Experimental study of high-speed ionized gas flow around plate and wedge model

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Abstract. In the development of magneto-plasma methods for controlling the aerodynamics of promising high-speed aircraft, an important place is occupied by studies of the interaction of ionized gas flows with a shock-wave flow structure. In this work, the flow near a model (a wedge and a plate) by a pulsed stream of air plasma is investigated. As a result of the work, it was shown that a change in the local Mach number in the stream ionized by an electric discharge leads to a change in the shape of the shock wave generated by the leading edge of the model. The temperature of the discharge plasma was estimated, which showed the predominance of the thermal effect on the flow structure.

Experimental techniques
An experimental study of the flow near a plate and a wedge with a high-speed ionized air flow was carried out on the magnetohydrodynamic (MHD) test rig of the ITAM SB RAS [1]. This test rig based on a shock tube allows to obtain a high-speed gas flow using various gases, in this work – air. Figure 1 shows the installation diagram. The low pressure channel 3 (LPC) is filled with the work gas. The high-pressure chamber 1 (HPC) is filled with a high-pressure pushing gas — helium under the test conditions. Quasi-stationary conditions are formed behind the reflected shock wave at the entrance to the nozzle 5 to obtain a flow of working gas at the nozzle exit with the necessary quasi-stationary parameters for 1–2 ms. A nozzle on the Mach number $M = 6$ was used in the work.

Visualization of the ionized flow pattern near the models was carried out by an optical schlieren-system with a high-speed camera. The optical scheme with an adaptive visualizing transparency as a Foucault's knife [2] made it possible to register both the wave pattern of the flow of models in the green light of a laser and the radiation from the plasma part of the stream.

The flow was ionized using a pulsed high-voltage (3 kV) discharge initiated between the electrodes installed in front of the model. The discharge pulse duration was 20 and 120 $\mu$s, depending on the experimental conditions. Measurement of discharge parameters was carried out using current transformers without galvanic coupling of the object being measured with oscilloscopes. Measurements were made of all electrical quantities that determine the required mode of operation of the installation.
Figure 1. Scheme of experimental test rig. 1 - HPC with power supply, 2 - diaphragm, 3 - LPC, 4 - diaphragm; 5 - nozzle, 6 - working chamber, 7 - magnetic system, 8 - receiver, 9 - piezoelectric pressure sensors, 10 - pulse generator, 11 - power of ionizing devices, 12 - optical system, 13 - diagnostic complex, 14 - monitor.

Experiment statement
Case of air flow with Mach number $M = 6$ were considered. The distance from ionizing flow electrodes to the leading edge of the models varied from 5 to 20 mm depending on the experimental conditions. Fig. 2 shows the experimental scheme with a flow around a plate and a wedge.

Figure 2. Scheme of MHD interaction in flow near wedge and plate model: 1 - electrodes, 2 - model.

Experimental results
1.1. Ionization of a flow before a wedge by a short pulse discharge
To clarify the effect of heating the flow during gas ionization, an experiment was conducted with a short discharge time according to the scheme shown in Figure 2,a. When the flow was ionized by a pulse discharge with a duration of 20 $\mu$s, the distance from the electrodes of the ionizing discharge to the leading edge of the model was 5 mm. The width of the electrodes is $b = 15$ mm, length is $l = 25$ mm. The flow passed the electrodes in 12.5 $\mu$s with rate of about 2000 m/s, almost ending at the time of passing the discharge through the electrodes space. At the same time, the heated region continued to move at an average flow rate. Figure 3 shows three schlieren-photographs of a flow around a wedge of 50 mm length. A flow was taken at a frequency of 330000 frames per second. The frame exposure time was 1.2 $\mu$s. Fig. 3 shows that as soon as the gas cools between frames $b$ and $c$ in 3 $\mu$s, the flow pattern of the upper edge of the wedge with a continuous shock wave corresponding to the change in the Mach number of the flow is restored.
Figure 3. Schlieren-photos of the flow around a wedge: undisturbed flow (a), ionized flow (b, c).

