Flow separation control on a smooth ledge using an arc discharge in a magnetic field

P N Kazanskii1,@, I A Moralev1 and A Ya Kotvitskii 1,2
1 Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
2 Bauman Moscow State Technical University, 105005, Moscow, Russia
E-mail: fokkoo@yandex.ru

Abstract. This paper presents results of experimental study for surface MHD arc actuator as vortex generator in boundary layer of smooth ledge. 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 80 A, while pulse duration was 80 μs. The flow velocity was measured by PIV method. It was founded that the location of the arc breakdown is critically impotent. The arc must be struck just above the separation point. The operation of the actuator in a pulse-periodic mode leads to a shift in the middle position of the flow separation point at frequencies up to 700 Hz and higher. A three-dimensional analysis of the separation region structure behind the MHD actuator shows that the main effect on the flow occurs in the interelectrode gap.

1. Introduction
Plasma actuators based on various discharge types are being investigated for mixing intensification, as well as flow control in various aerodynamic applications [1, 2]. It is known that main disadvantage of common devices based on a dielectric barrier discharge is their relatively low electromechanical energy efficiency (~ 0.1%) and limited unit force (<80 mH / m). Actuators based on an arc discharge in a magnetic field can serve as an alternative to sDBD actuators. Simple estimates show that the efficiency of gas acceleration by the ponderomotive force can be up to 1% and higher, and the amplitude of the impact on the flow at a magnetic flux density of 1 T can be up to 100 N/m at current of 100 A. An arc in a magnetic field was investigated for controlling the flow in the boundary layer [3], to intensify the mixing of reacting media [4], to control flow separation on bluff bodies [5] and aerodynamic profiles [6].

The flow around a stationary electric arc in a transverse magnetic field was actively investigated in the 70-80s, both experimentally and numerically based on the MHD approximation. It was shown [7, 8] that in the vicinity of the conducting region, due to the non-potential of the Ampère force, a pair of vortices appears, moving together with the arc. In [9], the study of the flow structure arising in the vicinity of the arc channel with pulse duration of 40-300 μs was carried out. It is shown that a pair of vortices appears in the vicinity of the channel, the lower of which dissipates due to viscous friction. For an arc of finite length, a pair of vortices is closed, forming a toroidal vortex elongated along the channel.

It is necessary to understand the formation processes of vortex by means of discharge in the presence of an external shear flow. Thuse will lead to solution of flow control in the boundary layer. The experimentally study the disturbances created in a turbulent boundary layer by a pulsed arc
discharge in a magnetic field, as well as to assess the prospects of this actuator type for problems of flow separation control was the purpose of this work.

2. Scheme of experiment

Experimental studies of flow separation control were carried out on a curvilinear model using an MHD actuator at the Dunya-2 gas-dynamic stand of the JIHT RAS. There was an insert consisting of a confuser, a flat plate, and a curved diffuser with an MHD actuator inside the rectangular channel of the tube working section. A diagram of the working part and the main elements of the measuring system is shown in figure 1. A special turbulisator and sandpaper were fixed on the plate, which made it possible to form a thick turbulent boundary layer with a displacement thickness of about 7 mm. A ceramic insert with tungsten electrodes was installed flush with the streamlined surface of the curved model. The electrodes had length 50 mm along the direction of arc movement and a thickness of 0.1 mm, the distance between the electrodes in the wide part was 7 mm, in the narrow part of the discharge initialization 1 mm. The electrodes were shaped like two parallel strips with a sharpener - a narrow section. To create a magnetic field, a permanent magnet was mounted under the ceramic support; the magnetic field was directed perpendicular to the wall, its value is 0.2 T. The experimental conditions corresponded to the initial air temperature ~ 293 K and atmospheric pressure. The oncoming flow velocity was from 20 to 50 m/s. The electrodes were installed at a zero angle to the flow, the flow studies were carried out in the central plane (between the electrodes) using the PIV method.

The velocity field was investigated using the Stereo PIV LaVision FlowMaster. The flow was seeded with oil particles with a diameter of ~1 μm and dynamic relaxation time of about 1–2 μs. The particles were illuminated by means of two successive laser pulses formed as a laser sheet with a thickness of 0.5 mm with a time delay of ~ 2 μs between them. The images were registered with two cameras which had resolution of 4 Mpix arranged at an angle of 20° with respect to each other. The cameras were equipped with the Micro-Nikkor f 205 objectives with an extended back flange and Scheimpflug adapters. The images were processed using the cross-correlation method with a window size of 32 × 32 pix and a 50% overlap. The resulting resolution of the vector fields was 0.2 mm in the plane of the laser sheet. To obtain the three-dimensional velocity field, 30 two-dimensional distributions of the components \((v_x, v_y, v_z)\) with a distance \(\Delta z = 1\) mm between them were taken. The resulting velocity field was obtained by averaging 75 instantaneous frames. To combat laser glare, the glossy surfaces of the model were painted over with matte black paint.

