest in this task, a detailed study was impossible because of insufficient spatial resolution of the experimental and numerical methods. This paper is a follow-up of [16], where the field optical method of Smoke Image Velocimetry (SIV) has been employed. The sequence of turbulent energy production, diffusion and dissipation processes in the region of the boundary layer of $y/\delta=0.45$ under conditions of streamwise adverse pressure gradient has been described for the first time using the SIV technique [17] with a good spatial and temporal measurement scale commensurate with the linear and temporal scales of the Kolmogorov vortex dissipation [18].
2. Experimental setup
The air flow in a smooth plane diverging channel has been studied. Experimental setup for study the flow structure using the optical method of Smoke Image Velocimetry (SIV) is shown for in Figure 1. The test section was an asymmetric diverging channel of rectangular cross-section with 4.5 degrees opening angle. The channel width was 150 mm, length was 410 mm, inlet and outlet section heights were 27 mm and 60 mm, respectively. There was an upstream straight-run pipe section 13 with the length of 210 mm and smooth inlet 10 with 12:1 contraction before the diverging section. A turbulence generating grid 9 with 5 mm cell size, 1.6 mm steel wire diameter was mounted downstream of the smooth inlet 10. Abrasive P24 (ISO 6344-2) 12 was glued to the channel perimeter along a 50 mm section. This provided fully developed turbulent boundary layer in the measurement area during the experiments. Channel walls were made of transparent materials (glass and polycarbonate). Stable air flow rate downstream of the test section was provided by a regulating gate 11 and a 1.3 m³ receiver tank 2 mounted downstream of the latter. Flow rate was measured by an ultrasonic flowmeter 3 IRVIS RS4-Ultra mounted downstream of the receiver tank. The relative error in flow rate did not exceed 1%.

To visualize the flow pattern, the air-aerosol mixture (MT-Gravity fluid with medium fog density and average particle size of 0.1…5 μm; Safex aerosol generator 5) was supplied from the preparation chamber 4 to the channel inlet. The measurement area 6 was illuminated by a continuous diode-pumped solid-state laser KLM-532/5000-h 7. The flow pattern in the channel symmetry plane recorded by a monochrome high-speed camera Fastec HiSpec 8. The camera was equipped with a Navitar 1″F/0.95 lens (focal length 25 mm, manual focus).

To estimate the instantaneous velocity vector fields, an optical method of SIV (scaling factor of 0.0652 mm/y⁺ and frame rate of 9578 1/s) with interrogation window size of 17x17 y⁺ at a distance of 274 mm from the diverging section inlet has been employed. The scaling factor and frame rate in each section were selected based on preliminary estimates of the boundary layer thickness and the average velocity at the measurement area. Table 1 gives the characteristics of the boundary layer at the test section 6.

![Figure 1 Experimental setup for APG TBL](image)

Table 1. Main measured characteristics of turbulent boundary layer at a distance of 274 mm from the diverging section inlet.

| Value                                      | Value |
|--------------------------------------------|-------|
| Local freestream velocity, \( U_\infty \) (m/s) | 4.58  |
| Thickness TBL, \( \delta_{99%} \) (mm)    | 26.0  |
| Displacement thickness TBL, \( \delta^* \) (mm) | 7.09  |
| Momentum thickness TBL, \( \theta \) (mm)  | 3.94  |
| Dynamic velocity, \( u_\tau \) (m/s)      | 0.16  |
| Dimensionless pressure gradient parameter, \( \beta \) | 5.88  |

3. Results
Profiles of velocity and turbulent fluctuation intensity were written in wall coordinates

\[
y^+ = \frac{y u_\tau}{\nu}, \quad U^+ = \frac{U}{u_\tau}, \quad u_i u_j^+ = \frac{u_i u_j}{u_\tau^2}, \quad u_i u_j u_k = \frac{u_i u_j u_k}{u_\tau^3},
\]

(1)
The terms of the transport equation of the second-order velocity fluctuation momentum were normalized by \( u_i^3 \nu \), where \( u_i \) is the dynamic velocity estimated by the Clauser method.

Figure 2 shows the velocity profiles, double and triple correlations obtained from the SIV measurements. The profiles of velocity a), b), Reynolds stresses c), triple correlations d), e), f), and terms of the turbulent energy balance equation g), h), i) were also estimated by the approximation of the measured profiles of turbulent velocity fluctuation moments by polynomials in \( \log(y^*) \). Estimation of the derivatives of polynomial functions has three undeniable advantages. First, the approximation procedure is a kind of filter from the random uncertainty of the experimental measurements. Secondly, questions about the choice of the approximation scheme order for the derivatives and interrogation window overlap are not considered already. Third, it allows extension for the range of estimation of the characteristics, because this range is considerably reduced due to impossibility of estimation of derivatives with high-order difference schemes at the boundary points of the measurement area.

