Air flow control around a cylindrical model induced by a rotating electric arc discharge in an external magnetic field

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Abstract. The structure and dynamics of a near-wall gas flow produced by a rotating electric arc discharge in an external magnetic field around a cylindrical model with and without an incoming flow has been investigated ($M < 0.2; Re < 9.10^4$). The electric arc on the model has been produced by a combined electric discharge (low-current RF discharge + high-current pulse-periodic discharge). Permanent magnets with induction $B \approx 0.1$ T have been placed inside the cylindrical models. Ring electrodes are arranged on the surface of the model. The structure and dynamics of the near-wall gas flow around the cylindrical model have been investigated using high-speed photography, as well as the shadowgraph and particle image velocimetry (PIV) methods. In the experiment were measured: the flow profile around the cylinder and the aerodynamic forces acting on the cylinder (drag and lift).

Keywords: cylinder flow control, flow circulation, flow separation, flow separation trace past a cylinder, magnetoplasma actuator (MPA).

Intensive research is being conducted nowadays in the field of plasma aerodynamics on the possibilities of the flow control around streamlined bodies by various plasma formations to [1-3]. The main advantage of plasma actuators (active devices for controlling the flow using local plasma formations) is their fast reaction, which is based on the electronic control of the parameters of electric discharges. This property, in turn, allows one to implement feedback control of the development of various gas-dynamic perturbations in the flow near streamlined bodies (for example: to control the moment of transition of the laminar boundary layer to turbulent, flow separation, etc.). An important task in plasma aerodynamics is to control the flow circulation around a blunt body or streamlined body (as a cylinder or a wing). However, there are few experimental works devoted to this issue only [1-3]. The present work fills the gap in this area and it is devoted to study of the flow around a cylindrical model by a magnetoplasma actuator (MPA). To control of the flow circulation around a cylindrical model by a rotating electric arc in an external magnetic field is used in this work. The aim of this work is to study...
the near-wall gas flow around a cylindrical model with working MPA using high-speed camera, PIV and shadowgraph methods.

1. Experimental setup. Aerodynamic model and MPA

The aerodynamic model used in this work is a cylinder made of a quartz tube with a diameter of 20 mm, length of 95 mm and a wall thickness of 2 mm, Fig. 1-a (1). The measured magnetic field induction on the model surface (between the electrodes) reaches a value of $B \approx 0.1$ T.

Ring electrodes are manufactured from cuprum wire. Spark gap (3) is used for discharge ignition at definite region of an aerodynamic model. Arrangement diagram of the spark gap electrode on the cylindrical models in position $\alpha = 5^\circ$ or $90^\circ$ relative to the direction of the air flow are shown in the fig 1b. These optimal spark gap arrangement are used according the recommendation of the works [2, 3].

![Figure 1. (a) General view of the model and schematic of the MPA on a cylindrical model with a single discharge gap: (1) quartz tube; (2) copper ring; (3) spark gap electrode; (4) polyamide nut and screw; and (5) Nd–Fe–B magnet. (b) Arrangement diagram of the spark gap electrode on the cylindrical models in position $\alpha = 5^\circ$ or $90^\circ$ relative to the direction of the air flow or to the horizontal (in the absence of flow).]

### 1.1. High-voltage power supply

To initiate an arc discharge, a high-voltage power supply was designed and tested. In our MPA, we used two types of power supplies: a DC source (DC generator) and a power supply for producing a high-power pulse-periodic discharge. For initiating these discharges, we used a high-voltage pulsed discharge produced by a RF Tesla generator. The technical characteristics of the source of a pulse-periodic discharge were as follows: pulse repetition rate $F_1 < 3$ kHz, maximal output voltage of the power supply $U_{\text{max}} < 20$ kV, maximal discharge current $I_{\text{max}} \leq 30$ A, maximal pulse power $P_{\text{max}} < 8$ kW, and mean power $P_{\text{mean}} \leq 200$ W.

Figure 2 shows typical voltage and current signals measured across the discharge gap of the MPA on the cylindrical model in experiments for flow visualization. It can be seen that the maximal pulsed current on the model surface attains a value of $I_{\text{max}} \approx 16$ A; the power pulse duration is $T_1 = 12$ ms, and the pulse repetition rate is $F_1 = 7$ Hz. The electric voltage amplitude is $U_{\text{d}} = 1.5$ kV. The maximal pulsed power can be as high as $P_{\text{max}} \leq 8$ kW; the mean power is $P_{\text{mean}} \approx 200$ W.
2. Experimental Results

