The parametric investigation of influence of DBD actuator on the boundary layer under various Reynolds number

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Abstract. In the previous research, the wall-jet-like flow or vortical structures were generated using a single dielectric barrier discharge (DBD) actuator in still air. It has been shown that the actuator can generated so-called vortex train if it is powered by modulated voltage waveform. Now, the plasma DBD actuator is placed inside a rectangular channel and an interaction with boundary layer (BL) is studied. The characteristics of the BL are modifying by varying inlet velocity. The actuator is adjusted to be set in spanwise orientation which means that the generated wall-jet-like flow is oriented in the same meaning as the main flow or in the opposite direction. The interaction of vortical structures generated by actuator with BL will be described quantitatively from mean flow field.

1. Introduction

Recently, the dielectric barrier discharge (DBD) plasma actuator was designed, fabricated and flow field structures generated by this actuator were experimentally investigated during PhD study [1]. This actuator is supplied by very high-voltage high-frequency waveform which makes it easy to control the actuation (via modulation of the waveform) and there are no strict demands on the voltage source. Plasma actuators based on direct current utilization cannot offer above mentioned advantages and thus are not preferable for active flow control over streamlined bodies. The actuator was operated during two different regimes. The first one is steady regime when the plasma discharge induces wall-jet-like flow, whose main feature is that the biggest velocity occurs very close to the surface. The current geometry of actuator and electrical characteristics of power source allowed to gain the maximal velocity inside the wall jet up to 2 m·s^{-1} in the mean flow (peak velocities reached the value of 3-4 m·s^{-1}). The power consumption is in order of watts. On the other hand, after the application of rectangular modulation, there are series of vortices generated inside wall jet. The vortex shedding frequency, vortex dimension etc. are related with input voltage properties of the actuator. This unsteady regime seems to be very convenient for purpose to use active flow control very effectively in regard to power consumption and mainly sophisticated control of the flow – e.g. the vortices with different circulation would affect the control volume of the flow in different way – which should be utilized by continuously changing flow conditions of streamlined body.

In [1], a physical model describing the process of vortex street generation by this DBD actuator was presented under various conditions of modulation parameters. The vortex size, the distance between two consequences vortices, the circulation of a vortex, vortex trajectory and convective velocity of the vortex as well as mean flow field were parametrically described in relation on mainly

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frequency of modulation, duty cycle and voltage magnitude. The equation 1 expresses the relation between convective velocity of the vortex core in dependency on used modulation frequency and duty cycle:

$$u_{conv} = a_1 + a_2 \cdot DC + a_3 \cdot f + a_4 \cdot DC^2 + a_5 \cdot DC \cdot f + a_6 \cdot f^2 \qquad (1)$$

where coefficients a_i were obtained by experimental measurement. Now, it is well-known how this actuator works in steady air and the generally valid physical model about vortex generation can be utilized for study of interaction the plasma induce flow with a boundary layer.

Before an investigation of plasma actuation over Glaubert-Goldschmiedt (GG) body will be performed, a simpler case of boundary layer generated inside rectangular channel will be introduced in this article. An experimental approach is proposed to solve this challenging problem due to complex character of this phenomenon. Results will be obviously treated as a comparison of velocity profiles measured by diverse conditions of the flow and quantitative effect of plasma actuation will be presented.

2. Experimental setup

2.1. Actuator description
The plasma DBD actuator is considered as in simple wire configuration which means that it has just two electrodes. The upper electrode is very thin wire (tungsten) and is powered by high-voltage high-frequency waveform. The lower electrode is thin layer of gold and is grounded. There is a layer of dielectric with thickness of only 1 mm. The material of dielectric is silica glass which has extraordinally dielectric strength and thermal expansion. Electrode gap was set to two millimeters.

The plasma actuator was significantly modified according to previous type. The wire electrode was changed to be more thin (now the diameter is only 30 µm) and the wire electrode stretching mechanism had to be completely reconstructed so that the holder of a spiral torsion spring did not affect the free flow. The position of wire electrode is in the center of the actuator. Consecutively, the position of wire electrode due to the channel inlet is the same for both orientation of the plasma induced flow.

