The structure of perturbations in boundary layer created by a pulsed electric arc in the transversal magnetic field

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Abstract. The paper presents results of experimental study of surface MHD arc actuator as vortex generator in boundary layer. The study was held at flow velocities 20 to 50 m/s. The pulsed arc discharge was organized in external magnetic field. The amplitude of current was varied in the range from 8A to 160A, while pulse duration was from 40 µs up to 380 µs. The flow velocity was measured by PIV method. It was found that the increase of pulse duration leads to increase circulation vortex. The destruction of induced vortex was observed at 40 mm downstream from spark gap.

Introduction

Plasma actuators based on discharges of various types are investigated as a method of mixing intensification and flow control in various aerodynamics problems [1,2]. It is known that the main disadvantage of commonly used devices based on a dielectric barrier discharge is their relatively low energy efficiency (~0.1%) and limited forcing amplitude (<80 mH/m). An alternative to DBD-based devices can be sought in actuators based on an arc discharge in a magnetic field. Simple estimates show that the gas acceleration efficiency by ponderomotive force can be at the level of 1% and higher, and the force magnitude at a magnetic field strength of 1 T can be as high as 100 N/m at a current of 100 A. An arc in a magnetic field was studied in connection with the boundary layer separation control [3], as well as mixing intensification in reacting media [4].

The flow around a stationary electric arc in a transverse magnetic field was actively studied in the 70-80s, both experimentally and numerically. It was shown [5,6] that in the vicinity of the conducting region, due to the nonpotentiality of the Ampere force, a pair of vortices arises, moving together with the arc. In [7], a study of the flow structure arising in the vicinity of the arc channel, fed by a pulse with a duration of 40-300µs was made. For an arc of finite length, the vortices join near the electrodes, forming a single toroidal vortex stretched along the channel.

For the boundary layer separation control, it is necessary to understand how the vortex created by the discharge will evolve in the presence of an external shear flow. The aim of this work was an experimental study of perturbations created in a turbulent boundary layer by a pulsed arc discharge in a magnetic field, as well as an estimate of the perspective of this type of actuator for flow separation control.
Scheme of experiment

Experimental investigation of the flow induced by arc discharge in an external magnetic field were carried out in the wind tunnel Dunya-2 JIHT RAS. A scheme of the test section and the main elements of the measurement system is shown in Figure 1. A ceramic plate with tungsten electrodes was mounted flush with the streamlined surface. The electrodes have a length of 50 mm along the arc direction and a thickness of 0.1 mm, the distance between the electrodes in the wide part is 7 mm, in the narrow part where the discharge is initiated – 1 mm. The electrodes had the shape of two parallel tapes with tips that form a narrow region between them. To create a magnetic field, a permanent magnet was mounted under the ceramic plate, the magnetic field is directed perpendicular to the wall, its magnitude was 0.33 T [8]. The experimental conditions corresponded to the initial air temperature T~293 K and atmospheric pressure. The velocity of the oncoming flow was from 20 to 50 m/s. The profile of longitudinal velocity component corresponded to a turbulent boundary layer; for a velocity of 20 m/s, the profile is shown in Figure 1b. The angle of the electrodes relative to the flow varied from 0 to π.

![Figure 1. a) Test section and PIV measurement scheme, 1 - electrodes, 2 - plasma, 3 - laser knife, 4 - two PIV cameras b) Speed profiles in different positions along the x axis.](image)

Experimental results

To form a current pulse, the LC circuit was used. A capacitor of 0.1–2 μF was charged up to 2.5–5 kV. The current pulse was triggered by thyatron. A high-frequency dielectric barrier discharge was used to pre-ionize the interelectrode gap and to provide an accurate time delay less than τ<1 μs for shooting measuring equipment. Current shape was a half-period of a sinusoid, the parameters of which varied in the range: amplitude – from 8 A to 160 A, pulse duration from 40 μs up to 380 μs so that the energy pulse input remained same (Figure 2); its duration and amplitude were determined by the parameters of the LC circuit. During the pulse duration 130 μs, current amplitude 47 A, an energy of about 0.5 J was deposited into the arc channel. The discharge characteristics did not have a significant effect on the current due to the low resistance of the arc channel R_d compared to the inductance L impedance L/τ≫R_d.