In order to analyze the effect of the MPA on the flow separation on the model, we used the regime of external synchronization of video recording and the PIV setup. The rotational frequency of the arc discharge measured in this experiment was $F_r \approx 290$ Hz. In this experiment, we used a pulse-periodic discharge with the following characteristics: $F_i = 7$ Hz, $U_{max} < 15$ kV, $I_{max} < 30$ A, $P_{max} < 70$ kW and $P_{med} = 200$ W. Figure 2 shows the typical voltage and current signals measured in the discharge gap of the MPA. The velocity of the air flow corresponded to $Re = 8 \times 10^3$ ($V_\infty = 6.5$ m/s). The spark gap electrode was in the position at $\alpha = 5^\circ$, [2, 3]. The velocity field in the vicinity of the cylindrical model with a working MPA in an external flow in this regime is shown in Fig. 3. The number of measurements for averaging each PIV pattern was 70. Under these conditions, a considerable effect of the rotating arc in the flow past the model was detected. Figure 3 shows the flow field around the model with working MPA after the completion of the second turn of the arc around the model. In this regime, the entire velocity field around the model, including its front and back part, is perturbed. The figure also contains a synchronized video image of the rotating arc discharge at the corresponding instant. An analysis of this figure also shows that the flow circulation around the model changes in the (1) head anode part and (2) tail cathode part of the arc discharge. It should be noted that the region of the stimulated circulation of the near-wall flow also exists in the back part of the model. The flow separation in this region is not observed up to angles of $\theta \approx 260^\circ$. This result makes it possible to determine the averaged field of induced vorticity around the model in this experiment. It is important to note that this result of induced vorticity is absent in the case of MPA operation off. An analysis of the shadowgraph pictures, arc temperature and PIV frames leads to the conclusion that the regime of a weakly compressible flow is realized in the entire layer of the near-wall flow around the cylinder except in the region near the electric arc (small variations in density $\delta \rho / \rho_0 \ll 1$ are observed, where $\rho_0$ is the density of air, as well as small change in the velocity of the induced flow, $\delta V / V_0 \ll 1$, where $V_0$ is the flow velocity). Thus, Zhukovsky’s theorem is valid for the entire integrated zone with the exception of the electric arc zone (where $\delta \rho / \rho_0 \sim 1$), which, in turn, is too small compared to the entire integrated zone in formulas 2.1 and therefore can be neglected. The value of the average stimulated vorticity of the flow around the model turned out to be equal to $\bar{\xi} \approx 1325$ s$^{-1}$.
Figure 3. Averaged PIV pattern of velocity field around cylinder with rotating plasma arc. Characteristic Reynolds number of incoming flow is $Re = 8 \times 10^3$ ($V_\infty \approx 6.5$ m/s). Delay time of discharge initiation is $T_2 = 4$ ms.

This high value of average vorticity $\xi$ (compared to that in the direct-current discharge experiment) was obtained due to the use of discharge with a high pulsed current in the experiment [7].

The magnitude of the stimulated circulation $\Gamma$ in Fig. 3 was determined using expression 2.1, according to the formula from [4-6]:

$$\Gamma = \iint_S (\nabla \times V) dS = \int_0^{2\pi} \int_{R_0}^{2\pi (R_0 + h)} (\nabla \times V)R_0 d\theta dr \approx 0.4 \text{ m}^2/\text{s} \quad (2.1)$$

where $R_0 = 10$ mm and $h = 4$ mm.

### 3. Discussions and conclusions

In conclusion, it can be noted that the electric arc has a complex three-dimensional appearance, this result was confirmed using high-speed camera.

A typical width of a perturbed entropic vortex flow or induced flow circulation jet induced by the rotating electric arc around the cylindrical model is about 10 mm or more, which is much more than the luminous electric arc diameter of the order of mm. In Fig. 3, it is clearly seen that there is an asymmetric flow around the cylindrical model caused by an induced flow circulation around the model, which is created by the rotating electric arc. Such an asymmetric flow around the cylindrical model can lead to lateral lift force acting in the model. The practical absence of flow separation on the model in this mode makes it possible to estimate the value of the lift coefficient $C_L$, due existence of stimulated circulation $\Gamma$, according to the formula from [4-6]:

$$C_{L,t} = \frac{1}{2\rho_\infty V_\infty^2 w d} \frac{2\Gamma}{V_\infty d} \approx 0,5 \quad (3.1)$$

where $\Gamma = 0.4 \text{ m}^2/\text{s}$ and $V_\infty = 72$ m/s.
It was revealed that the calculated $C_L$, calculated by formula (3.1) is close to the experimental $C_L$, $exp \approx 0.3$ measured by balance [7]. The lift force in our experiments achieved maximum values of about $L = 0.37$-$0.45$ N.

In conclusion, it should be noted that the developed MPA can produce a near-wall vortex flow around a cylindrical model, which affects the external subsonic gas flow past this model ($M < 0.2$, $Re < 9 \times 10^4$). This statement has been confirmed by results of direct measurements, using the PIV, shadowgraph methods and by aerodynamic force measurement by balance [7]. It concluded that the lift force that acts in the cylindrical model emerges due to stimulated circulation of the flow around it.

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