2.2. Power source
The power source was designed and manufactured in the Institution of Thermomechanics. The maximum voltage peaks is up to 12 kV and frequency can be adjustable, but is set to optimum value of 16 kHz. It has also so-called shut down function which enables to use amplitude modulation of the voltage waveform. Besides voltage magnitude and the frequency of waveform, the frequency of modulation and duty cycle of one period can be utilized as another control parameters of power feeding.

The parameters related to the modulation are to be fully adjustable during plasma actuator run and are determine to define the characteristics of generated vortices. If no modulation is applied, there is no presence of significant vortical structures inside wall-jet-like flow. The modulation frequencies range from units of Hz to tens of Hz. It was observed that if this parameter is higher than 80 Hz, the vortex train starts to be similar to unmodulated continuous jet (vertical structures are too small and distance between each other is tiny – limitations in spatial resolution of measurement system). Duty cycle determine the rate between the working cycle of the actuator (when plasma is on) and relaxation time (plasma is off). Note that DC of 30% means that the plasma discharge is on for 70% of one period.

2.3. Experimental layout
Since the aim of that study was to study the influence of plasma induced flow to the boundary layer, this actuator was placed inside plexi-glass channel connected to the outlet of the blow-down wind tunnel. The cross-section dimensions were 100 x 250 mm and total length was 3000 m (figure 1). The

actuator was mounted in spanwise configuration so that the distance of wire electrode from inlet edge of the channel was 2275 mm for both corresponding direction of induced flow and for opposite direction of induced flow. This distance was used to determine the Reynolds number (see table 1). The wall of the tunnel was smooth without no turbulators or VGs.

Table 1. The Reynolds number based on conventional BL thickness and on horizontal distance inlet-wire.

	Re_x	Re_δ
$V_{ext} = 5$ m·s^{-1}	$18 \cdot 10^3$	$750 \cdot 10^3$
$V_{ext} = 10$ m·s^{-1}	$34 \cdot 10^3$	$1500 \cdot 10^3$
$V_{ext} = 20$ m·s^{-1}	$55 \cdot 10^3$	$3000 \cdot 10^3$

The parameters of the boundary layers were modified by changing velocity inside the channel. These velocities were set to 5, 10 and 20 m·s^{-1} resulting in conventional boundary layer thickness (at the position of wire electrode) of 54, 51 and 41 mm, respectively. The thickness of BL was evaluated from the base case (the actuator was mounted inside the channel but actuation was off). The Reynolds numbers based on conventional thickness are listed in the table. 1.

The experiment was carried out under three different regimes of the actuator. The first regime - base case - was already introduced. The second regime is continuous wall jet generated by the actuator with condition of maximum applicable voltage magnitude and third regime is unsteady characterized by the varying modulation frequency of 10 or 20 or 50 Hz with the constant duty cycle of 30 %.
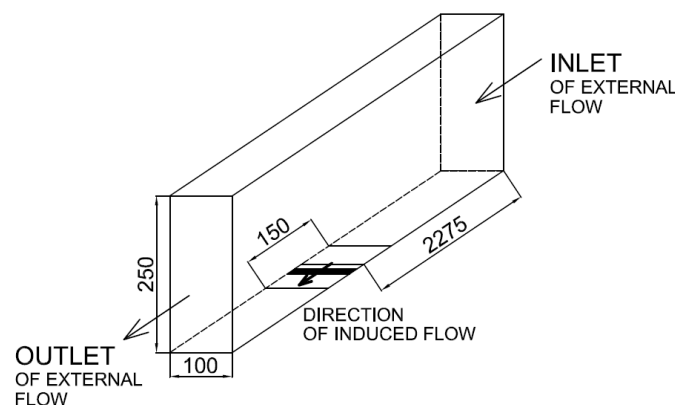

Figure 1. Experimental layout.