![Figure 1. Scheme of an experiment to study flow separation on a curved wall. 1- electrodes, 2- arc discharge, 3- laser knife, 4- camera.](image-url)
3. Experimental results

Power supply was based on the LC circuit. A capacitor $C = 1 \, \mu\text{F}$ was charged up to $3–5 \, \text{kV}$. The thyratron acted as a controlled key. A high frequency DBD was used to preionize the interelectrode gap and to provide better delay time accuracy (less than $\tau < 1 \, \mu\text{s}$) with the PIV system. The current shape was a half-cycle of a sinusoid with an amplitude of $80 \, \text{A}$ and a pulse duration of $80 \, \mu\text{s}$ (figure 2); the duration and amplitude were determined by the parameters of the LC circuit. The $0.5 \, \text{J}$ energy deposited into the arc channel was obtained by integrating current and voltage oscillograms. The characteristics of the discharge did not significantly affect the shape of the discharge current strength signal due to the low resistance of the arc channel $R_d$ compared to the inductance $L$ of the impedance $L / \tau \gg R_d$.

![Figure 2. Oscillograms of current and voltage of typical operating modes of a plasma MHD actuator.](image)

After arc discharge breakdown, a conductive channel was formed in the interelectrode gap. In first $30 \, \mu\text{s}$, the shock wave is observed. However, its effect on the flow separation point apparently insignificant, therefore a detailed analysis of the parameters of the shock wave was not carried out. A hot area of low density remained at the surface of the model. The formed conducting channel was set in motion in an external magnetic field. At this stage, the flow structure was determined mainly by the Joule heating of the current region and its acceleration under the action of the Ampere force. As a result, an asymmetric expansion of the arc cavity occurred, which led to the compression of the surrounding cold gas in the head of the cavity. At the end of the current pulse, the energy input to the hot region of the gas disappeared. In the process of flow relaxation, cold gas was sucked into the bottom of the cavity, which was caused by the asymmetry of the pressure field in the rarefaction wave. The maximum gas suction rate could reach $30 \, \text{m/s}$ and was up to $30\%$ of the maximum gas expansion rate at the moment of power supply. The structure of the disturbance recorded in the boundary layer on a flat plate is shown in figure 3. One can see that it is a horseshoe-shaped vortex elongated along the

![Figure 3. The structure of the vortices created by the MHD actuator in the boundary layer. The actuator angle towards flow was 0 degrees. Pulse current 80 A, duration 80 μs.](image)
flow. In this case, the upper part of the disturbance turns out to be farther from the wall, in a higher-speed flow. As the vortex moves, the vortex filament is stretched. The three-dimensional structure of the flow in the vicinity of the surface MHD actuator is described in [10] circumstantially.

It can be assumed that the displacement of the flow separation point is possible both due to the expansion of the gas at the head of the cavity at the moment of active energy supply, and due to the suction of gas into the bottom of the cavity after the discharge is turned off. A detailed study of the flow separation point evolution arising during and after the existence of the discharge was carried out for the 80A 80μs regime, the incident flow velocity of 50 m/s. Two locations of the gas discharge breakdown region were tested. One was immediately before the flow separation point 15° and the other was immediately after the flow separation region 30°. The velocity fields were investigated in the phase-averaged mode (with a fixed delay), the averaging was profiled over 75 frames.

![Figure 4](image-url)

**Figure 4.** Velocity field of the longitudinal component \( V_x \) for reference flow (a), arc breakdown location below the flow separation point (b), the arc breakdown location above the flow separation point (c). \( V = 50 \text{ m/s}, I = 80 \text{ A}, t = 80 \mu \text{s} \).
The evolution of the velocity fields after the pulse for three cases: reference case and for two actuator positions is shown in figure 4. While discharge is off, the average position of the separation point corresponds to an angle of 18 degrees measured from the vertical figure 4a. When the arc is ignited above the separation point, it can be seen that the MHD interaction leads to a displacement of the separation point down the model surface by 9 mm in 0.5 ms (figure 4b). Then in next 0.5 ms the flow relaxes to an unperturbed state with a damped oscillation of the separation point position. When the discharge gap is located below the separation point, gas suction is clearly seen. It is formed in the wake behind the arc. In this case, the resulting vortex structure quickly moves to the area of the backflow (figure 4c). In the wake behind the arc, gas leaks from the core of the flow, which divides the area of the backflow into parts. The flow separation point shifts downward along the surface of the model slightly, and a small area of backflow reappears in 0.1 ms and merges with the main zone of the backflow (figure 5). Thus, it is shown that the rate of cold gas suction into the aerodynamic wake of the arc is insufficient for a significant shift of the separation point, and the location of the discharge gap above the separation point is critically important. The relaxation time of the flow to the unperturbed state, equal to 1 ms, makes it possible to estimate the minimum frequency of the generator operation in the pulse-periodic mode - not less than 1 kHz for the given flow mode.

