Research of the boundary layer with an adverse pressure gradient by the Smoke Image Velocimetry method

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Abstract. The results of an experimental evaluation of velocity profiles, turbulent pulsations, generation and dissipation of turbulent energy in a nonequilibrium boundary layer under the adverse pressure gradient are presented. The profiles of characteristics are estimated by means of the field dynamics of the two-component instantaneous velocity vectors measured by the optical method Smoke Image Velocimetry. The opportunities of using the field measurement method SIV to study the spatial evolution of small-scale characteristics in a boundary layer with a pressure gradient have been showed.

1. Introduction
Flows with an adverse pressure gradient are often found in the equipment, for example, in the diffuser channel or when the airfoil flow. The adverse pressure gradient (APG) as well as the change of the kinematics and the dynamics of a turbulent boundary layer under certain conditions is an initiator of its separation.

Experimental studies of the turbulent boundary layer with APG perfomed by measuring the instantaneous velocity by the point contact methods by [1-13] have sufficiently fully explained the physical basis of such flows. By results of the measurement by the point contact methods it is shown that in the boundary layer with the adverse pressure gradient the velocity profile in a viscous sublayer, in the transition and in the part of logarithmic region corresponds to the velocity profile at zero-pressure-gradient (ZPG) flow. However, related to the outer edge of the boundary layer the adverse pressure gradient leads to the growth of a deviation of the profile shape from the law of the wall. Accordingly, the determination of a universal relation for the describing the influence of the pressure gradient on the velocity profile in the coordinates of the wall law was one of the first actual problem. [14] on the basis of empirical data has proposed to consider the function describing the velocity profile in the boundary layer of the divergent channel as a superposition (the linear combination of two universal functions) of the logarithmic law of the wall and the law of the wake

\[ U^* = 5.5 + 5.5 \log_{10} y^* + \Pi \sin \left( \frac{\pi y}{2\delta} \right) \]  

(1)

where \( \Pi \) according [8, 15] is a linear function of \( C_f^{0.5} \).
It is known the expression proposed by [2] in which the deformation value of a profile is independent of the wall shear but related instead to the local maximum in the Reynolds stress profile. In [2] is also noted the inconstancy of the obtained experimental data to some aspects of the mixing length theory valid for the zero-pressure-gradient boundary layer.

In [5] this discrepancy was investigated and described in more detail: the increase of the gradient of the mixing length from \( \kappa = 0.41 \) at the beginning of the logarithmic layer to \( \kappa = 0.78 \) on the boundary layer edge is found. However, this did not influence the mean velocity profile near the wall which satisfied the law of the wall with the conventional von Karman constant of \( \kappa = 0.41 \).

Research [5] has shown that despite the significant differences in the magnitude and distribution of Reynolds stress and triple correlations of velocity fluctuations in comparison with a boundary layer without the pressure gradient, the ratio between various components of stress remained unchanged. This is an indication that the adverse pressure gradient does not fundamentally affect the mechanism of the turbulent energy exchange.

In the works [4, 5, 8], there is noted the appearance of the second peak on the shear stress profiles in the central part over the thickness of the boundary layer in the region of \( y/\delta \approx 0.45 \) which is almost sixteen times higher than the value of the wall shear stress [5]. It is demonstrated the appearance of a new energy generation zone and its diffusion towards the wall. The turbulence production in the area of \( y/\delta \approx 0.45 \) is not inferior in intensity to the near-wall zone and depends linearly on the dimensionless parameter of the pressure gradient \( \beta \).

These facts made it necessary to pay close attention to the equation of turbulent energy balance

\[
\frac{\partial k}{\partial t} + \vec{V} \cdot \nabla k = -\frac{\partial}{\partial x} \left( \nu \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial y} \left( \nu \frac{\partial u}{\partial y} \right) - \frac{\partial}{\partial z} \left( \nu \frac{\partial u}{\partial z} \right) - 1 \frac{\partial}{\partial y} \left( \nu T_{xy} \right) \mu \frac{\partial u_{xy}}{\partial x} \nu \frac{\partial u_{xy}}{\partial y},
\]

but everything was complicated by an adjective "point" in the name of measurement method as all terms of the energy balance equation are expressed in spatial gradients of the turbulent fluctuations velocity. Interest in the terms of the energy conservation equation under the conditions of the adverse pressure gradient is also caused by the desire to improve the accuracy of numerical modeling of RANS with the semi-empirical models of turbulence.