2.4. Measurement technique
The standard time-resolved Particle Image Velocimetry (TR-PIV) was used as a measurement technique. PIV composes mainly from a camera and a laser. Laser New Wave Pegasus Nd:YLF is a double-head pulse laser with a cylindrical optics and its wavelength is 527 nm, maximal frequency is 10 kHz and shot energy of one pulse is 10 mJ for 1kHz (10 W per head). Phantom V711 is a CCD camera with maximal resolution 1280 x 800 pixels and corresponding maximal frequency is 6 kHz (3000 double-images per second). The total memory of camera is 8 GB.

This experiment could be handled from two diverse points of view. The first one is to investigate the mean flow field and to compare the statistical characteristics. That is why the lower acquisition

frequency was utilized with longer time of data acquisition (100 Hz and 20 sec). This resulted in very good statistical properties. The second point of view, which is not considered in this article, is to study the interaction of induced flow with BL from dynamical point of view where maximal available acquisition frequency will be used.

3. Results

The flow field generated by plasma DBD actuator in still air can be seen at [2]. Further, only the interaction with boundary layer will be presented. Since the resolution of the camera in streamwise direction is not sufficient, the camera was traversing through five distinct positions. The position 0 was set to capture the flow instabilities upstream the wire electrode. Then the positions 1, 2, 3 and 4 were established to sample the flow downstream the actuator. The distance between two consecutive positions was set to allow the image covering. In this paper, there will be presented results from position 0 and position 2 which corresponds to the upstream distance $L = -5$ mm and downstream distance $L = 150$ mm, respectively.

Firstly, results based on velocity vector field will be presented. Figure 2 and 3 shows velocity vector map in position 2 with distribution of u-component of velocity. It can be seen that boundary layer with turned actuation on disposes with higher velocities close to the surface. The figure 4 shows the velocity field in the position 0 when the actuation is turned on and the plasma induced flow has opposite direction. A small region of velocity increase upstream of the wire electrode extends. Here, the velocities are increased instead the opposite ionic wind causes the deceleration of the flow. This effect is obviously caused by some instabilities and it should be studied with respect to the dynamics. Further downstream of the wire electrode, the boundary layer velocities are decreased (figure 9).
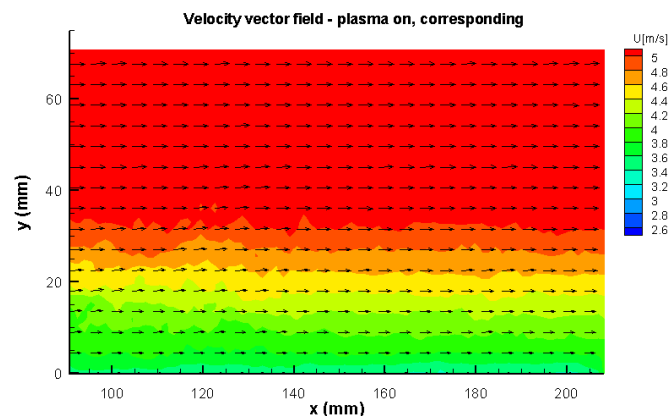

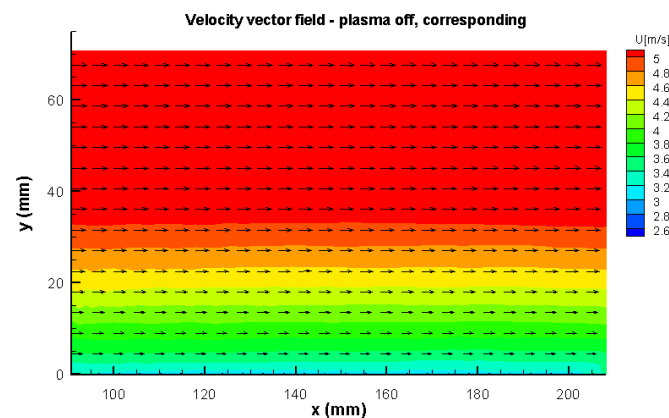**Figure 2.** *U*-component; plasma on – corresponding, $5 \ \text{m} \cdot \text{s}^{-1}$.

