Investigation of Pulsed Electric Discharge in Hypersonic Air Flow and in Magnetic Field

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Abstract. The problem of local braking of a high-speed air flow (M = 6) using an electric discharge plasma in a magnetic field has been considered. The studies were carried out on an experimental MHD test rig based on a shock tube, at the end of the low pressure channel of which a Laval nozzle was placed with gas flowing into the Eiffel chamber. The discharge was initiated across the flow, between narrow electrodes, and across the magnetic field. It was shown that with increasing of the magnetic field the discharge is localized between the electrodes and then moved toward the flow as a result of strong MHD-interaction. At the same time the bow shock in front of MHD-interaction zone is observed. A comparison of the shock wave structures during the flow around the discharge on free electrodes, near the plate and in front of the blunt body has been shown.

1. Introduction
The development and construction of promising high-speed aircraft is associated with solving problems aimed at finding effective ways to control the external and internal gas dynamics of aircraft and engines. At high flight speeds, conditions for the exhibition of plasma effects arise, which can be used to apply magnetohydrodynamic flow control methods based on physico-chemical conversion of the gas. In works devoted to the study of magnetohydrodynamic methods for controlling high-speed flows, it was shown that gas-discharge plasma sources can be used to effective flow control, for example [1–5]. The most complete state of the problem of using various plasma sources to control high-speed flows is presented in the review [6], in which a wide range of works by leading experts is discussed. Moreover, upon the initiation of discharges in a magnetic field, volumetric electromagnetic forces arise in the flow, which can lead to a significant change in the flow parameters. Depending on the direction, these forces can both accelerate a moving gas and slow it down. Thus, it is possible to change the flow pattern near the streamlined surface, generate forces and moments acting on the vehicle, and also change the distribution of heat fluxes to the surface. In this paper, we consider the problem of the hypersonic air flow around a region occupied by a pulsed discharge in a magnetic field on electrodes placed in the stream. The obtained flow patterns were compared with the patterns obtained by flowing around the plate surface and the model of the reentry vehicle [7, 8].

2. Problem statement and experiment technique

2.1. Problem statement
The problem of the flow around the region of an electric discharge in a magnetic field and in a hypersonic air flow is considered. A superposition of the flow directions, discharge current and magnetic field
ensures the braking of the discharge region under the action of a volume electromagnetic force \( j \times B \) directed towards the incoming flow. The initiation of a high-voltage pulse discharge occurred between two parallel narrow electrodes with dimensions of 15 mm along the marching coordinate and 2 mm in the transverse direction each. The distance between the electrodes was 30 mm. The scheme of the problem is presented in Figure 1, a. A general view of the electrodes installed in the stream on flat pylons is shown in Figure 1, b. The main gasdynamic and electrodynamic parameters of the problem are presented in table 1.

![Figure 1. Test schematic (a) and experimental model (b).](image)

| Table 1. Experimental parameters. |
|-----------------------------------|
| Parameter                        | Value    |
|-----------------------------------|----------|
| Flow velocity                     | 2 km/s   |
| Flow Mach number                  | 5.8      |
| Static pressure                   | 1.5 kPa  |
| Flow density                      | 0.02 kg/m³ |
| Static temperature                | 150 K    |
| Magnetic field                    | 0–1.8 T  |
| Discharge voltage                 | 90–600 V |
| Discharge current                 | 160–90 A |
| Discharge power                   | 14–80 kW |

2.2. Experiment technique and facility
To simulate a hypersonic air flow in a magnetic field, MHD test rig was used, which is a pulsed aerodynamic facility, built on the basis of a shock tube with gas flowing through a Laval nozzle to the working part of the rig - the Eiffel chamber. The working gas in the high-pressure chamber is the arc heated helium. The low pressure channel was filled with air. The use of a shock tube allows to keep in practically constant values of the working gas parameters at the entrance to the nozzle behind the reflected shock wave. Using a set of interchangeable nozzles, the rig allows to simulate high-speed flows with Mach numbers \( M = 6–12 \). The flow parameters in the Eiffel chamber correspond to flight conditions at altitudes of 30–50 km. The time of the quasi-stationary flow is at least 1 ms for the largest critical nozzle cross section, calculated at \( M = 6 \). The working part has dimensions of 200×140×240 mm, the diameter of the nozzle is 105 mm. The working chamber is located inside a powerful electromagnet that provides a uniform magnetic field with induction up to 2.5 T. There is also
the possibility of installing ionizing devices in the working chamber. Figure 2 shows the principal scheme of the test rig. An electric discharge for 120 μs was carried out using a long line of capacitors. The electrical characteristics of the discharge were measured using current transformers. The gas pressure and the velocity of the shock wave in the prechamber of the nozzle were recorded using piezoelectric sensors PCB. Visualization of the shock-wave structure of the flow and the glow of the discharge plasma were realized using an optical schlieren system with a high-speed camera.

