Supersonic plasma jets in experiments for radiophysical testing of bodies flow

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Abstract. The action of differently oriented magnetic fields on the parameters of bow shock created in the vicinity of aerodynamic bodies placed into the supersonic gas-plasma flows is studied. For these experiments two types of the high speed plasma jet sources are used—magnetoplasma compressor (MPC) and powerful pulse capillary type discharge. MPC allows to create the plasma jets with gas flow velocity of $10 \pm 2$ km/s, lifetime 30–50 $\mu$s, temperature $T_e \approx 3 \pm 0.5$ eV, electron density about $n_e \sim 10^{16}$ cm$^{-3}$ and temperature $T_e \approx 3 \pm 0.5$ eV. The jet source based on powerful capillary discharge creates the flows with lifetime 1–20 ms, Mach numbers 3–8, plasma flow velocity 3–10 km/s, vibration and rotation temperatures 9000–14000 and 3800–6000 K respectively. The results of our first experiments show the possibility of using gas-plasma sources based on MPC and powerful capillary discharge for aerodynamic and radiophysical experiments. Comparatively small magnetic field $B = 0.23–0.5$ T, applied to the obtained bow shocks, essentially modify them. This can lead to a change in shape and an increase in the distance between the detached shock wave and the streamlined body surface if $B$ is parallel to the jet velocity or to decrease this parameter if $B$ is orthogonal to the oncoming flow. Probably, the first case can be useful for reducing the thermal load and aerodynamic drag of streamlined body and the second case can be used to control the radio-transparency of the plasma layer and solving the blackout problem.

1. Introduction

Now, high velocity and intensity plasma jets, which are based on magnetoplasma compressors (MPCs) and high-current pulse capillary discharge technique, are investigated and used in different plasma-dynamics experiments very actively. In our previous works [1–3] we noted, that this comparatively simple and cheap plasma jet sources may be used effectively in different magnetoplasma aerodynamics applications. In particular, it may be experiments for modeling of gas-dynamic and physical-chemical processes of a gas-plasma flow and aerodynamic body interaction under hypersonic velocities. The range of parameters of thus obtained plasma jets (velocities—0.5–10 km/s, lifetime—from 20 $\mu$s to 50 ms, static pressure—1–500 Torr) allows to simulate a large number of the topical issues of magnetoplasma aerodynamics in laboratory
conditions. The problem of controlling the parameters of high-speed flows is the urgent one. This problem plays a key role in issues of heat and mass transfer and reducing of aerodynamic drag of rapidly moving bodies [4], of radio waves propagation through a layer of thermal plasma [5, 6] etc. In conditions of hypersonic flight, when the stagnation of the gas behind the shock wave causes ionization, the control of the flow parameters in the vicinity of the streamlined body can be achieved by applying the magnetic field. The effectiveness of this action depends on both the magnitude and the direction of the magnetic field. In this work, we made the attempt to simulate this action in laboratory conditions using a MPC and a powerful pulsed discharge in a capillary with ablating wall as sources of gas-plasma flows. The aim of this work is to study the possibility of using of such gas-plasma sources for laboratory modeling of gas-dynamic effects of hypersonic flight, and also to evaluate the effectiveness of the magnetic field action on the parameters of the stagnation zone.

2. Magnetoplasma compressor
We used MPC with outlet diameter of 23 mm for creating a high-speed gas-plasma flow in the first series of experiments. Principal design and parameters of MPC is presented elsewhere [1]. MPC was mounted in the test chamber, the air pressure was 15 Torr. The typical trace for discharge current through MPC is presented in figure 1(a). The AcE0640gm camera (minimum camera gate 4 $\mu$s) is used for imaging the plasma jet in different moments after the discharge beginning. The images of free MPC jet obtained at 15 and 25 $\mu$s after the discharge beginning are presented in figure 1(b). These images were obtained using the interference filter 393 nm (spectral interval corresponding to ion lines O II 386.61–395.46 nm). The well-formed torch of quasi-stationary plasma jet in compression zone of MPC, position 1 in figure 1(b), and the stagnation zone of MPC jet in ambient gas, position 2, are clearly seen in 15 $\mu$s after the discharge beginning. The drift velocity of stagnation zone is about 2.3 km/$s$. Starting from 20–25 $\mu$s after the discharge beginning, the quasi-stationary flow is established over the most part of the jet. The flow section, starting from the distances of 1–1.5 calibers relatively outlet diameter, can be used as working area for test bodies.