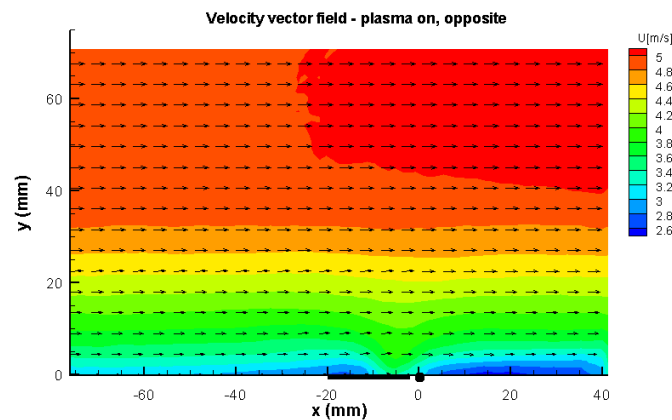**Figure 3.** *U*-component; plasma off, $5 \ \text{m} \cdot \text{s}^{-1}$.

Figure 4. *U*-component; plasma on – opposite, 5 m·s^{-1}.

The effect of plasma actuation is better to see from velocity profiles of the BL that are normalized with respect to the external flow. The base case (when the actuator was mounted in the channel but actuation was off) was compared for the case of corresponding and opposite direction of plasma induced flow. As it was expected, the actuator did not disturb the BL so both profiles look the very same. The figure 5 shows the comparison with the actuation on in steady regime and in unsteady regime (10 Hz and 30% DC) for the external velocity 5 m·s^{-1}. The velocity profile was improved about 8% in bottom part for steady actuation and slightly less for unsteady actuation. Naturally, the effect of plasma actuator became weaker after that the external flow velocity was increased (figure 6 and 7). When the velocity was enhanced to the value of 10 m·s^{-1} and 20 m·s^{-1} the effect was about 6% and 2%, respectively. The comparison of various modulation frequencies is not plotted here, but the most promising results seems for the highest modulation frequency when the vortex train starts to be similar to the continuous wall-jet-like flow which is more effective.
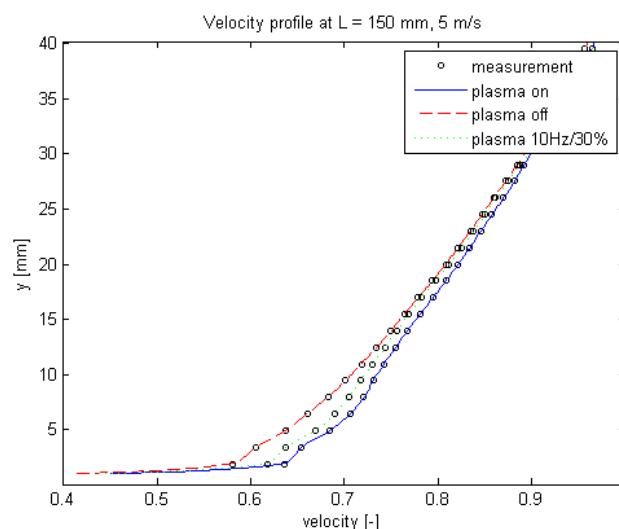

Figure 5. Effect of plasma actuation – steady/unsteady.

The comparison of standard deviation of velocities showed that plasma induced flow could stabilize the BL under specific conditions. The actuation by 5 m·s^{-1} was able to significantly decrease standard deviations in the area of 20 mm from the wall (figure 8) without distinction if the steady or

unsteady actuation was used. This stabilization effect became weaker for higher velocities of external flow.
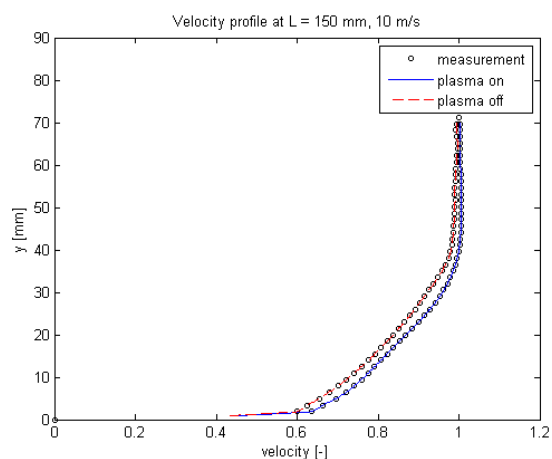

