An Experimental Complex for Researching High Velocity Magnetic Hydrodynamic Flows

I. A. Masloboev\textsuperscript{a,b,*,} V. P. Fomichev\textsuperscript{c}, A. B. Shevchenko\textsuperscript{c}, and M. A. Yadrenkin\textsuperscript{c}

\textsuperscript{a} Novosibirsk State Technical University, Novosibirsk, 630073 Russia
\textsuperscript{b} Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia
\textsuperscript{*} e-mail hawkeye90@yandex.ru

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Abstract—A magnetohydrodynamic (MHD) stand based on a shock tube is described. A distinctive feature of this apparatus is the presence of a system for generating a magnetic field with an induction of up to 2.5 T and devices for ionization of the flow (electron gun, current generators), which makes it possible to solve a wide range of problems in magnetoplasma aerodynamics. The design features of the MHD test bench make it possible to simulate the MHD effect on the flow structure during flow around the investigated bodies under conditions of high-speed flight in the Earth’s atmosphere at the flow Mach numbers $M = 6–12$. The main experimental techniques used at the stand are considered. Examples of the results of the study of MHD effects obtained with this setup are presented.

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INTRODUCTION

Studies of new methods for controlling high-speed gas flows by localized supply of energy to the incident flow or by using magnetohydrodynamic (MHD) action on ionized gas flows in the presence of electric and magnetic fields have not lost their relevance. An aerodynamic apparatus adapted in size and parameters is required to conduct an aerophysical experiment with the use of systems for generating strong magnetic fields and external ionization of the gas flow. One of the simplest ways to create an experimental complex for this kind of research is the use of shock tube technology [1]. In the shock tube, the working gas is compressed and heated behind the shock front. The constancy of the parameters of the working gas behind the reflected shock wave in the prechamber of the supersonic nozzle makes it possible to obtain a stable mode of gas outflow in the working chamber of the apparatus for carrying out various gas-dynamic studies [2]. The undoubted advantage of the shock tube technique is the ability to use any gases and gas mixtures to simulate high-speed flows in a wide range of parameters. However, due to the short duration of the working process, this approach makes high demands on the operation of high-speed and high-precision systems for recording and measuring flow parameters. With a shock tube length of several meters, the characteristic time scale of a quasi-stationary gas flow at the nozzle exit is on the order of 1 ms. The use of modern high-speed equipment and experimental methods for recording the parameters of a high-speed flow makes it possible to solve the above problems.

The literature contains examples of experimental MHD stands based on shock tubes designed to solve fundamental and applied problems of magnetoplasma aerodynamics. A distinctive feature of such devices is the presence of a system for generating a magnetic field in the studied flow region. As an example, in [3], the results of studies of MHD interaction on a facility capable of simulating supersonic ($M = 3–4$) flows of nonequilibrium plasma in a magnetic field with an induction of up to 2 T are presented. The flow was ionized using a high-voltage short-pulse high-frequency plasma generator.

In [4], the study of MHD interaction was carried out on a shock tube with a flow Mach number $M = 1.5$ in the working chamber. Helium with addition of cesium was used as a working gas. A magnetic field with an induction of 2.3 T was created using an electromagnet. To create an ionized flow region, a discharge section was used, which consisted of 19 pairs of circular electrodes with a diameter of 5 mm that were flush mounted into the wall of the working chamber. The distance between the pairs of electrodes increased from 45 mm for the first pair to 48.5 mm for the last one; 19 separate capacitors were used as energy sources for the electrodes.

In [5], experiments were described that were carried out on a setup that was also based on a shock tube; the working chamber of the setup was a supersonic
rectangular nozzle. A set of brass electrodes was installed in the upper and lower walls of the nozzle to generate gas discharges. The setup additionally included a system for generating a gas discharge based on a cascade of long lines designed to organize current pulses in a flow with a duration of up to 600 \( \mu \)s, as well as a system for organizing a pulsed uniform transverse magnetic field in the entire flow region with a magnetic induction of up to 1.5 \( T \) and a quasi-stationary region duration, exposure of approximately 600 \( \mu \)s. The inert gas xenon was used as a working gas for research. For the research, the shock tube operating mode was selected, as characterized by the presence of a cross-linked flow contact surface. The pressure of the pushing gas (hydrogen) is 2.1 MPa, the hydrogen pressure in the low-pressure chamber is 3.0 kPa, and the Mach number of the shock wave in the shock tube is \( M_3 = 8 \).

