Flow turbulence characteristics in channels under conditions of combined effect of pressure gradient and superimposed flow pulsations

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Abstract. Experimental data on the averaged and pulsating characteristics of the flow in divergent channels within a wide range of unsteadiness parameters have been obtained. To measure the dynamics of instantaneous velocity vector fields and Reynolds stresses, the optical method of Smoke Image Velocimetry (SIV) has been employed. The effect of forced flow pulsations on these characteristics has been described depending on the correlation between the maximum pressure gradient related to the variable cross-sectional area of the channel and flow unsteadiness.

1. Introduction
Significant number of papers on periodic pulsating flows in a turbulent boundary layer of a constant cross-section channel deal with a detailed state-of-the-art review of this issue carried out in [1]. Numerous experimental and numerical studies of such flows [2-20] and their analysis by criterial similarity numbers allow distinguish five regimes of turbulent flow in the boundary layer. However, there is no up-to-date experimental data on the effect of forced flow pulsations on the flow pattern in the boundary layer. This is due to the complexity of this task; in addition to the criterial similarity numbers used in the classification of pulsating zero-gradient flows, it is necessary to take into account the magnitude of the adverse pressure gradient caused by the change in the cross-sectional area. For example, one of such parameters is $\beta = \delta^*(dP/dx)/\tau$ - the dimensionless pressure gradient parameter, where $\delta^*$ is the displacement thickness, $dP/dx$ is the streamwise adverse pressure gradient, and $\tau$ is the wall shear stress.

Pulsating flow with a defined frequency $f$ and amplitude of the velocity $A_U$ (pressure) can be characterized as a flow with local pressure gradients (velocities) of defined level according to [21]. Hence, pulsating flows in diverging (converging) channels can be conditionally divided into 3 groups:

1) The pressure gradient in the flow related to the channel geometry is much larger than the local pressure gradient (in absolute values), which emerges due to the wave structure of pulsating flow. Here it is reasonable to expect that the superimposed pressure gradient will have a major effect on hydrodynamic and thermal processes.

2) The pressure gradients in the flow governed by the channel geometry and wave structure of the pulsating flow are of the same order of magnitude. In this case, both the superimposed pressure gradient and superimposed flow pulsations will have a comparable effect on the flow parameters.
3) The magnitude of the superimposed pressure gradient is much smaller than the value of the local pressure gradient due to superimposed flow pulsations. In such flows, the features of hydrodynamic and thermal processes apparently, will be mainly determined by superimposed pulsations of velocity (pressure).

According to [21], the following ratio was proposed for determining the type of pulsating flow regime in plane diverging and converging channels:

\[ fA \sim U \frac{\tan \phi}{2\pi h} \]  

where \( U \) is the average velocity, \( \phi \) is the opening angle, \( h \) is the section height. The left-hand side of (1), derived from the Euler equation for an ideal fluid in a one-dimensional formulation, describes the pressure gradient related to the wave structure of pulsating flow. The right-hand side, derived from the Bernoulli equation, describes the pressure gradient due to the channel geometry.

This paper presents the Smoke Image Velocimetry technique (SIV) used to study the spatial and temporal structure of turbulence in the boundary layer of the above three regimes of pulsating flows with adverse pressure gradient downstream [22, 23]. An extensive experimental data on the averaged and pulsating flow characteristics in diverging channels within a wide range of unsteady flow parameters were obtained based on the results of the SIV measurements.

2. Problem statement and experimental setup

The air flow in a smooth plane diverging channel has been studied. Experimental setup for study the flow pattern using the optical method of Smoke Image Velocimetry (SIV) is shown in figure 1. The test section was a plane channel of 150 mm width with transparent walls (polycarbonate). The inlet height of channel with opening angle \( \phi = 4.6^\circ \) was 24 mm, its outlet section was 60 mm. The inlet height of channel with opening angle \( \phi = 17^\circ \) was 40 mm, its outlet section was 100 mm.

Four pulsating flow regimes with the same time-averaged air flow rates were studied for each test section. Measurements for steady and pulsating flow regimes were performed in four sections. Section No. 1 was located in the inlet cross-section of diverging channel at the beginning of the change in the cross-section area; by analogy, section No. 4 was located in the outlet of diverging channel. Sections No. 2 and No. 3 were located between sections No. 1 and No. 4, dividing the channel into three sections of equal length. Tables 1 and 2 give the values of pressure gradients estimated by (1) related to the wave structure of the pulsating flow and due to the channel geometry presented for each regime and section. For clarity, the prevailing pressure gradient is highlighted for each case in the tables.