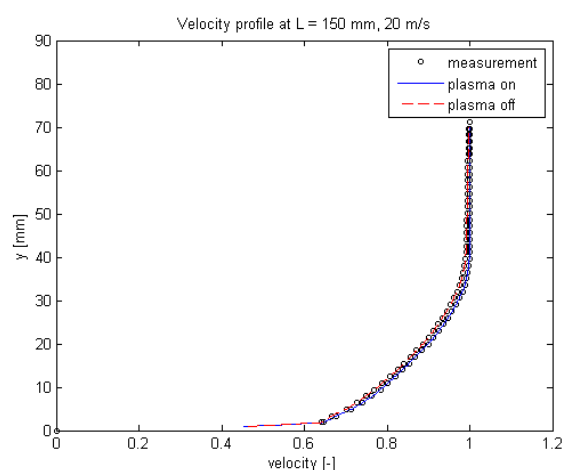**Figure 6.** Effect of plasma actuation – steady/unsteady.

Figure 7. Effect of plasma actuation – steady/unsteady.
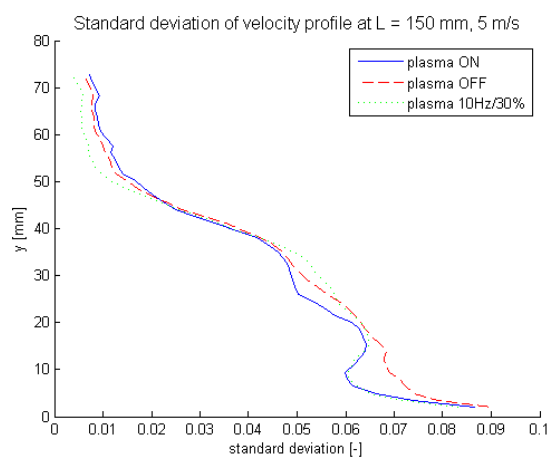

Figure 8. Velocity standard deviations.

Very interesting results were obtained for opposite orientation of the actuator. The figure 9 shows how the velocity profile is decelerated (about 6%) far from wire electrode downstream. And again the deceleration is not so significant for the case of unsteady modulation. The standard deviation distribution shows the destabilization effect of opposite actuation on the BL (figure 10).
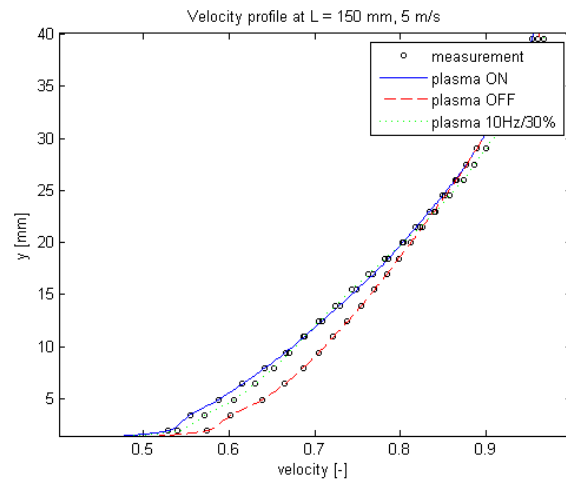