Nevertheless, the use of the various unchecked hypotheses of the isotropic and frozen turbulence for flows with the adverse pressure gradient made it possible to reveal the number of interesting differences from the non-gradient case. Dissipation term has been evaluated in [5] in three ways: using the Taylor's hypothesis of frozen turbulence by the isotropic turbulence model [17, 18], using the onedimensional spectral density and by the full ratio. Although the fact that three approaches led to three different dissipation profiles, there is no doubt that the adverse pressure gradient influenced the appearance of a local increase zone in dissipation near the coordinate \( y/\delta \approx 0.4 \). Similar results were obtained in earlier studies [16, 19]. In [16] there was a twofold increase in dissipation in comparison with the results [19]. However, in [8] the dissipation profile also estimated on the basis of the hypothesis of Taylor's frozen turbulence and isotropy does not differ in shape from the ZPG boundary layer profile. In these studies, the similar influence of the adverse pressure gradient has been found and described for profiles of the generation terms, diffusion and advection, but as in the case of dissipation it is difficult to find the equivalent profiles among the published papers.

Thus, point measurement methods don't provide complete information about the coherent structures and terms of the turbulence energy balance equation which is extremely necessary for understanding the physical processes and development of semi-empirical turbulence models for the numerical solution of the RANS system.

Using a field optical method (PIV or PTV) as an instrument for measuring [20-26] has quite recently allowed to obtain the information about the spatial dynamics of coherent flow structures in channels with an adverse pressure gradient. However, the estimation of the equation terms of the turbulence energy balance isn't presented in these papers. It can be explaining by an actual problem of the PIV method.
in the balance between the spatial resolution and accuracy of small-scale turbulence structures measurement [27-39].

It is worth mentioning the potential use of the 3D-methods such as Shake-The-Box (STB) [40] and VIC+ [41] for estimating the values and dynamics of the small-scale turbulence characteristics in a boundary layer with a pressure gradient. The STB method is a Lagrangian particle tracking method (LPT) based on iterative particle reconstruction [42] which allows to reconstruct a three-dimensional trajectory of particles with their dense seeding (as in PIV). In the STB method the typical for Tomo-PIV reconstruction of the pixel volumes the cross-correlation method are not used. The results of [43] obtained by means of the Shake-The-Box method showed the potential of a 3D LPT method for reconstructing particle trajectories in flows with a high density of a seeding which would allow to carry out a direct evaluation the strain rate tensor components and dissipation, respectively. The VIC+ method [41] though showed high accuracy in measuring the small-scale characteristics in non-gradient boundary layer, unfortunately it isn’t an autonomous method and uses the results of particle velocity measurements (VIC+PIV) or acceleration (VIC+PTV) as the basic data. As a consequence, the accuracy of VIC+ depends strongly on the quality of the original data.

The Smoke Image Velocimetry measurement technique (SIV) [44] has been appeared not so long ago. The main difference between the SIV technique and the classical PIV method is the use of a much higher concentration of tracers. For particle seeding the same aerosol generators as PIV are used. Particles also well track the movement of the carrier gas phase, but due to the higher concentration the aerosol on the video image does not look like the separate illuminated particles whereas smoke with a continuous distribution of brightness in the image. In response to the better reflecting ability of smoke in comparison with separate particles it is possible to obtain sufficient brightness for image processing while recording with the high speed camera with normal sensitivity even at a high frame rate in the light sheet created by a low-power continuous laser. Therefore, the SIV technique allows to measure the dynamics of two-component vector fields of the flow velocity with a frequency of 10 kHz using rather simple equipment. It opens up new possibilities for investigating nonstationary processes. With such a sufficiently good temporal resolution, the use of a high tracer concentration also promotes to improve spatial resolution and reduce measurement noise.

In this paper an attempt to evaluate the generation and dissipation profiles of the turbulent energy in the boundary layer of the channel flow with the adverse pressure gradient based on the SIV flow velocity vector field measurements has been made.

2. Experimental setup
The air flow in a smooth plane expanding channel has been studied. Experimental setup for study the flow structure using the optical method of Smoke Image Velocimetry (SIV) is shown in figure 1. The test section J was an asymmetric diffuser channel of rectangular cross-section with 5 degrees angle of expansion, a 150 mm width, a 410 mm length, 27 mm entrance section, 60 mm output. Before the diffuser there was a prewired section K3 which was a rectangular 27×150 mm² channel with the length of 210 mm and a smooth inlet I0 with 12:1 contraction. A turbulence generating grid 9 with 5 mm cell size, 1.6 mm steel wire diameter was mounted downstream of the smooth inlet I0. Abrasive P24 (ISO 6344-2) I2 was glued onto 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 II and a 1.3 m³ receiver tank 2 mounted downstrsteam 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 at the distance of L=100 mm from the inlet was recorded by a monochrome high-speed camera Fastec HiSpec 8 with the
Frame resolution of 665×110 pixel (scaling factor of 0.0615 mm/pixel), frame rate $f = 9578$ 1/s. The camera was equipped with a Navitar 1”F/0.95 lens (focal length 25 mm, manual focus).

Figure 1. Experimental setup

Flow velocity fields were measured by optical SIV technique based on digital processing of flow pattern video recordings. Velocity vector fields here were estimated by the analysis of turbulent structure displacements visualized by smoke. Interrogation window size was 16×6 and 16×16 pixel. Velocity vectors were calculated from the digital images at the nodes of Cartesian grid with grid spacing of 2 pixels. Maximum displacement of turbulent structures between two consecutive frames was 12 pixels (at the boundary layer edge). Image resolution in Y+ coordinates was 1 pixel = 1.06 $Y^+$.

