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Radiation of nanosecond surface sliding discharge in a supersonic air flow

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Received November 1, 2023
Revised January 31, 2024
Accepted February 1, 2024

The radiation of a surface sliding discharge in supersonic air flows with an oblique shock wave has been experimentally studied at the flow Mach numbers of 1.20−1.60 and density of 0.01−0.50 kg/m^3. A discharge about 500 ns in duration was initiated in the shock tube test section at the pulsed voltage of 25 kV. The discharge radiation was analyzed based on streak images and 9-frame ICCD images with the nanosecond resolution. It has been established that the discharge channel radiation in supersonic flows undergoes a two-stage attenuation within 2−3 μs and then decays with a characteristic time of 800−1300 ns which significantly exceeds the decay time in still air.

Keywords: nanosecond surface sliding discharge, supersonic flow, radiation dynamics, ICCD camera.

DOI: 10.61011/TPL.2024.05.58421.19791

In recent decades, there has been widely discussed the use in aerodynamic problems of electric discharges as plasma actuators applicable to control the gas flow [1–4] and fuel combustion in engines [5]. Among the advantages of plasma actuators there are fast response and high integrability into complex flows. Actuators based on surface discharges are regarded as promising devices for controlling boundary layers [1,3,4]. Pulsed discharges generate also shock waves which can affect the flow as a whole as well as its boundary layer, local shock waves, and separation zones [4,6]. Measuring the discharge parameters directly in high-speed flows is necessary to predict the specific impact on the flow. The goal of this work was to experimentally study the glow dynamics of the surface sliding discharge in supersonic air flows with oblique shock waves, and also to estimate characteristic times of processes in relaxing plasma.

The experiments were carried out in a shock tube with a discharge chamber having a rectangular cross-section of $24 \times 48\,\mathrm{mm}^2$ [4,6]. At the initial air pressure of 10−50 Torr, the setup produced uniform supersonic air flows 200−600 μs in duration with Mach numbers of 1.20−1.60 at the density of 0.01−0.50 kg/m^3. The shock wave speeds were measured based on signals from pressure sensors; the discharge start was synchronized with the position of the initial shock wave front in the shock tube channel (Mach numbers of 2.50−4.40). Application of pulsed voltage of 25 kV to the electrodes on the working section upper wall (Fig. 1) initiated the surface sliding discharge. The discharge current was recorded with a low-inductance shunt. The current oscillograms were of the oscillatory character with the maximum of up to 1500Å and attenuation depending on the gas density. The maximum current was observed in 30 ns, the current oscillations got decayed within 500−700 ns. Reduced electric field E/N (E is the field strength, N is the molecule concentration) was estimated within the range of $(2{-}10) \cdot 10^{-15}\,\mathrm{V \cdot cm^2}$.

The discharge electrodes were extended by 100 mm along the flow. In the case of the supersonic flow around a rectangular parallelepiped located on the lower wall of the working section there was created an oblique shock wave reflected from the upper wall (Fig. 1). The discharge was being developed in the form of an intense single rectilinear channel (Fig. 2, b). The discharge localization into a single channel is associated with formation in the flow boundary layer on the upper-wall of a lower-density region where a higher reduced electric field is realized [7]. The electron concentration calculated from the maximum channel current amounts up to $(1{-}6) \cdot 10^{15}\,\mathrm{cm}^{-3}$. The main part of the emission spectrum is determined by the second positive nitrogen system ($C^3\Pi_u \to B^3\Pi_g$) and contains the continuum [7]. The discharge glow was recorded with photo— and electron-optical cameras (K008, K011 [8]) through the side quartz walls of the working section. The spectral sensitivity range of electron-optical cameras was 380−850 nm. The cameras were mounted at an angle to the discharge plane. They were started just after supplying from the generator a discharge-initiation signal. The streak images and nine-frame ICCD images of the glow were processed using a scanning program created in the Matlab environment. After selecting a rectangular processing area, the average intensity was determined and related to the time moment. Based on the obtained values, time dependences of the discharge glow intensity were plotted. The decay time was determined at the final stage of the glow from exponential approximation of the intensity decay.

