AN EXPERIMENTAL INVESTIGATION
OF MAGNETOHYDRODYNAMIC INFLUENCE
ON A SPERSONIC FLOW ABOUT A BODY OF REVOLUTION

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Abstract
An approach to implementation of a magnetohydrodynamic (MHD) impact on a supersonic nitrogen flow is discussed. For MHD interaction the working gas must be ionized. An electromagnetic facility for this purpose was designed, manufactured, and tested. This facility located at the body of revolution initiates an electric discharge near the nose body surface and rotates the discharge around the body. The rotating plasma exerts appreciable influence on the supersonic flow about the body.

Measurements of the heat flux toward the surface of a body of revolution in a supersonic nitrogen flow with Mach number 4 is carried out. It is found out that during operation of the electromagnetic facility, the heat flux toward the body surface increases and depends on the direction of the electric current flowing through the plasma. The heat flux is measured by heat flux sensors with a high-speed response.

The experiments is carried out at the Ioffe Institute double-diaphragm shock tube. The results of the tests are presented.

Introduction
The search for ways of an MHD influence on high-speed flows of ionized gases is of interest in view of designing hypervelocity vehicles. Investigations in this area have proceeded during several decades and bear the fundamental character [1,2]. Experimental investigations are mainly concentrated on studying flows through planar channels, that is, internal flows. Such an approach allows one to employ powerful external magnetic systems, on the one hand, and to simplify treatment of the results, on the other hand. At the same time, studying external flows about bodies is also of considerable interest. The aim of the present work consists in designing, manufacturing, and testing an electromagnetic facility that can be housed inside a body being in a supersonic flow.

Our previous experimental investigations [3,4] carried out during the preceding years with the use of convenient and comparatively simple means (planar models and nitrogen as a working gas) for studying interaction between a supersonic flow of weakly ionized plasma and magnetic field allowed us to make the following conclusions:

1. the effective MHD interaction is realized at a comparatively low magnetic induction of ~ 1 T and at an electric current through the plasma of an order of 1 kA;
2. the region of MHD interaction can be formed under the influence of the current passed through the plasma and practically independently of the initial plasma ionization.

Both conclusions above stimulated our intention to turn to a diatomic gas as the working one and a body of revolution as the object under study.

Model under study and experimental setup

As a model we chose a body of revolution being a typical module of vehicles. The model is a 60° sharp cone mated with a cylinder, see Fig. 1. The cylinder diameter is 28 mm. Within the cylindrical part, near its surface there is a magnetic coil consisting of 20 turns of a copper wire of 1 mm in diameter. Near the cross section of mating the cone and cylinder there is a metal ring serving as an electrode connected with one of ends of the coil. Along the body axis the central electrode is located (brass bar of 6 mm in diameter with the conical nose part). The central electrode and the second coil end are connected with an external voltage source. The voltage source is a circuit consisting of LC cells charged up to a needed voltage. Into the circuit, a pulsed transformer Tr is connected in series. With the help of transformer Tr an electric discharge is initiated between the central and ring electrodes. The discharge current flowing through the coil establishes the magnetic field schematically shown in Fig. 1. The magnetic field causes rotation of the constricted electric discharge around the cone surface in the azimuthal direction. The heating of the gas by the electric current and MHD impact on the ionized gas should cause variation of the flow parameters and flow structure as a whole.

The device described was tested at the Ioffe Institute Big Shock Tube [5, 6]. The shock tube of 18 m in total length consists of the high-pressure chamber and low-pressure channel (both of 100 mm in inner diameter). These sections are separated from one another by a metal diaphragm. The driver gas is hydrogen, the driven one is an inert gas or nitrogen. The other end of the low-pressure channel is connected with the test section of rectangular inner cross section (75 mm × 150 mm) with a wedge-shaped plane nozzle. These units are separated from one another by a thin plastic diaphragm. The test section is equipped with two windows for flow visualization. The model under study (see Fig. 2) is located in the view field of a Schlieren device near the nozzle outlet.

**MHD influence on a supersonic nitrogen flow**

The experiments were carried out in the supersonic nitrogen flow about the body. In the shock tube, nitrogen was heated by the reflected shock wave up to the temperature ~ 1800 K. The parameters of the supersonic mainstream at the nozzle outlet was: pressure ~ 5 kPa., density ~ 0.04 kg/m³, temperature ~ 440 K, velocity ~ 1600 m/s, Mach number ~ 4. Constancy of the parameters behind the reflected shock wave in front of the nozzle inlet was retained during ~ 1.5 ms.
The initiation of the discharge of the external voltage source through the MHD facility was implemented after initiation of the steady-state flow in the nozzle. The pulse of electric current through the electromagnetic device possesses approximately the same duration as the flow and attained ~ 1 kA in amplitude (see Fig. 1).