1- electrodes, 2- wedge.

The slope angle the oblique shock wave in the undisturbed flow, Figure 2,a, is 23 degrees, which corresponds to the flow around the wedge with Mach number $M = 5.8$. The slope of the shock in the central part of the MHD-interaction region, Figure 2,b and Figure 2,c, is 32 degrees, which corresponds to the Mach number $M = 3$ in this part of the flow. You can see that the slope angle of the shock in the middle part of the flow persists when the disturbed area passes over the wedge surface. In this case, in the flow region near the leading edge of the wedge, after passing through the disturbed zone, the angle of inclination of the shock is restored to the undisturbed value. Comparison of two consecutive frames, the time between which is 3 $\mu$s, allows us to conclude that the flow recovery time under the experimental conditions does not exceed 3 $\mu$s. These experiments showed that the plasma flow acts as a well-heated gas. The gas heated by an electric discharge leads to the modulation of the local Mach number under the test conditions.

1.2. Ionization of a flow before a wedge by a long pulse discharge

With a longer discharge time (120 $\mu$s) the temperature and conductivity of the flow were maintained during the ionized gas flows around the wedge. This led to a change in the shock wave structure of the flow. Figures 4 and 5 show several frames (frame rate of 160 000 fps) of plasma flow over the wedge and the plate. From the pictures in Fig. 4 and 5 it can be seen that the plasma flow destruct the shock wave generated by the leading edge of the models. The shock is restored after passing through the plasma region (Fig. 4,d-f). When the discharge plasma is localized under the shock wave formed in the cold flow, a change in the shock wave angle is observed, Fig. 4,e and Fig. 4,f. This suggests that in the observed flow patterns, the plasma flow acts as the gas heated up to a high temperature.

Figure 4. Hypersonic air flow ionized by pulsed electrical discharge around wedge model: 1 – electrodes, 2 – model, 3 – shock, 4 – measuring electrodes area, 5 – discharge plasma.
Fig. 5 shows hypersonic flow with electrical discharge near the model in magnetic field ($B = 0.17$ T). Direction of discharge current and B-field induction leads to accelerating the gas downstream. One can see that the shock wave on the leading edge of the plate is destructed in the plasma region, Fig. 5c, and is not generated again when it moves further along the plate, Fig. 5,d. With further advancement of the plasma part above the plate surface in the cold part of the flow, the shock wave is restored, Fig. 5,e, Fig. 5,f.

**Discussion and conclusions**

To clarify the thermal effect on the flow by an electric discharge, the determination of the gas temperature in the plasma part of the flow was performed. The temperature was determined from the plasma radiation power using the “gray body” radiation model, with the emissivity taken from table [3]. To determine the plasma emissivity, we used the static pressure in the flow and the thickness of the radiating plasma layer, which was assumed to be equal to the distance between the electrodes, Fig. 2. After exiting the area between the electrodes, this part of the plasma flow was connected to the electrodes with relatively thin, in the direction of the flow, parts of the electric discharge arc directed along the flow, Fig. 5,c-f. Therefore, the acting plasma region of the flow was only that volume in which the current flowed crosswise the gas flow. Long parts of the arc discharge in flow direction are visible, but between them there was a cold gas with the temperature of the incoming flow, Fig. 5,d-f and Fig. 6,e,f.
Fig. 6 and Fig. 7 shows the temperature of the plasma region of the flow near the wedge and the plate. The plasma temperature can be estimated as 6500-7000 K, which is corresponds to the temperature for low-pressure arc discharge [4]. According to the temperature of the plasma flow, it was obtained the sonic rate of about 2100 m/s. The flow velocity determined by the photography was about 1900 m/s. The Mach number of this part of the flow was about 0.8 – 0.9. Since the flow was subsonic, a shock did not form. It can be assumed that this was the main effect of the ionization of the flow of electric discharges under the conditions of this experiment.

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