The presented apparatuses were designed, as a rule, to solve a narrow range of problems and had small cross-sectional dimensions of the working part (no more than \( 55 \times 80 \) mm\(^2 \)) and the studied models (\( \leq 40 \) mm). In these works, it was found that it is possible to change the position of the shock wave generated when flowing around the models, both in the direction of moving away from the model and in the direction of approaching the wave to the body, changing the direction of the gas-discharge current and the parameter of the MHD action.

This article discusses the operation of an MHD stand created on the basis of a shock tube at the ITAM SB RAS that is intended for modeling ionized high-speed gas flows in the presence of electric and magnetic fields; it also presents examples of various studies on this apparatus.

**EXPERIMENTAL**

The experimental MHD stand of the ITAM SB RAS was created to solve a wide range of problems in magnetoplasma aerodynamics in high-speed gas flows. The apparatus makes it possible to implement flight conditions in the Earth’s atmosphere at an altitude of 30–60 km above sea level with a Mach number \( M = 6–12 \).

The experimental stand consists of the following parts:

1. impulse aerodynamic apparatus based on a shock tube,
2. a magnetic system,
3. gas flow ionization systems,
4. a diagnostic complex (optical schlieren system, high-speed means for registering flow and plasma parameters, devices for synchronizing control pulses).

**The Features of the Operation of an Impulse Aerodynamic Apparatus Based on a Shock Tube**

The diagram of the MHD stand and the general view of the setup are shown in Fig. 1. A distinctive feature of a pulsed aerodynamic unit based on a shock tube is the principle of implementing the parameters in the prechamber of a supersonic nozzle, based on the compression of the working gas behind the reflected shock wave. The shock tube we used consists of a low pressure channel (LPC) and a high pressure chamber (HPC), separated by a steel diaphragm. The length of the LPC is 7 m, the inner diameter of the channel is 76 mm, respectively, and the volume of the channel is \( \sim 30 \) L. The high-pressure chamber is a balloon with a diameter of 180 mm and a volume of 20 L, along the axis of symmetry of which there is an electrode for electric arc heating of the pushing gas. In aerodynamic studies, air was used in the LPC and helium was used in the HPC.

The pressure and temperature of the pushing gas in the HPC is increased by supplying energy in the form of a pulsed electric arc discharge between the HPC wall and the central electrode isolated from it. The latter is connected to a capacitor bank with a total capacity of 36 mF and a voltage of up to 3 kV. An electric arc discharge is initiated by plasma injection into the region of the minimum gap between the electrode and the HPC body using an injector, which is built into the electrode and has a separate power source. Measurements of the current and voltage across the discharge gap showed that the energy of the electric discharge is usually \( W = 40–60 \) kJ at a battery voltage of approximately 3 kV and a current of 400–430 kA. The duration of the current pulse is 0.8–1 ms.

As a result of an increase in pressure in the HPC, the steel diaphragm ruptures, which leads to the formation of a shock wave propagating in the LPC. A prechamber of the supersonic nozzle is located at the opposite end of the LPC from the diaphragm. Another copper diaphragm is installed between the nozzle and the prechamber, which makes it possible to achieve further gas outflow into the previously evacuated volume of the working chamber, ensuring the launch of the nozzle and the mode of underexpansion of the flow.

The opening of the diaphragm at the inlet to the nozzle occurs as a result of a jump in gas pressure behind the reflected shock wave in the LPC. In this case, in accordance with the one-dimensional theory of the development of gas-dynamic processes in the shock tube, quasi-stationary air parameters are maintained behind the reflected shock wave. Measurements of the shock wave velocity in the LPC and the pressure in the nozzle prechamber are carried out using high-frequency piezoelectric sensors, whose signal is also used to synchronize ionization devices and recording equipment of the diagnostic complex. These parameters make it possible to calculate the operating mode of the supersonic nozzle using well-known gas-dynamic functions. The working gas is accelerated in the nozzle to a speed of approximately 2000 m/s, forming a gas jet that flows out into the working part of the apparatus, which is connected through a flange to a receiver with a volume of 0.7 m\(^3 \). The initial pressure in the receiver is approximately \( 10^{-3} \) Torr. The geometry of the rectangular test section and the diameters of
the observed windows make it possible to study the
gas-dynamic processes of models with a characteristic
size along the cruise coordinate of 30–100 mm.