In Fig. 3, there are two Schlieren patterns of the supersonic nitrogen flow about the body of revolution at Mach number 4. In the photograph, on the left, a Schlieren pattern is shown which was obtained with no magnetic field and electric discharge. This pattern is a typical one corresponding to an undisturbed supersonic flow about a cylindrical body with a conical nose part. In the photograph, on the right, there is a Schlieren pattern observed when the electromagnetic facility operated. In this photograph, it is seen that the attached shock wave changed its position. The gas-discharge plasma is imaged by a bright region attached to the cone surface. Between the discharge and front of the attached shock wave, a region of less heated gas is located. The flow over the cylindrical part is featured by a strong turbulent inhomogeneity. Both Schlieren patterns were obtained at an instant of ~ 1 ms from the beginning of the efflux of the gas into the nozzle. Comparison between these two patterns convincingly evidences a strong impact of the rotating discharge affected by the magnetic field on the shock wave structure of the flow. An analysis of the Schlieren patterns obtained at different polarity of the electrodes showed identity of the shock wave structures in the cases considered.

Similar to the operation of the electromagnetic facility in a quiescent gas, in the experiments with the supersonic flow, the frequency of plasma rotation turned out to be dependent of the polarity of the electrode. In a variant of connection shown in Fig. 1, when the ring electrode plays the role of cathode, the mean frequency of the discharge rotation around the body amounted approximately to 30 kHz. In the case of the reverse connection, when the ring electrode played the role of anode, the frequency of the discharge rotation decreased almost in half and amounted approximately to 15 kHz.

In Fig. 4, there are three fragments of space-time scanning of the plasma glow against the cone surface at different connections of the central and ring electrodes to the external voltage source. The time coordinate corresponds to the abscissa, the ordinate coincides with the direction from the central electrode to the ring one along the cone generatrix. The positions of the central and ring electrodes in the image are marked by figures 1 and 2, respectively. Fragment (a) corresponds to the case when the electromagnetic facility operates in quiescent air at a pressure of 6 kPa, and the ring electrode plays the role of cathode. The mean frequency of plasma rotation amounts approximately to 66 kHz. Scanning (b) corresponds to operation of the facility in a supersonic nitrogen flow at a pressure approximately of 6 kPa and at
the same connection of the electrodes as in the previous case. Comparing the scannings one can see that in case (b) the rotation frequency (~30 kHz) is less approximately by half than in case (a). However, the regularity of repetition of glow maximums is retained in both cases.

Reversing the polarity of the electrodes causes a change in the plasma rotation frequency. Comparison between scanning (b) and (c) illustrates this phenomenon. Scanning (c) corresponds to a supersonic flow about the electromagnetic facility when the ring electrode is anode at the same flow parameters but at the reverse polarity of the electrodes as compared with case (b). It is seen that the rotation frequency in case (c) (~15 kHz) is noticeably less as compared with case (b), the regularity of repetition of the glow maximums is destabilized, and inner structure of the light-striking spot at the film also changes.

A reason for such an effect is probably associated with formation of cathode spots at the electrode surface. Since the electromagnetic force is proportional to the density of electric current, in the latter case the velocity of plasma rotation is lower than at the reverse connection. Note also that because of nearness of the ring electrode to the solenoid, the magnetic field near this electrode is considerably stronger than near the central one, therefore, one can suppose that the phenomena dynamics is mainly governed by the process in the vicinity of the ring electrode.

Similar to the situation with no flow, in this case, it is found out that the rotation frequency does not practically depend on the current strength in the plasma and on the magnitude of the magnetic induction. The current strength varied in the experiments in the range 300 ÷ 1000 A, and the maximum induction of the magnetic field at the solenoid center attained 0.4 T.

Thermal measurements

The most important issue in experimental investigations of control of the flow structure and heat flux with the aid of a magnetic field is the choice of instrumentation and technique for thermal measurements in supersonic flows.

At present, we use a heat sensor on the base of Bismuth monocrystal [7] which is applied for the direct measurement of steady-state heat fluxes in various investigations [8, 9]. Before application, the sensor is calibrated at a special testing setup. The calibration consists in determination of the coefficient of proportionality between the known steady-state heat flux passing through the sensor and the electric signal generated by it. Volt-Watt characteristic obtained in such a way remains linear up to the melting temperature of Bismuth (545 K).

The first experience of application of these sensors for studying fast processes in a shock tube [11] demonstrated their working ability at a pulsed thermal load of a duration of ~ 10^{-3} s and the gas temperature ~ 7000 K. In investigations [3, 4] these sensors were employed in a pulsed supersonic flow of a weakly ionized plasma (flow duration ~ 1.5 ms) in the presence of magnetic and electric fields.