Figure 1. Discharge current for MPC (a) and images of MPC jet obtained on 15 and 25 $\mu$s time delay from the discharge beginning (b). Area 1—quasi-stationary compressive jet; 2—stagnation zone in ambient air.
The gas velocity in working area was estimated by measuring the jets Mach number (M) and its temperature using the spectral methods. Mach number measurements were performed by the investigations flow around asymmetrical wedge for different delays of time (figure 2). The averaged Mach number for time interval 15–35 µs was about 3.3–3.1.

The spectral measurements were performed using the multichannel and strobing spectrometer AvaSpec-ULS-2048 for spectral interval 300–1000 nm, spectral resolution of 2.4 nm and a minimal gate of 2 µs for variable delays after the discharge beginning. Unfortunately, usage of the classical methods for plasma temperature measuring (for example by line intensity ratio) with so low spectral resolution is very difficult, and temperature estimations were made by matching of synthesized spectrum, containing all ion lines observed in experiment with obtained spectra. The mentioned above procedure shows that most probable parameters of MPC flow are the following: the temperature $T_e \approx 3 \pm 0.5$ eV and the electron density $n_e \sim 10^{16}$ cm$^{-3}$. So high temperature for MPC flow gives the estimation for gas flow velocity of $10 \pm 2$ km/s.

The investigations of the influence of the value and orientation of magnetic field on stagnation zone parameters for hypersonic flow around spherical aerodynamic bodies were performed using the spherical Fe–Nd–B magnets with 15 mm diameter. The Hall sensor (diameter of 1 mm) is used for measuring the magnetic field induction $B$ on the surface of these magnets. Its value was about $B = 0.53 \pm 0.2$ T for normal field component on the pole of magnet. The tangential component at the distance 1 mm from surface of magnet was about $B = 0.23 \pm 0.1$ T. For the first experiment, the normal component of magnetic field was oriented along the jets velocity direction (figure 3), for the second experiment the tangential component of magnetic field was perpendicular to the jet velocity (figure 4). The flow pattern is obtained by AcE-640 camera with a gate of 4 µs and time delay of 20 µs.

Figures 3 and 4 clearly show that applying even comparatively small (less than $B = 0.23$ T) orthogonal to the oncoming velocity magnetic field essentially decrease the width of stagnation zone, but magnetic field parallel to the jet velocity increase it. The general intensity of bow shocks luminescence from the same analyzed zones is essentially lower for tangential field. In figure 5 the most informative parts of registered spectra are presented.

To the conclusion of discussion of spectral measurements, it may be noted, that presented spectra clearly show the changing of related intensities for spectral parts, contain ion lines N I, N II, O II located in the spectral range of 390–420 nm. These spectra modifications demonstrate the trend to decreasing the plasma temperature in stagnation zone when the tangential to the surface of aerodynamic body magnetic field is applied.

**Figure 2.** Wedge flow for MPC jet. Mach number $M = 3.3$ for 15 µs (a) of discharge process and $M = 3.21$ for 35 µs (b). The discharge conditions and camera gate are the same in figure 1.
3. The powerful pulsed capillary discharge

The pulsed capillary discharge with an ablative wall is another perspective method for creating the high-speed plasma flows. The detailed description of capillary discharger is presented in [7]. Polymethylmethacrylate (C₅H₈O₂) is used as wall material. The initial diameter of the capillary and its depth are \( d = 1 \text{ mm} \) and \( h = 5 \text{ mm} \). Capacity storage is used as power source and provide following parameters of discharge pulse: storage energy \( Q = 90–260 \text{ J} \), power algorithm—sine half-wave, peak value of discharge current \( I_m = 90–160 \text{ A} \), duration of discharge \( t_{1/2} = 7.5 \text{ ms} \). In laboratory simulation experiments on gas-plasma flow around the bodies the discharger was
Figure 5. The most typical spectra from investigated area of bow shock for different orientation of magnetic fields relatively jets velocity. Time delay from discharge beginning is 25 $\mu$s, the camera gate—2 $\mu$s.