Figure 2. MHD test rig: 1 – high pressure chamber, 2 – diaphragm, 3 – low pressure channel, 4 – nozzle, 5 – work chamber, 6 – vacuum tank, 7 – electromagnet, 8 – light source, 9 – high speed camera, 10 – diagnostic section.

3. Results and discussion

3.1. Discharge in magnetic field between free electrodes in hypersonic flow
Experiments have shown that without a magnetic field, the discharge moves downstream and periodically shunts between the electrodes. In a magnetic field, a gas-discharge plasma is localized between the electrodes as a result of strong MHD-interaction. Figure 3 shows the frames of high-speed video shooting of the MHD-interaction of an electric discharge plasma with an incoming flow at magnetic field induction \( B = 1.8 \) T. The video shooting frequency is 96 kHz, the exposure time is 1 μs, which makes it possible to determine the areas with the contracted and diffuse phases of the gas discharge.

Figure 3. Frames video capturing of local MHD-interaction in the electrodes region at flow \( M = 5.8 \).

It can be seen, that a shock wave forms in front of the discharge plasma, which indicates a local decrease in the Mach number in the interaction zone due to the simultaneous heating and deceleration of the discharge plasma in a magnetic field. The figure shows that as the discharge plasma advances toward the flow, that it behaves unstably and repeatedly passes from the contracted phase to the diffuse one. When the magnetic field induction is greater than 1 T, the discharge area moves upstream and then shunts in the electrode region at the voltage increasing up to critical value. This process repeats periodically as it was observed in [7] devoted to the MHD interaction near the plate.
3.2. Discharge in magnetic field between electrodes mounted in the models

Figure 4 shows the test schematic and some results from the work [7]. One can see the same orientation of the flow direction, discharge current and magnetic field, led to the air flow braking in the MHD-interaction region. The discharge region is also moves upstream and shifts it in the electrode region, but at less values of B-fied induction. One can see the transformation of the oblique shock on the leading edge.

In [7], it was shown that, when the MHD interaction zone is localized in front of the blunt body, there is a formation of a reverse flow near the critical point. It happened because the plasma moving towards the flow along the central axes, which leads to the formation of a vortex near the surface of the body. This process is the reason of reducing heat fluxes to the surface locally. It that was shown in experimental and numerical studies [8]. Figure 5 shows the test schematic and some results from the experiment with the blunted body.

The ionization of the flow necessary for effective MHD-interaction depends on the current strength and the magnetic induction, which are included in the determination of the parameter of the hydromagnetic interaction – the Stuart number

\[
S = \frac{j \times B}{\rho \infty v_{\infty}^2} .
\]  

The Stuart number characterizes the ratio of electromagnetic forces work to inertial forces work of the flow. In the work, the Stuart number is chosen as a criterion that determines the efficiency of MHD-interaction in experimental and numerical studies. Figure 6 presents photographs of the flow under conditions of strong MHD-interaction between free electrodes, electrodes on a plate, and on the surface of a blunt body. In all cases, a shock wave is formed in front of a gas-discharge plasma inhibited by a
magnetic field during strong MHD-interaction with a Stuart number of about 0.2 and more. The existence of a similar character of the flow during the movement of the gas-discharge region in a magnetic field between the electrodes requires additional research.

Figure 6. Formation of a bow shock in front of the MHD-interaction zone (bottom line) during the flow around various models (top line): (a) free electrodes, (b) plate model, (c) blunt body.

Acknowledgments
The research has been carried out partly within the framework of the Program of Fundamental Scientific Research of the state academies of sciences in 2013-2020 (project No. 0323-2019-0010) and the grant from the Russian Science Foundation (project No. 17-19-01375).

References
[1] Shang J S 2001 Progress in Aerospace Sci. 37 1-20
[2] Gurijanov E P, Harsha P T 1996 J. AIAA 96-4609 (doi:10.2514/6.1996-4609)
[3] Fomin V. M, Tretyakov P K, Taran J-P 2004 Aerospace Science and Technology 8 No. 5, 411–421
[4] Bletzinger P, Ganguly B N, Van Wie D and Garscadden A 2005 J. Phys. D: Appl. Phys. 38 R33–R57 (doi:10.1088/0022-3727/38/4/R01)
[5] Bityurin V A, Bocharov A N 2006 J. AIAA Paper 2006-3235
[6] Joussot R, Courmar S, Lago V 2015 J. Aerospace Lab 10 (doi: 10.12762/2015.AL10-04)
[7] Fomichev V P, Yadrenkin M A 2013 Tech. Phys. Letters 39(1) 66-70 012015 (doi: 10.1134/S1063785013010082)
[8] Korotaeva T A, Fomichev V P, Yadrenkin M A 2020 J. of Appl. Mech. and Tech. Phys. 61(2) 162-170 (doi:10.1134/S0021894420020029)