Profiles of velocity, turbulent fluctuation intensity and turbulent energy dissipation are written in wall coordinates $y+$, where shear velocity $u_\tau$ was estimated by the Clauser method. Turbulent energy dissipation was estimated by the hypothesis of local axisymmetry [45], which uses much less restrictive assumption to the full dissipation estimating compared to other hypotheses used to estimate the dissipation from 2D measurements of the velocity vector fields. A three-point central difference scheme was used to approximate the derivatives.

The presence of the adverse pressure gradient obviously increases the parametric dimension to describe the similarity laws. In addition to the classical the Re number for ZPG turbulent boundary layers, in the case of APG the dimensionless pressure gradient parameter $\beta$ proposed by Francis Clauser in 1954 is usually considered. This parameter describes the ratio of the pressure force to the friction force $\beta = (dp/dx)\delta^*/\tau_w$, where $dp/dx$ is the static pressure gradient. During the experiment pressure measurement was not performed, therefore the static pressure gradient was estimated according to the Bernoulli’s equation for the adverse gradient of the dynamic pressure calculated from the average velocity in the neighboring sections.

3. Results and discussion

Table 1 presents the main characteristics of the investigated turbulent boundary layer with the adverse pressure gradient calculated from the results of measuring the instantaneous velocity field by the SIV method. Also in Table 1 similar characteristics are presented for the non-gradient boundary layer studied by the authors earlier by means of SIV-measurements, which results were used to analyze the influence the adverse pressure gradient on the flow pattern.

| Characteristic                        | APG  | ZPG  |
|--------------------------------------|------|------|
| Freestream velocity, $U_\infty$ (m/s)| 6.14 | 4.06 |
| Thickness TBL, $\delta_{99\%}$ (mm)  | 13.44| 15.88|
| Displacement thickness TBL, $\delta^*$ (mm)| 2.81 | 2.44 |
| Momentum thickness TBL, $\theta$ (mm) | 1.76 | 1.58 |
| Dynamic velocity, $u_\tau$ (m/s)    | 0.26 | 0.204|
| Dimensionless pressure gradient parameter, $\beta$ | 2.68 | 0   |

The velocity profiles obtained by the SIV measurements for ZPG and APG in the coordinates of the wall law $y+$ correspond to the coordinate of $y+ \approx 90$ (Figure 2). Starting from $y+ \approx 90$ the deviation from the logarithmic distribution is clearly traced on the velocity profile with APG: the region appears
with a shape similar to the influence of the wake law. In the coordinates of the wall law the velocity profile measured under APG conditions is well described by the Coales ratio (1) with $\Pi = 4.7$.

To date, there is no clear description of the effect of APG on the turbulent pulsation profiles. Moreover, the results of the work (8, 26, 45) have changed the established ideas about this influence. In particular, it was found that under the influence of APG, the peak of the turbulent pulsation profiles shifts from the coordinate $y + \approx 10$ to the region of the middle of the boundary layer thickness and this process is evolutionary along the channel length.

The small adverse pressure gradient realized in this experimental study at a relatively small distance from the measurement section to the entrance into the expanding channel made it possible to fix only the initial stage of the evolution of the boundary layer under the APG conditions. The turbulent pulsation profiles in the region $30 < y + < 300$ compared to the TBL at ZPG increased almost threefold (Figure 3), which agrees well with the increase in the ratio of the generation level to the dissipation of the turbulent energy $P^+ / \epsilon^+$ in this section (Figure 4).

![Figure 2. Velocity profiles; - by (1) at $\Pi = 4.7$; - SIV, ZPG, 16x6; - SIV, APG, 16x16](image)

![Figure 3. Turbulent pulsation profiles; - DNS [46]; - SIV, ZPG, 16x6; - SIV, APG, 16x16](image)

![Figure 4. Profiles of generation $P^+$ and dissipation $\epsilon^+$ of turbulent energy; - DNS [47]; - SIV, ZPG, 16x16; - SIV, APG, 16x16](image)

4. Conclusions

The optical method SIV with a sufficient accuracy allows to measure the instantaneous velocity vector fields. The results of 2D measurements make it possible to apply more exact hypotheses about the turbulence isotropy in estimating the spatial large-scale and small-scale turbulent characteristics in comparison with point methods. Based on the results of measuring instantaneous velocity vector fields in the coordinates of the wall law, velocity profiles, turbulent pulsations, generation and dissipation of turbulent energy were estimated and well correlated with the theory of the boundary layer with the adverse pressure gradient. The presented in this paper approach is relevant for studying the influence of the adverse gradient on the evolution of the boundary layer along the channel length from the point of view of turbulent energy dynamics, which is one of the most demanded problems of modern mechanics.

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