The supersonic Laval nozzle is made of two parts:
a profiled diffuser and a replaceable confuser. The
outlet section of the diffuser has a diameter of 105 mm.
The replaceable part of the nozzle allows one to change
the Mach number of the flow in the working chamber
by reducing the critical section area. When the ratio
of the throat diameter to the LPC diameter was approxi-
mately 1 : 10, the gas outflow from the region behind
the reflected shock wave had little effect on the
parameters of gas deceleration at the nozzle inlet.
Thus, the calculated Mach numbers of the flow at the
nozzle exit are limited to the lower side by $M = 6$. The
maximum value of the Mach numbers of the flow $M = 12$
is determined by the possibilities of using modern
optical methods for recording the structure of the
flow. With a strong decrease in the flux density, diffi-
culties arise in the use of many optical methods for
studying flows when flowing around various test mod-
els. In total, the facility has four options for inter-
changeable convergers for modeling the Mach num-
bers of the flow 6, 8, 10, and 12.

The clear advantages of using the shock tube tech-
nique are the simplicity and good accuracy of calculating
the parameters of the working gas behind the transmitted
and reflected shock waves, as well as at the exit of the
supersonic nozzle. The values of the flow deceleration
parameters for the selected values of the Mach numbers
are determined by the calculated pressure values for the
shock wave reflected from the end of the prechamber.

The parameters of the gas behind the reflected shock
wave can be quite accurately determined from the value
of the initial pressure of the working gas and the velocity
of propagation of the shock front in the LPC.

**Magnetic System**

The used electromagnet, in whose center the work-
ing chamber is located, is capable of generating a con-
stant and uniform magnetic field with an induction of
up to 2.5 T during the entire operation time of the
apparatus. The magnet consists of a set of windings in
an iron yoke. The top of the magnet also has a channel
for installing an electron gun used to ionize the flow.
A steel core is installed in the lower part of the magnet,
which, together with the placement of optical windows
in the walls of the magnet case, leads to an insignifi-
cant inhomogeneity of the magnetic field over the vol-
ume in the working part of the apparatus (no more
than 10%). With an increase in the magnetic field, the
degree of its spatial inhomogeneity decreases. This is
due to the saturation of the steel elements of the elec-
tromagnet body that surrounds the working chamber.
As a result of saturation, the influence of these ele-
ments on the distribution of the magnetic field
decreases. Acceptable uniformity of the magnetic field
is achieved when its induction is over 0.15 T. At lower
values of the magnetic field induction, it is worth tak-
ing its inhomogeneity into account, depending on the
conditions of the problem.
AN EXPERIMENTAL COMPLEX FOR RESEARCHING

Devices for Ionization of Gas Flows

To solve the problems of magnetoplasma aerodynamics, it is necessary to have an ionized gas exposed to electric and magnetic fields. According to Fig. 2, the stagnation temperature of the flow, depending on the initial pressure of the working gas in the LPC, practically cannot reach values that provide thermal ionization of the gas without the use of additional devices. For volumetric ionization of a high-speed flow in the operation of the experimental stand, electron beams introduced into the flow along the magnetic field [6] can be used, as well as electric discharges of electrodes installed on the surface of the model or in the flow using various current generators. A pulsed high-voltage unipolar discharge can be created using a long line of capacitors [7–10]. To initiate high-frequency discharges of direct and alternating currents with a frequency of up to 1 MHz, appropriate current generators are used [11]. Thus, it is possible to create conditions for local gas ionization to solve various interaction schemes, depending on the task at hand.

Diagnostic Equipment

The short duration of the realized quasi-stationary regime of outflow from the nozzle and gas ionization using pulsed discharges requires the use of appropriate equipment and techniques. High-frequency piezoelectric pressure sensors are used to measure gas-dynamic parameters, and high-frequency current transformers and oscilloscopes are used to measure discharge parameters. To synchronize the operation of all executive and measuring devices, high-precision pulse delay generators are used.

Optical registration of the flow structure is carried out using high-speed schlieren video recording. An adaptive visualizing transparency [12] is used as an optical knife, which makes it possible to simultaneously study low-density gas-dynamic processes and observe the radiation of plasma formations. To ensure short exposure times (1 μs) and high shooting rates (up to 480 kHz), the optical system uses CMOS (Complementary Metal–Oxide–Semiconductor)-camera Photron Fastcam SA-Z.

The gas-Dynamic Parameters of the Operating Modes of the Apparatus

The presented MHD test bench makes it possible to simulate the flow parameters typical for high-speed flight conditions in the Earth’s atmosphere at an altitude of 30–60 km above sea level. Fig. 3 shows the ranges of the simulated Reynolds numbers and the main parameters of the air flow depending on the Mach number of the flow. The ranges are limited by the curves of the minimum and maximum values due to the choice of the initial parameters of the gases in the shock tube and the energy of the electric arc heating of the pushing gas in the HPC. It should be noted that the apparatus makes it possible to simulate the high-speed motion of bodies in the atmospheres of other planets when using gas mixtures other than air.

