Experimental investigation of the interaction of supersonic airflow with transverse discharge

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Abstract. We have experimentally studied the interaction of a supersonic air flow with transverse electric gas discharge. Spectra of radiation emitted from various regions of the flow in the 600–700 nm wavelength range have been measured. Composition of the supersonic air flow is determined and peculiarities of its interaction with discharge have been studied. In particular, significant transfer of the electrode material with gas flow was observed.

1. Introduction

The interaction of high-velocity gas flows with low-temperature plasma is a topical area of research of magneto-plasma aerodynamics [1, 2]. Physical processes accompanying the interaction of plasma with supersonic flow are very complicated and have yet to be sufficiently studied. In particular, the process of gas ionization at high velocities of the flow has some specific features related to the transport of charged particles away from the region of a strong electric field.

This work is a continuation of our investigations devoted to peculiarities of the interaction of supersonic flows with low-temperature plasma. Previously, we have studied the capabilities of a flow control in a supersonic diffuser via the MHD method [3], the influence of gas-discharge plasma on the structure of flow past a body and on the heat flux toward its surface [4]. It was established that a rotating discharge significantly modifies the shock-wave configuration near a body and, hence, heat fluxes toward its surface. It was also established [5] that local near-electrode processes significantly influence the entire discharge dynamics. In the case of subsonic gas flows, similar results were obtained in [6]. Recent investigation [7] of a short-time interaction of a supersonic gas flow with low-temperature laser-generated plasma showed evidence of significant changes in the flow structure and the formation of shock waves. The present investigation is devoted to elucidating peculiarities of the interaction of a supersonic flow with gas discharge plasma.

2. Experimental setup

The experiments were carried out in a pulsed gasdynamic setup based on a Ludwig tube (Figure 1). Conical nozzle 1 with a 60° opening angle had critical and output cross section with diameters of 10 and 60 mm, respectively. The output cross section of the nozzle was placed inside cylindrical vacuum chamber 2 with a 0.3 m inner diameter and height of 0.4 m equipped with a roughing pump. The
subsonic part of the nozzle was separated from atmosphere by a plastic diaphragm. The side wall of the chamber was provided with windows 3 for spectroscopic diagnostics. The optical emission spectra were measured using monochromator 4 with a CCD array linked to a computer. A pair of aluminum electrodes was situated 20 mm away from the nozzle output cross section. Central electrode 5 with a diameter of 4 mm was arranged on the nozzle axis, and side electrode 6 was mounted 20 mm away from the nozzle edge. The electrodes were connected to pulsed current source 7 representing an LC line consisting of 14 unit circuits, each with capacitance $C = 300 \, \mu\text{F}$ and inductance $L = 3.5 \, \mu\text{H}$. This circuit generated nearly rectangular current pulses with a duration of about 1 ms. Serially connected low-inductance high-voltage transformer formed a voltage pulse of $t \approx 10^{-6} \, \text{s}$ duration and amplitude up to $U \approx 30 \, \text{kV}$ that initiated electric gas discharge.

Before to the experiment, the chamber was evacuated to a residual gas pressure of $P = 0.1 \, \text{Torr}$, which corresponded to pressure in supersonic flow at the nozzle output edge. After destruction of the diaphragm, the atmospheric air was ejected into the chamber via the nozzle. The current source was switched on at $t = 200 \, \mu\text{s}$ after destruction of the diaphragm, when airflow in the supersonic nozzle could be considered steady-state. At this moment, an initiating high-voltage pulse was applied between the central and side electrodes, which formed the initial region of discharge. Then, the main storage bank exhibited discharge during $t \approx 1 \, \text{ms}$ via the initiated channel. In these experiments, the output voltage was varied within $U = 300–600 \, \text{V}$ and the discharge current reached $I = 1.7 \, \text{kA}$. The total energy deposited in discharge during this pulse varied within $Q = 250–700 \, \text{J}$ depending on the initial voltage of the source.

Parameters of the supersonic air flow in the nozzle output section were determined by simulating non-viscous gas flow in the nozzle, where the pressure was $P \approx 0.1 \, \text{Torr}$ and the flow Mach number was $M \approx 5.5$. According to calculations, the gas pressure growth in the vacuum chamber during discharge ($t \approx 1 \, \text{ms}$) was no more than twofold. At this ratio of pressures, there is no supersonic gas flow separation in the nozzle and the flow structure is close to the calculated pattern.

In these experiments, peculiarities of the interaction of supersonic flow with electric discharge were studied by means of spectroscopic diagnostics in the visible spectral range. For this purpose, we measured the spectra of emission from regions I–IV spaced by 30, 50, 70, and 90 mm, respectively, from the nozzle output along the line passing via the middle of the interelectrode gap.

