Effect of Electric Discharges in Magnetic Field on Hypersonic Flow around Bodies

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Abstract. To investigate the possibilities of magnetohydrodynamic (MHD) effects on a hypersonic flow structure, it is necessary to ionize the gas flow. It is possible to create a local region of conductivity of the flow using electrical discharges under experimental conditions. The paper considers the MHD interaction of a high-speed air flow and electrical discharges (high-voltage pulse and high-frequency) in a homogeneous magnetic field when flowing around test models. It is shown that the use of discharges in a magnetic field makes it possible to significantly change the shock-wave structure of the flow near a streamlined surface: to change the angle of the oblique shock, to generate new shock, to transform attached oblique shock to the bow shock. Systematization of the obtained data on the value of the hydromagnetic interaction parameter $S$ characterizing the strength character of the observed effects is performed. Thus, $S < 0.05$ corresponds to the weak MHD-interaction, $S = 0.05 - 0.15$ – moderate MHD-interaction, $S > 0.15$ – strong MHD-interaction.

Introduction

The control of the aerodynamics of advanced hypersonic vehicles is a crucial task requiring new approaches and principles. Under conditions of hypersonic flight for the realization of effective MHD interaction become advantageous. This way of controlling the structure of the flow avoids the use of massive and complex mechanical systems for changing the shape of the aerodynamic surfaces of the hypersonic jets, and also reduces the response time of the system to control commands. Various experimental and numerical studies have shown the effectiveness of this type of interaction: from a weak deviation of the oblique shock waves to the generation of new and even a total reorganization of the shock-wave structure of the flow [1-15]. However, so far there are practically no attempts to classify the observed effects by some characteristic value. To estimate the force component of the MHD effect, this parameter can be the Stewart number, which shows the ratio of the work of volumetric electromagnetic forces to the work of the inertial forces of the high-speed flow. In the paper, an example of the realization of MHD interaction near models of various geometries and corresponding values of the Stewart parameter are presented.

Problem statement

The flow near a plate, a wedge and a blunt body with a hypersonic airflow $M=6-7$ is considered. Figure 1 shows the experimental schemes for the test models.
Flow parameters: speed about 2 km/s, density 0.02 kg/m³, temperature 250 K. The discharge current between the electrodes is directed across the air flow and across the magnetic field so that the force determined by the product of the electric current density value by the magnitude of the magnetic induction, was directed upstream for the local gas braking.

**MHD test rig and experimental techniques**

To simulate the MHD interaction in a hypersonic flow, MHD test rig, based on a shock tube, is used (Figure 2). After the diaphragm break, the gas from the high-pressure chamber 1 compresses the working gas in the low-pressure channel 3, and behind the reflected shock quasistationary parameters of the working gas at the supersonic nozzle inlet are formed. The test rig allows simulating high-speed flows of various gases with Mach number \( M = 6 - 10 \). When using air, the flow parameters are simulated correspond to conditions at an altitude of 30-50 km. The time of existence of the quasi-stationary mode is about 1 ms. The working chamber 5 is located inside a powerful electromagnet 6, generating a constant magnetic field of 0-2.5 T. It is also possible to install various ionization devices for the flow. In the experiment, the ionization of the flow was carried out using a high-voltage pulse discharge and a radio-frequency (RF) discharge. To generate a pulsed discharge, a long line of capacitors was used, and for a RF discharge a special generator was used. To observe the structure of the flow near the model, an optical schlieren-system with an adaptive visualizing transparency is used instead of Foucault knife [16]. That approach allows recording density gradients at low density of the working gas. Recording of images is carried out on a high-speed camera.

**Figure 1** Experimental schemes for the investigation of the local MHD-interaction. a) – hypersonic flow, 2 – electrodes, 3 – electrical discharge, 4 – magnetic field, 5 – model, 6 – pressure sensor.