Figure 6. The flow pattern around sphere in the absence ($a$) and in the presence ($b$) of magnetic field ($B = 0.5$ T). Camera gate $\tau = 1$ $\mu$s.

mounted in vacuum chamber. Test bodies of different shapes installed along the capillary axis at a predetermined distance (1.5–5 cm) from its outlet. Experiments were performed in an air atmosphere in the pressure range $p = 3$–20 Torr.

The study of the flow pattern was carried out by recording the own image of the selected area of gas-plasma flow on a high-speed video camera MotionPro N3 (camera gate 1 $\mu$s, frame rate 4–5 kHz). The spectrometer AvaSpec UL-2048 is used for recording the emission spectra of plasma in the spectral range 280–800 nm. These spectra were used for determining the
plasma composition and for estimating its main parameters—the electron density, the vibration and rotation temperatures. Estimations of the flow gas dynamic parameters were prepared by measuring the stand-off distance of central shock wave (a Mach disc) from the capillary outlet and by measuring the stand-off distance of the detached shock-wave from the surface of test body. The range of Mach numbers registered in our experiments is $M = 3–8$ that correspond to the plasma flow velocity $v = 3–10$ km/s. Estimations of the vibration and rotation temperatures, obtained by emission spectra processing, give the following values: $T_v = 9000–14000$ K and $T_r = 3800–6000$ K.

The experiments to study the influence of a longitudinal magnetic field on a pattern of a supersonic flow around a blunt body were carried out. The dielectric sphere, whose diameter is 20 mm, was used as a test body in these experiments. The Fe–Nd–B cylindrical magnet ($D = 10$ mm and $H = 5$ mm), mounted inside the sphere, is used for producing a magnetic field induction $B = 0.5$ T on its surface. Turning on the magnetic field has a significant influence on the flow pattern in the vicinity of the streamlined body. This results in an increase the stand-off distance of the detached shock wave and in increase the radiation intensity from the stagnation zone (figure 6). Moreover, the increase of the discharge pulse energy (and also the flow velocity) is accompanied by the increase of the magnetic field action on the detached shock wave stand-off distance. The ratios of the stand-off distances of the detached shock wave for the cases when a magnetic field is on $\Delta_M$ and is off $\Delta_0$ (i.e. $\delta_{\text{rel}} = \Delta_M/\Delta_0$) are shown on the plot in figure 7. One can see that $\delta_{\text{rel}}$ is increased with discharge pulse energy.

### 4. Conclusion

Thus, our experiments have shown the possibility of using gas-plasma sources based on MPC and powerful capillary discharge for aerodynamic and radiophysical experiments. The undertaken
experimental studies explicitly confirm the availability of modification the stagnation zones in the vicinity of streamlined bodies by applying the magnetic field and varying its direction relatively to the incident flow. The magnetic field action causes the increase of the detached shock distance from streamlined body if its direction is parallel to the flow or the decrease of mentioned distance if directions of the flow and magnetic field are orthogonal. The first case can be useful for reducing the thermal load and aerodynamic drag of streamlined body and the second case can be used to control the radio-transparency of the plasma layer and solving the blackout problem. Even small quantities of applied field ($B = 0.23 \text{ T}$ in our experiments) give a reassuring effect. In the future, we plan to increase the induction of the magnetic field up to $B = 1–1.5 \text{ T}$, which will improve the accuracy of measurements. Also it is necessary to increase spectral resolution up to 0.05–0.06 nm, which will increase the accuracy of determining the electrophysical parameters of the plasma on the basis of spectral methods. An important step in future work should be an increase in the spatial resolution of the flow pattern, especially in the stagnation zone, by the use of modified schlieren methods [8].

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