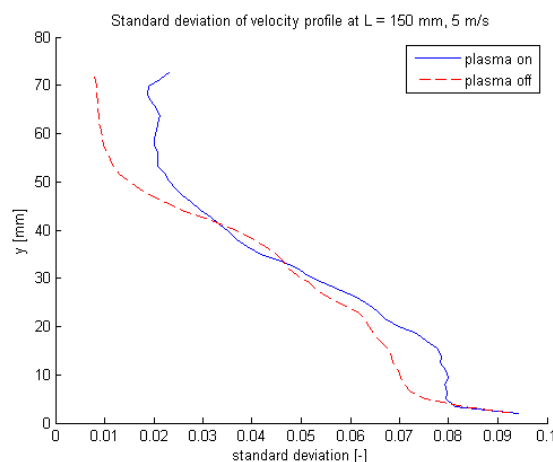**Figure 9.** Effect of opposite plasma actuation.

Figure 10. Velocity standard deviations – opposite actuation.

There is also effect upstream of the wire electrode (L = -5 mm) as it can be seen at the figure 11. In this very tiny region, plasma actuation can increase the velocities about 9 % close to the surface. This diagram also shows the case when actuation is in corresponding direction with respect to the external flow (green dotted line) where one can also observe the velocity gain which is caused by suction effect of plasma induced flow. Last picture denotes extensive standard deviation decrease (about three times).

4. Conclusions
The interaction of plasma induced flow with BL in a rectangular channel was investigated via velocity profiles from mean flow fields. Plasma actuation is capable to enhance velocities close to the surface about approx. 10%. Further, analyses of velocity standard deviations showed that plasma actuation can

stabilize the region inside the BL. If the induced flow is oriented in opposite direction than mean flow, the velocities are decelerated downstream and are increased in small region upstream.
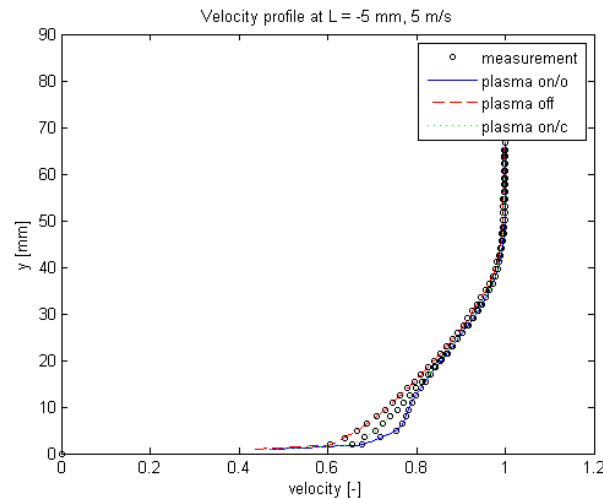

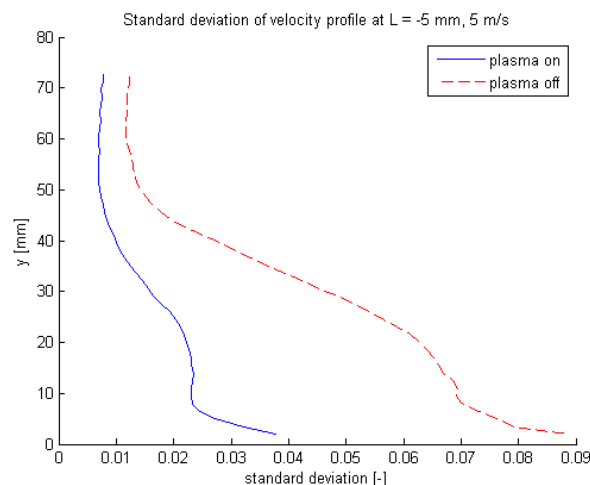**Figure 11.** Effect of opposite actuation upstream.

Figure 12. Velocity standard deviations upstream.

5. References

[1]   Procházka P 2013 Dissertation thesis. Praha ČVUT
[2]   Procházka P, Uruba V, Antos P 2013 *Proceedings in Applied Mathematics and Mechanics* **13** 1 343
[3]   Procházka P, Uruba V 2013 *Experimental Fluid Mechanics 2013. Kutná Hora* 577