**Figure 2** Test rig with optical system: 1 – high pressure chamber, 2 – diaphragm, 3 – low pressure channel, 4 – nozzle, 5 – working chamber, 6 – electromagnet, 7 – receiver, 8 – laser, 9 – AVT, 10 – filters, 11 – camera, 12 – diagnostic section, 13 – PC.
Experimental study of the pulse discharge in a hypersonic flow

When a discharge was initiated between two narrow electrodes (Fig.1a), a volumetric electromagnetic force appeared in the hypersonic air flow with $M = 6$ and in a magnetic field, directed toward the incoming flow. As a result of the MHD interaction at $B \geq 1$ T, the arc of the discharge moved toward the flow and the appearance of a head shock wave in front of the interaction region (Figure 3). This can be explained by local gas deceleration as a result of strong MHD interaction. The duration of the electric discharge is 120 μs. During this time, a quasistable region of the inhibited flow has time to form, but in general the observed process can not be considered stationary.

![Figure 3](image)

**Figure 3** Pulsed electrical discharge in a flow of $M = 6$ and a magnetic field. a), b) $B = 0$ T, c), d) $B = 0.34$ T, e), f) $B = 2$ T; 1 – flow direction, 2 – electrodes, 3 – discharge plasma, 4 – magnetic field direction, 5 – bow shock.

- **Experimental study of the MHD interaction near the plate model**

When the MHD interaction is realized on the plate surface (figure 1b) at similar test conditions, the initiation of the discharge does not occur in the free flow, but between the electrodes flush with the model surface in the region behind the attached shock wave generated by the leading edge of the model (Figure 4a).

![Figure 4](image)

**Figure 4** Pulse discharge on the plate surface in the $M = 6$ flow and in a magnetic field. a) $B = 0$ T, b) $B = 0.1$ T, c) $B = 0.34$ T, d) $B = 0.8$ T; 1 – flow direction, 2 – electrodes, 3 – discharge plasma, 4 – model, 5 – shock wave, 6 – shield plates, 7 – direction of magnetic field.

In this case, even when the magnetic induction reaches 0.1 T, it is possible to stabilize the position of the arc of the discharge in the region of the electrodes, while the attached shock deflects to a larger angle (figure 4b). And if the value of the magnetic induction is 0.3 T and higher, the discharge protrudes toward the leading edge and the shape of the attached shock significantly changes (figure 4c). At a magnitude of the magnetic induction above 0.6 T, the attached shock transforms to the detached bow shock, since the discharge arc is pulled out towards the flow in front of the model under the action of
electromagnetic forces. It should be noted that at $B > 0.6$ T, pulsations in the position of the shock are observed and the current and voltage pulsations are associated with this. This process is similar to the shunting process in plasmatrons with a self-setting arc length. The shunting frequency was about 35 kHz under the test conditions, and the speed of the arc element’s movement in upstream direction was up to 700 m/s at a flow rate of about 2000 km/s.

When the RF discharge with a frequency of 900 kHz was using for the local ionization on the plate model, the discharge burning time was 300 μs. In this case, the process of flowing occurs differently. Unlike a pulsed discharge, the RF discharge has not a force effect on the flow, but only support a sufficient level of ionization. Force action occurs as a result of the appearance of an induced current in the discharge circuit as a result of the motion and deceleration of a conducting gas closed to electrodes in a magnetic field.

At $B \geq 0.9$ T, the appearance of a new shock wave in the region of the MHD interaction, is observed (figure 5b). As B-field induction was increasing, the shock angle was also increasing (figure 5c). In Figure 6 shows the dependence of the shock wave angle on the magnitude of the magnetic field at flow Mach number $M = 7$. A similar effect is observed when using a pulsed discharge, but at very low value of $B \sim 0.05$ T. This is explained by the significant difference in the current value of electric discharges obtained from various sources.

**Figure 5** Generation of the oblique shock on the MHD-region with RF-discharge: 1 – plate model, 2 – oblique shock generated by the leading edge, 3 – electrodes, 4 – oblique shock formed on the MHD interaction region.

**Figure 6** The shock wave angle vs the magnitude of the magnetic field.

**Experimental study of the MHD interaction near the blunt body**
A similar configuration of the electrodes was mounted in the surface of the model of the blunt body (the model of the reentry capsule). Then when the discharge is initiated in a magnetic field $B > 1$ T in a
hypersonic airflow, the discharge plasma concentrates in front of the model will be observed and the head shock wave will move upstream (Figure 7c).