The shock tube theory was described in detail in [13, 14], whose main provisions were used to calculate the parameters of deceleration in the nozzle prechamber. The calculation of the flow parameters at the exit of a supersonic nozzle is carried out using the well-known gas-dynamic functions [15]. The calculation uses the initial parameters of the working and pushing gases, as well as the energy characteristics of the electric arc heating of the pushing gas in the HPC. A more accurate calculation of the parameters in the nozzle prechamber is carried out using the velocity of the passing shock wave, which is measured by the time of its passage between high-frequency pressure sensors installed in the LPC wall. To verify the calculation, the values of the pressure behind the transmitted and reflected shock waves in the LPC are used, as well as the value of the stagnation pressure in the flow at the nozzle exit.

As can be seen from the graphs, the modeling of high-altitude flight conditions at the MHD stand is mainly based on the magnitude of the pressure and air density. The use of a shock tube makes it possible to implement the design mode in a wide range of parameters and to solve specific problems of magnetoplasma aerodynamics.

EXAMPLES OF THE RESULTS OF MHD RESEARCH PERFORMED ON THE EXPERIMENTAL STAND

At the MHD stand of the ITAM SB RAS, experiments were carried out aimed at studying the MHD effect on the shock-wave structure of a flow in a supersonic flow around bodies of various geometries, such as a plate, wedge, blunt body, etc.

The results of experimental studies have shown that both electron beams [6] and electric discharges of var-
Fig. 3. The gas-dynamic parameters of the experimental stand operating modes: (a) range of realizable Reynolds numbers; (b) pressure ranges $P$ and density $\rho$ gas simulating the flight of an aircraft at an appropriate altitude; (c) working gas pressure range behind the shock wave; (d) the range of density of the working gas behind the shock wave; (e) working gas temperature range behind the shock wave.
ious types [7–11] can be used to ionize high-speed flows when simulating MHD interaction near a streamlined body. Studies of the MHD interaction at high values of magnetic induction have demonstrated the possibility of significant changes in the shock-wave structure of the flow and the local Mach number of the flow under conditions of high-speed flight. Figure 4 shows photographs of the wave structure of the flow around the plate and the glow of the plasma of a pulsed electric discharge, illustrating the MHD interaction in the flow near the model—the plate.

The experimental results were used to determine the characteristic values of the hydromagnetic interaction parameter at which changes in the angle of inclination (Fig. 4a) and the shape of the attached shock wave (Fig. 4b) are observed, as well as the formation of a detached shock in the region of local MHD interaction (Fig. 4c). In these experiments, at a magnetic field of more than 0.8 T, a strong MHD interaction occurred and unsteady processes of oscillation of the MHD interaction region and the bow shock wave along the model surface were observed [7]. However, there are also quasi-stationary conditions for the flow around the model under the MHD action on the flow structure. It was shown that an increase in pressure in the MHD interaction zone near the surface of a streamlined model can lead to the generation of hanging shock waves [11], which can be used to create control moments as an equivalent to the action of an aerodynamic shield. In this work, this effect can be characterized by the term MHD aileron.

When flowing around a blunt body (a model of a descent vehicle), the localization of the MHD interaction region in front of the model can lead to the departure of the bow shock and to a decrease in the heat flux to the surface [9, 10]. The region of local flow acceleration near bodies using MHD interaction can significantly affect the drag of the model. Figure 5 shows images of the process of MHD interaction in an air flow with Mach number $M = 6$ at various values of the magnetic field. It is seen that at low values of the magnetic field, $B = 0.3$ T, the electromagnetic force that acts on the discharge cannot overcome the force of the velocity head of the incident flow, the discharge arc burns outside the bottom of the model. When the field is $B = 1$ T, the discharge is concentrated near the boundaries of the spherical head of the model. At the magnitude of the magnetic field $B > 1.5$ T, the plasma moves towards the flow, which leads to the departure of the bow shock and a change in the effective shape of the head.

The experiments we performed have shown that by choosing the optimal MHD interaction scheme near the model surface, one can significantly change the aerodynamic characteristics of the flow around an object and create additional forces and moments on the body surface.

Fig. 4. The magnetohydrodynamic interaction in a supersonic flow around a plate surface at different values of magnetic induction $B$: (a) 0.1; (b) 0.3; (c) 0.7 T.
CONCLUSIONS

The use of the shock tube technique in the creation of the MHD test bench at the ITAM SB RAS makes it possible to carry out various experiments in high-speed air flows. The presence of a powerful electromagnetic system and devices for ionization of the flow makes it possible to use the apparatus for conducting magnetoplasma studies in a wide range of parameters.

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