When performing SIV measurements, the scaling factor and frame rate in each section were chosen using the preliminary estimates of the boundary layer thickness and average velocity at the measurement section. The interrogation window size of 16x16 pixel were determined based on relative displacement (pixel/frame) of turbulent structures in the considered flow area and according to the recommendations [22]. Maximum displacement of turbulent structures between two consecutive

\[ \text{Figure 1. Experimental setup: 1 – test section, 2 – receiver tank, 3 – flowmeter, 4 – air-aerosol mixture preparation chamber, 5 – aerosol generator, 6 – SIV measurement area, 7 – continuous laser, 8 – high-speed camera, 9 – turbulence generating grid, 10 – smooth inlet, 11 – pulsator, 12 – abrasive, 13 – upstream straight-run pipe section, 14 – downstream straight-run pipe section.} \]
Table 1. Estimation of pressure gradients in the considered cross sections of channel with an opening angle of 4.6°.

| Section | f | 6 | 12 | 6 | 12 |
|---------|---|---|----|---|----|
| fA      | 1.8 | 1.8 | 1.8 | 3.6 | 3.6 | 3.6 | 5.3 | 5.3 | 5.3 | 5.3 | 11 | 11 | 11 | 11 |
| Utgg/2πh | 4.1 | 2.1 | 1.2 | 0.8 | 4.1 | 2.1 | 1.2 | 0.8 | 4.1 | 2.1 | 1.2 | 0.8 |

Table 2. Estimation of pressure gradients in the considered cross sections of channel with an opening angle of 17°.

| Section | f | 6 | 12 | 6 | 12 |
|---------|---|---|----|---|----|
| fA      | 1.8 | 1.8 | 1.8 | 3.6 | 3.6 | 3.6 | 5.3 | 5.3 | 5.3 | 5.3 | 11 | 11 | 11 | 11 |
| Utgg/2πh | 7.1 | 3.1 | 1.8 | 1.1 | 7.1 | 3.1 | 1.8 | 1.1 | 7.1 | 3.1 | 1.8 | 1.1 |

frames was 12 pixels (at the boundary layer edge). Image resolution in y+ coordinates was 1 pixel = 0.7 ... 1.0 y+. Flow velocity fields were measured by optical SIV technique [22, 23] based on digital processing of flow pattern video recordings.

Velocity profiles and Reynolds stresses were written in wall coordinates (2)

\[ y^+ = yu_r / \nu, \quad U^+ = U / u_r, \quad \overline{u'_j u'_j} = \overline{u_j u_j} / u_r^2, \]

where \( u_r = (\tau_w / \rho)^{1/2} \). Wall shear stress \( \tau_w \) was estimated using the Clauser method: correlation with the logarithmic section of the measured velocity profile and wall law.

3. Results

Imposed unsteadiness has almost no effect on the velocity profiles averaged over the phase of the flow pulsations for boundary layers in a diverging channels with pressure gradient governed by the change in the cross-sectional area that substantially exceeded the maximum gradient due to the flow unsteadiness. A slight impact is expressed only in a small decrease in the absolute values of velocity at the region of wake law (\( y^+ > 100 \)). Similarity of the velocity profiles in different sections of the diverging channel and pulsation phases is preserved in wall coordinates to \( y^+ < 50 \). The effect of superimposed unsteadiness on the time-averaged Reynolds stress profiles in wall coordinates was found to be strongly dependent on the cross section of diverging channel: there was no effect of unsteadiness closer to the inlet, if compared with the steady regime, and a decrease in these characteristics was observed downstream. This singularity could be caused by a change in the class of flow, namely, a gradual decrease in the pressure gradient related to the channel geometry, which is characteristic of the diverging channel (figure 2).

Forced pulsations have almost no effect on the velocity profiles averaged over the phase of the flow pulsations for boundary layers in a diverging channels with pressure gradient governed by the change in the cross-sectional area that is substantially smaller than the gradient due to the flow unsteadiness; however, the velocity profiles are split over the phase angle of the imposed flow pulsations after \( y^+ = 50 \). Forced pulsations led to a decrease in the time-averaged profiles of Reynolds stresses compared to the steady regime. Change in the second peak level of the profile of pulsations over the phase in the region of \( y^+ = 150 \) characteristic for diverging channel flows is revealed (figure 3).

4. Conclusions

An extensive experimental data has been obtained on the averaged and pulsating characteristics of the flow in divergent channels within a wide range of unsteadiness parameters in the channel. It was
established that the ratio of the pressure gradient governed by the change in the cross-sectional area to the gradient due to the flow unsteadiness for the considered flow regimes has almost no effect on the velocity profiles averaged over the phase of the flow pulsations in the wall units. The obtained profiles of Reynolds stresses averaged over the phase pulsations of flow have been shown to be fairly stable to the effect of the pressure gradient. However, in the case where the pressure gradient from superimposed flow pulsations is larger than the gradient governed by the change in the cross-sectional area averaged over the phase of the pulsations, the Reynolds stress profiles become similar to the pulsating flow profiles in a smooth channel of constant cross section (the peak on the profiles disappears near the coordinate $y^+ = 150$).

Figure 2. Pulsating boundary layer on the wall of the diverging channel with pressure gradient governed by the change in the cross-sectional area. Diverging channel 4.6°, section No. 2, $f = 6$ Hz, $A_U = 0.3$ m/s.
- log law; - steady regime; - pulsating regime, profile averaged over the phase of superimposed unsteadiness; - pulsating regime, profile in the current phase of pulsations.

Figure 3. Pulsating boundary layer on the wall of the diverging channel with pressure gradient governed by the change in the cross-sectional area. Diverging channel 4.6°, section No. 3, f = 6 Hz, $A_U = 0.89$ m/s.

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