The emission spectra were measured using a monochromator based on the Seya–Namioka scheme with a CCD array TCD1304DG (Toshiba) detector. The operation of CCD arrays of this type in spectral instruments for diagnostics of pulsed radiation sources was studied in [8]. The minimum time of charge accumulation in these CCD arrays is $t \approx 20 \, \text{ms}$. In the given case, this circumstance allows measuring only the integrated emission spectra. In one run, the spectra were measured within $\Delta\lambda \approx 100 \, \text{nm}$ wavelength interval. The inverse linear dispersion of the instrument employed with a
1200 cm$^{-1}$ grating was 1.9 nm/mm. Calibration of the spectrometer with respect to the wavelength scale was performed using Ne I lines from the NIST Atomic Spectra Database [9]. The error of wavelength determination in the entire spectral range studied was Δλ < 0.01 nm.

3. Results and discussion

Here we present the results of experiments performed with supersonic gas flows emitted from the nozzle at pressures P = 0.1 and 10 Torr. The emission spectra were measured in a wavelength range of λ = 600–700 nm. This interval was selected with allowance for specific features of the spectrometer employed and the presence of a small number of emission lines of the material of electrodes (Al) and main atmospheric gases (N and O).

Figure 2. Emission spectra measured in (a) regions I (curve 1) and II (curve 2) for a supersonic flow and (b) region III for stagnant gas at pressures (1, 3) P = 0.1 and 10 Torr, respectively, and (2) for the supersonic flow.

Figure 2 shows the emission spectra measured in various probed regions under conditions of stagnant gas and supersonic flow. The presence of strong emission lines of Al$^+$ ions (Al II, λ = 622.62, 623.17, and 624.34 nm) is indicative of a noticeable supply of electrode material to the region of discharge. The intensity of these lines in the supersonic flow slightly decreases with distance from the nozzle output and significantly exceeds the intensity of the same lines measured during discharge in the stagnant gas at the same pressure (P = 0.1 Torr). Note also that increasing distance from the nozzle edge is accompanied by changes in the relative intensities of Al II emission lines, which can be explained by the variation of temperature in the flow.

The obtained emission spectra show emission lines due to excited atoms of oxygen (O I, λ = 615.82 nm) and nitrogen (N I, λ = 648.27 nm). It should be noted that these lines only appear at some distance from the nozzle edge (regions II–IV) and their intensities slightly decrease with increasing distance.

In the case of a supersonic flow, regions II–IV exhibit continuous emission spectrum with a maximum at λ ≈ 640 nm. Assuming that this emission has a thermal origin, the temperature corresponding to this maximum can be estimated at T ≈ 0.4 eV. Note that, in the stagnant gas at P = 0.1 Torr, no continuous emission spectrum was observed.

We have estimated plasma temperature using relative intensities of a pair of spectral lines belonging to the same ion [10]. The temperature in region II was determined using aluminum ion lines Al II with wavelengths λ = 683.71 and 691.99 nm and the lines of excited nitrogen atoms N I with λ = 664.49 and 672.26 nm. In the former case, the estimated temperature was T = 0.13 eV, while the latter estimation gave T = 0.29 eV. In regions III and IV, the temperature estimated using relative intensities of Al II lines was found to be T = 0.22 and 0.27 eV, respectively. This, the time-averaged temperature at a distance of 50–90 mm from the nozzle edge amounts to T = 0.1–0.3 eV.

The discharge develops in air with a concentration of atomic species on the order of N ~ 10$^{16}$ cm$^{-3}$ and the discharge current density reaches j ~ 10$^3$ A/cm$^2$ [5]. Under these conditions, the ion
component of plasma is represented by the electrode material supplied from small-size local emission centers operating on the cathode surface with a current density up to \( j \approx 10^7 \) A/cm², while the total current is determined by the thermionic emission [11]. According to estimations, the electron concentration in the discharge channel is \( n_e \approx 10^{13} \) cm⁻³ and a large current density is related to a low frequency of electron collisions with molecules in the gaseous medium, which leads to a low degree of ionization in the airflow. This is confirmed by the absence of emission lines due to N⁺ (and higher charged) ions in the spectrum of discharge plasma emission from air flow in region I and large intensity of emission in Al⁺ ion lines.

4. Conclusion

The obtained spectral pattern of emission leads to the conclusions that (I) the discharge region is driven downstream by the oncoming gas flow and (II) there is significant transfer of the electrode material with gas flow over a distance comparable with the transverse size of the supersonic flow. The absence of emission lines corresponding to nitrogen and oxygen ions as well as the continuous emission with a maximum at \( \lambda \approx 640 \) nm in the spectra of regions spaced by 50–90 mm from the nozzle edge indicates that heating of the supersonic flow in discharge takes place without significant ionization.

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