![Figure 5](image)

**Figure 5.** The evolution of separation point position after the arc discharge ignition. \( V = 50 \text{ m/s}, I = 80 \text{ A}, t = 80 \mu \text{s}. \)

Average velocity fields at different ignition frequencies are shown in figure 6. An insignificant region near the discharge breakdown is still unseeded and has empty vectors of velocity field because of random 75 frame averaging. However, it is easy to see that an increase of discharge ignition frequency leads to separation point shift downstream. The displacement of the separation point monotonously depends on the discharge ignition frequency and does not saturate at the selected frequency range. Conceivably, saturation will be observed at a pulse repetition rate of more than 10 kHz. The experimental data are given for actuator operating frequencies up to 700 Hz, since at frequencies above 1 kHz the power supply did not provide stable operation at a given pulse current.
Figure 6. Velocity field of the longitudinal component $V_x$ for an undisturbed flow and when the arc breakdown location is above the flow separation point. $V = 50 \text{ m/s}$, $I = 80 \text{ A}$, $t = 80 \mu\text{s}$.

Since the perturbations created by the actuator occupy a relatively small area of the model's range, the question arises about the necessary periodicity of the arrangement of the actuators. In the course of the study, the three-dimensional structure of the boundary of the separation region was evaluated during the operation of the actuator. Figure 7 clearly shows that the displacement of the flow separation point occurs in the region bounded by the electrodes. Strong velocity gradients are observed at the discharge boundary. Beyond the limits of the electrode gap, the effect of the discharge on the flow separation is insignificant.
4. Summary

The ignition of an arc discharge in a magnetic field can affect the structure of the flow behind a smooth step. During the operation of the actuator, the displacement of the flow separation point is observed; with the parameters used in this work, it was up to 10 mm. The location of the arc breakdown has been found to be critical. The arc must be struck just above the separation point. The operation of the actuator in a pulse-periodic mode leads to a shift in the middle position of the flow separation point at frequencies up to 700 Hz and higher. A three-dimensional analysis of the structure of the separation region behind the MHD actuator shows that the main effect on the flow occurs in the interelectrode gap. The three-dimensional structure of the flow separation line on the aerodynamic model confirms that the effect of the discharge on the flow structure outside the electrode gap is insignificant.

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References

[1] Wang J-J, Choi K-S, Feng L-H, Jukes T N and Whalley R D 2013 Recent developments in DBD plasma flow control Prog. Aerosp. Sci. 62 52–78
[2] Kriegseis J, Simon B and Grundmann S 2016 Towards In-Flight Applications? A Review on Dielectric Barrier Discharge-Based Boundary-Layer Control Appl. Mech. Rev. 68 020802
[3] Bocharov A, Leonov S, Klement’eva I and Bityurin V 2003 A study of MHD assisted mixing and combustion 41st AIAA Aerospace Sciences Meeting and Exhibit p 0378
[4] Pafford B, Choi Y-J, Sirohi J and Raja L L 2013 Experimental characterization of the RailPAc plasma flow actuator 44th AIAA Plasmadynamics and Lasers Conference p 2886
[5] Munkhoz D.S., Bityurin V.A., Klimov A.I., Kazanskii P.N., Moralev I.A., Polyakov L.B., Tolkunov B.N. 2017 Air flow control around a cylindrical model induced by a rotating electric arc discharge in an external magnetic field. part i Technical Physics Vol: 62 N: 7 pp: 1013-1018

[6] Kazanskiy P.N., Moralev I.A., Bityurin V.A., Efimov A.V. 2016 Active flow control on a NACA 23012 airfoil model by means of magnetohydrodynamic plasma actuator Journal of physics: conference series Vol: 774 N: 1 pp: 012153

[7] Lord W T 1969 An electric arc in a transverse magnetic field: a theory for low power gradient J. Fluid Mech 35 689–709

[8] Cowley M D 1967 A boundary-layer model for balanced arcs (Report of Department of Mechanical Engineering Massachusetts Institute of Technology)

[9] Moralev I, Kazanskii P, Bityurin V, Bocharov A, Firsov A, Dolgov E and Leonov S 2020 Gas dynamics of the pulsed electric arc in the transversal magnetic field J. Phys. D. Appl. Phys.

[10] P. N. Kazanskii, A. Ya. Kotvitskii, and I. A. Moralev 2021 Three-Dimensional Flow Structure in the Vicinity of the Pulsed Surface Arc Discharge in a Magnetic Field ISSN 1063-7850, Technical Physics Letters Vol. 47, No. 6, pp. 536–539