Very important properties of sensors on the base of Bismuth monocrystal should be noted. The first consists in the high sensor sensitivity ~ 10 mV/W. This allows one to carry out measurements without amplifiers of the signal. Another feature is a low resistance of the sensor amounting to ~ 10 Ohm. Due to the combination of these characteristics, the sensor on the base of Bismuth monocrystal possesses a high immunity to electromagnetic fields, which allows one to employ it for measurements in MHD channels and electric generators. An apparent worth of the heat sensor is its short response time. In the tests aimed at evaluation of the response time, the heat sensor was exposed to an impact of short pulsed laser radiation. These tests showed high speed of response of the sensor: the response time amounted to ~ 20 ns.
The magnitude of the electromotive force of a thermal sensor is proportional to the difference between the temperatures of the sensor faces, both in the presence of an external electric circuit [10] and without it [11]. At the initial stage of a pulsed process, when the temperature of the substrate surface remains invariable and equal to the initial one, and the electric signal of the sensor is proportional to variation of the temperature of the working sensor surface, the process of heating the sensor can be considered as a warm-up of the half-space [12].

Relation between heat flux $q(t)$ toward the surface and its temperature is expressed by the relationship

$$q(t) = \frac{\lambda}{\sqrt{a\pi}} \left( \frac{\vartheta_0(t)}{\sqrt{t}} + \frac{1}{2} \int_0^t \frac{\vartheta_0(t) - \vartheta_0(\tau)}{(t-\tau)^{3/2}} d\tau \right),$$

where $\vartheta_0(t)$ is the known function describing variation of the sensor surface temperature, $\lambda$, $a$ are the heat conductivity and thermal diffusivity of the sensor material.

When processing the measurement results when the surface temperature is presented in the form of table of $N$ numbers, the following formula is used [13]

$$q(t_n) = \frac{2\lambda}{\sqrt{a\pi}} \left( \sum_{i=1}^{N} \frac{\vartheta_0(t_i) - \vartheta_0(t_{i-1})}{(t_n-t_i)^{1/2} + (t_n-t_{i-1})^{1/2}} \right).$$

Duration of the initial phase of the warm-up and, consequently, applicability of the approach to be used is confined and depends on the sensor material properties, sensor thickness, as well as on the rate of variation of the sensor surface temperature. For the Bismuth sensor of 0.2 mm in thickness the duration of this phase does not exceed 1 ms [11]. For time intervals longer than 1 ms, the process of warm-up of the sensor is also governed by heat transfer through the sensor–substrate boundary.

The body of revolution with the facility under study described in detail in [5] is located inside the test section downstream from the outlet nozzle cross section. The objective of the present study is measurements of the heat flux toward the body surface in two variants of the connection of the electrodes with the voltage source. The measurements were carried out by sensor D2 of 4 mm × 6 mm in area located at the cylindrical part of the body of revolution 15 mm distant from the ring electrode (see Fig. 2).

Variations of the body surface temperature observed in this case in two variants of connection of the voltage source are shown in Fig. 5.

An attention is attracted by the noticeable distinction between the model surface temperatures at the opposite polarities of connection of the voltage source: line 1 corresponds to connection of the ring electrode with the negative terminal of the voltage source, line 2 – with the positive one. Probably, this is explained by nonuniformity of the potential distribution in a linear gas discharge: it is known that the potential gradient in the cathode vicinity is larger than near the anode, consequently, the heat release will be also larger in the cathode vicinity. Note
also that the temperature pulsation frequency in curve 2 corresponds to the frequency measured with the help of the photo recorder.

Figure 6 shows distributions of the averaged heat flux for two variants of connection between the electrodes and voltage source. These distributions are results of processing the temperature measurements by formula (5). In the plot is seen that before the instant approximately 200 µs the heat fluxes corresponding to the opposite variants of connection strongly differ from one another. At later instants, this distinction practically vanishes, although the difference between the surface temperatures (see Fig. 5) remains noticeable. This fact evidences that experimental investigations of nonstationary thermal processes should be conducted in linking way: measurements of only one quantity (temperature or heat flux) are insufficient for the adequate description of the process being investigated.

Conclusions

The approach described, in our opinion, indicates interesting and promising direction of investigations in the area of MHD control of supersonic flows. The design of the device combines all components necessary for implementation of an effective MHD interaction – magnetic system and set of electrodes, and makes it possible to model MHD processes in external flows. Clear physical principle and simplicity of the design allow one after some constructive changes to independently vary the current strength and magnetic induction, as well as to simply modify the device varying its dimensions and employing various systems of electrodes in accordance with the problem under study.

The experiments carried out show that the gradient sensor on the basis of anisotropic Bismuth crystal can be successfully employed as a high-sensitive tool for measurements of temperature in pulsed gasdynamic processes accompanied by strong electromagnetic interferences. The thermal sensor model we used allowed us to evaluate magnitudes of the heat flux toward the surface of an object in a flow, which gives additional information about the process under study.

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REFERENCES