The features known in the literature [10, 19] and caused by the streamwise adverse pressure gradient are well observed in the velocity U* and Reynolds stresses profiles. The velocity profile U* obtained by the SIV measurements for APG and log law in wall coordinates \( y^* \) corresponds to the coordinate of \( y^* \approx 50 \), Figure 2 a). Starting from \( y^* > 50 \), the deviation from the logarithmic distribution is clearly traced on the velocity profile with APG: the region appears with a shape similar to the effect of wake law. The peak of the turbulent pulsation profiles shifts from the coordinate \( y^* \approx 10-20 \) to the region of the middle of the boundary layer thickness of \( y^* \approx 100 \). The velocity profile V*, Figure 2 b), has positive values, which appropriate to the flow with APG.

More substantial effect of the streamwise adverse pressure gradient was obtained for triple correlations, Figure 2 d), e), f). A new peak in the region of \( y^* \approx 200 \) was found on all the considered triple correlation profiles. The values of the triple correlations in the region of this coordinate exceed the maximum values of the triple correlations for a zero-gradient turbulent boundary layer in the region of \( y^* \approx 30-50 \) by a factor of 4-5. The growth of third-order moments indicates an increase in the convective transport of Reynolds stresses by a turbulent velocity fluctuation in the boundary layer under the streamwise pressure gradient.

In zero-gradient turbulent boundary layer, the terms of the Reynolds stress conservation equation reach their maximum in the viscous sublayer and buffer region and decrease monotonically toward the outer edge of the boundary layer. Changes in the profiles of turbulent velocity fluctuation moments indicate possible changes in the distribution of the densities of their production, diffusion, and dissipation in the case of the streamwise pressure gradient. Figure 2 g), h), i) clearly shows the substantial increase in the production and dissipation of Reynolds stresses in the region of \( y^* > 50 \) of the considered boundary layer. The deviation of velocity profile from the logarithmic law is observed in the region of \( y^* > 50 \) as it was above mentioned.

Turbulent diffusion defines the transport of Reynolds stresses from one flow region to another, without generating or damping them. This transport prevents the formation of large gradients in the spatial distribution of the Reynolds stresses. As Figure 2 c) demonstrates, the spatial gradient of the Reynolds stresses in the region of \( y^* \approx 100 \) is substantially smaller than in the near-wall region of the boundary layer (the profiles are presented in logarithmic coordinates \( y^* \)), so the streamwise pressure gradient did not cause a significant change in the distribution of the turbulent diffusion transport term. The streamwise pressure gradient had almost no effect on the molecular diffusion transport term: the latter, as expected, occurs only in the viscous sublayer of the boundary layer.

4. Conclusions
In present paper, we obtained new results from SIV measurements (profiles of triple correlations and the main terms of the Reynolds stress energy conservation equation) and tried to find a connection with the features known for APG TBL.

The profiles of triple correlations and terms of the Reynolds stress energy conservation equation estimated from the SIV measurements allowed us to describe in more detail the mechanisms of production, diffusion, and dissipation of turbulence in a boundary layer with a streamwise adverse pressure gradient. In the considered boundary layer, the profiles of velocity, second and third-order turbulent velocity fluctuations, production, dissipation of turbulent and molecular diffusion transport
in the wall coordinates do not differ from the same in the zero-gradient turbulent boundary layer in the viscous section, buffer region and initial section of the logarithmic sublayer. Further, the presence of streamwise adverse pressure gradient causes a substantial increase in the moments of turbulent velocity pulsations, accompanied by an increase in the values of energy production and dissipation along the boundary layer thickness in the case of deviation of velocity profile from the logarithmic law. However, the level of turbulent diffusion is comparable with the one for a zero-gradient boundary layer due to the insignificant gradient of the Reynolds stresses in the boundary layer thickness in this region.

Figure 2 Profiles of flow characteristics in a boundary layer with APG; a) streamwise component of the velocity vector; b) transverse component of the velocity vector; c) Reynolds stresses; d), e), f) third-order moments of turbulent velocity fluctuations; g), h), i) terms of the Reynolds stress energy conservation equation. Markers - SIV data, lines - SIV data polynomial approximation, dashed lines – profiles for zero pressure gradient TBL (on Fig. a) log law; on Fig. c) DNS [20])

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