**Figure 7** Pulse discharge in front of the blunt body in the flow \( M = 6 \) and in a magnetic field: a) \( B = 0 \) T, b) \( B = 0.34 \) T, c) \( B = 2.2 \) T; 1 – flow direction, 2 – electrodes, 3 – model, 4 – bow shock, 5 – discharge, 6 – B-field direction.

**Methods for determining the parameter of hydromagnetic interaction**

The effectiveness of the force effect of plasma in a magnetic field on the structure of the incoming flow is most conveniently expressed in terms of the ratio of the work of electromagnetic forces to the work of inertia forces (the Stuart number):

\[
S = \frac{j \times B l}{\rho_\infty v_\infty^2}
\]

where \( j \times B \) is the volume electromagnetic (the product of the current density by the magnitude of the magnetic induction), \( l \) is the characteristic size along the march coordinate, \( \rho_\infty v_\infty^2 \) is the work of inertia forces. To determine the parameter \( S \) under test conditions, it is necessary to adapt it to the measured characteristics of the process.

**Figure 8** Data from the pressure sensor installed at the critical point on the model of a blunt body without MHD interaction (\( S = 0 \)) and for strong MHD interaction (\( S \approx 0.3 \)).

When analyzing the data of experimental studies of a pulsed discharge in a hypersonic air flow on free electrodes and on a plate model, the parameter \( S \) was estimated from the total discharge current \( I \) and the size of the interaction region across the flow and along the magnetic field \( b \):

\[
S = \frac{I B}{\rho_\infty v_\infty^2 b}
\]
In the case of using a high-frequency discharge, it is difficult to determine the magnitude of the induced current. Therefore, it was assumed that all work of electromagnetic forces is expressed in the work of pressure forces $\Delta p$, which leads to the formation of an oblique shock with an appropriate angle of inclination:

$$ S = \frac{\Delta p}{\rho_{\infty} V_{\infty}^2} $$

A similar approach is applicable when analyzing the data of experimental studies of MHD interaction on a blunt body. At the critical point of the model, a high-frequency piezoelectric pressure sensor was installed, which fixed the pressure drop $\Delta p$ behind the bow shock (Figure 8).

**Discussions and conclusions**

Experiments have shown that by varying the discharge current and the magnitude of the magnetic induction at a constant flow rate, a weak, moderate, and strong MHD effect on the flow can be realized. Thus, $S < 0.05$ corresponds to the weak MHD-interaction, $S = 0.05$–$0.15$ – moderate MHD-interaction, $S > 0.15$ – strong MHD-interaction.

With a relatively weak effect, $S \approx 0.05$, the angle of inclination of the attached oblique shock, generated by the leading edge of the model, changes.

With a moderate MHD interaction, increasing $S$ to 0.15 results in generation of a new shock wave and an increase in the angle of inclination of the attached oblique shock generated by the leading edge and a change in its shape.

A further increase in $S$ to 0.2–0.25 leads to the formation of a detached shock wave in front of the leading edge of the model or to the removal of the bow shock wave from the surface in the case of a model of a blunted body – a strong MHD interaction. At $S > 0.2$, shunting of the discharge in the electrode region was observed, which leads to oscillations in the shock position.

It have shown that different types of electric discharges can be used to efficiently change the shock-wave structure of flow around various bodies in a hypersonic flow and in a magnetic field.

A strong MHD interaction at $S > 0.2$ leads to the appearance of a bow shock both in the case of free electrodes flowing and in the case of flowing various bodies with electrodes built into their surface. For comparable values of the parameter $S$, the observed shock-wave structure of the flow practically no depends on the shape of the model (Figure 9).

![Figure 9 Photos of the shock waves at strong MHD-interaction near different systems of electrodes](image)

This paper shows the principal possibility of using electric and magnetic fields to control the aerodynamics of aircraft moving in the upper layers of the atmosphere at a hypersonic speed. Obviously, the maximum efficiency of the method can be achieved under conditions of natural thermal ionization.
at the surface of the apparatus, since the energy will be spent only on the creation of a magnetic field. However, in some cases it is worth considering the use of electrical discharges for solving local problems.

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