It should also be noted that during first 3 μs after the discharge initiation there is an additional energy input to the discharge. This energy is supplied from the capacitance of a coaxial cable (~250 pF) after the formation of a spark channel in the gap. On current traces this leads to the formation of powerful oscillations with amplitude of up to 90 A. The upper estimate of the energy deposited in the channel during the first 3 μs after the breakdown gives a value of 0.03 J.

A detailed investigation of the evolution of the flow arising during and after the pulse was performed experimentally for the peak current 47 A and pulse duration 130 μs and numerically [9]. At the moment of the breakdown in the interelectrode gap, a conductive channel is formed, accompanied by the propagation of a cylindrical shock wave in the gas surrounding the discharge, which dissipates quickly enough into the compression-rarefaction wave. After the wave leaves, a hot region with a low density remains at the plate surface. The formed conducting channel is driven into motion in an external...
magnetic field. At this stage, the flow structure is determined mainly by Joule heating of the gas channel and its acceleration under the action of the Ampere force. As a result, an asymmetric expansion of the arc cavity occurs, which leads to compression of the surrounding cold gas in the head of the cavity. In the vicinity of the arc channel, a pair of vortices is formed, initiated by the dipole structure of the pressure distribution in the region of the front part of the arc cavity. At the end of the current pulse, the energy supply into the hot region of the gas disappears. In the process of flow relaxation, cold gas is sucked into the bottom of the cavity, which is due to the asymmetry of the pressure field in the rarefaction wave. The maximum gas suction rate can reach 30-50 m/s that constitute up to 30 % of the maximum gas expansion rate at the time of energy supply.

It is worth noting that since the arc velocity at these conditions significantly exceeds the flow velocity ($V_{\text{arc}} = 100$ m/s, $V_\infty = 20$ m/s), the process of the formation of a vortex disturbance in the flow can be considered, at a first approximation, as a combination of two simple steps. The first step is responsible for the formation of a vortex in a quiescent medium, and the second – for its convection by the flow in a boundary layer. Viscous friction at the wall leads to the dissipation of the lower part of the toroidal vortex and its transformation into a horseshoe-shaped structure. The presence of a shear in the boundary layer deforms the vortex. Resulting disturbance structure consists of a pair of vortex filaments elongated with the flow and a short bridge between them in a downstream region. The characteristic size of this structure is 5-10 mm. The appearance of a vortex in the boundary layer leads to mixing of the media and the transfer of an external flow momentum into the boundary layer (Figure 3). The vortex dissipation occurs is 40 mm.

The disturbance magnitude can be estimated from the circulation (vorticity integral) of the velocity in the longitudinal vortices. Figure 4 shows the typical dependence of circulation at various durations of the discharge pulse, with the integral of the current in the pulse remaining constant. It can be seen from the figure that an increase in the pulse duration from 40 to 380 μs leads to a significant increase in circulation from 0.6 to 12.5 m$^2$/s with a systematic measurement error of 0.2 m$^2$/s. This growth is mainly due to an increase in the size of the vortex structure, while the velocity in the vortex decreases. Similar dependencies were obtained for free stream velocities up to 50 m/s. However, at high velocities, the effect of the arc discharge on the flow was reduced.

![Figure 2](image.png)

Figure 2. Current and voltage waveforms of typical plasma actuator operating modes.
Figure 3. Velocity field of the longitudinal component $V_x$ (above). $V_x = 20$ m/s, $I = 50$ A, $T = 130$ μs, $x = 1$ mm. On the left – the discharge is off, on the right – the discharge is on. Three-dimensional visualization of a vortex by the Q criterion and longitudinal vorticity in the wake of the discharge.

Figure 4. Vortex circulation in the wake of the actuator in the region of negative vorticity as a function of pulse duration $V_x = 20$ m/s, $\alpha = \pi/2$.

Summary

As is known, one of flow separation delaying mechanism is the introduction of additional momentum into the boundary layer from the main flow by mixing the gas at the interface [10]. The operation of the MHD actuator was shown to induce such kinematic momentum transport. On the other hand, it should
be noted that the obtained parametric data do not give an explicit answer to the question of universal operating regime of the actuator in the tasks of boundary layer separation control. Thus, the discharge operation with high pulse duration and high level of circulation in the vortex core will be optimal in thick boundary layers. Apparently, the crucial parameter will be the correspondence between the size of the perturbation region created by the discharge and the thickness of the boundary layer near the separation point. At the same time, the data obtained make it possible to estimate the characteristic scales of the disturbances created by the discharge, as well as to draw conclusions about the length of the vortex dissipation in the boundary layer.

Acknowledgments

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