The still-air discharge photographic image presented in Fig. 2, a exhibits the glow of a plasma layer consisting

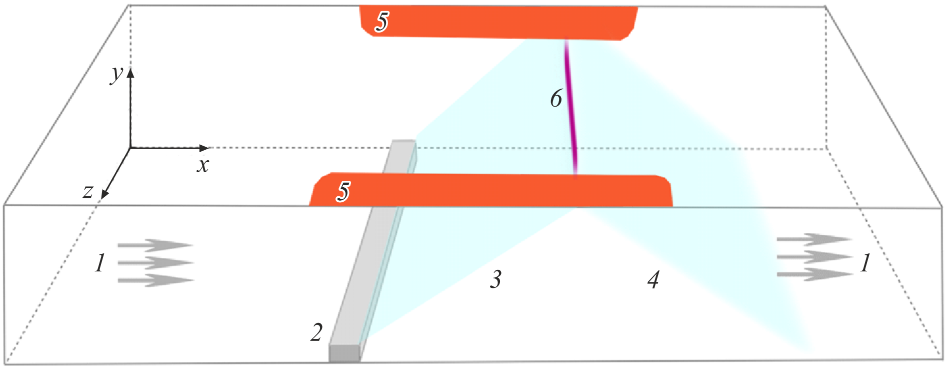

Figure 1. Schematic diagram of the flow in the discharge chamber channel. *1* — supersonic flow, *2* — obstacle, *3* — oblique shock wave, *4* — reflected shock wave, *5* — discharge electrodes, *6* — discharge channel.

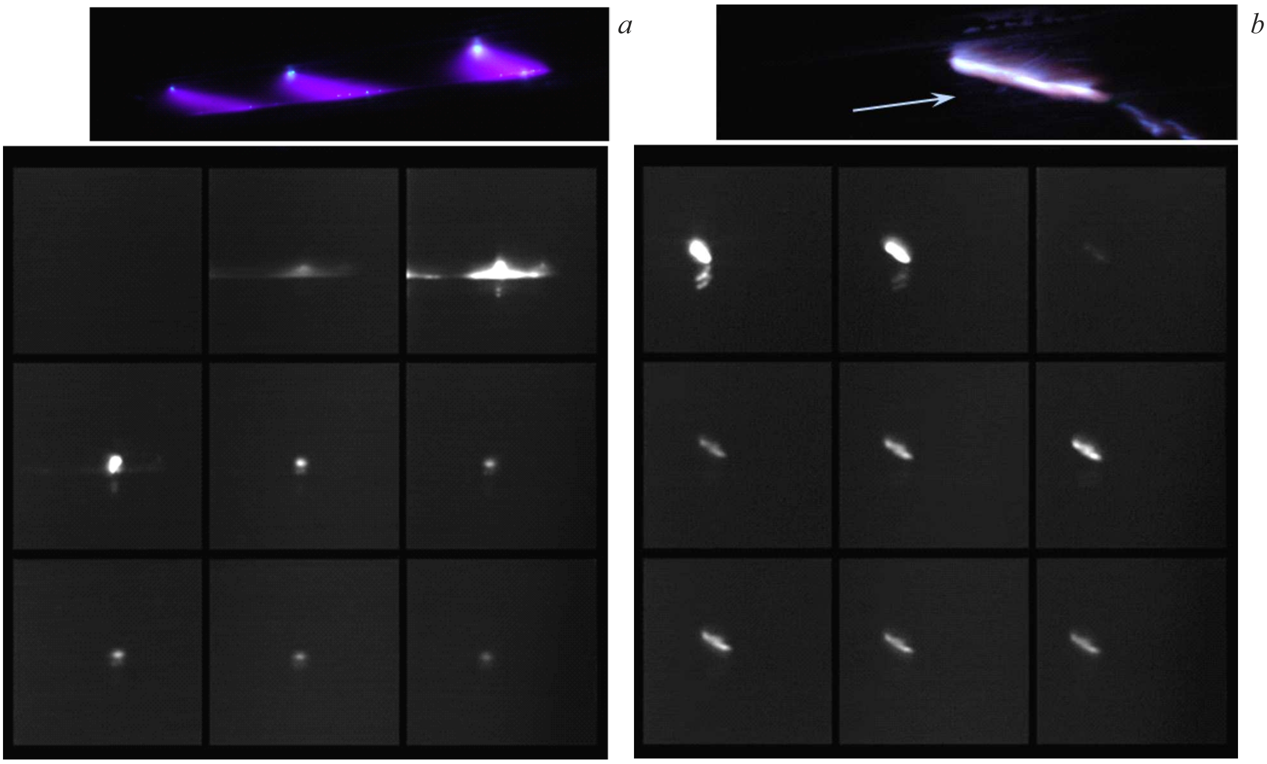

Figure 2. Photo images (upper panels) and nine-frame images (lower panels) of the surface sliding discharge glow in still air at the density of 0.02 kg/m^3 (*a*) and in the flow with the oblique shock wave (*b* /). The flow Mach number is 1.55, density is 0.08 kg/m^3. The flow direction is indicated with the arrow. In the nine-frame images, the frame exposure is 100 ns, the inter-frame pause is 100 ns.

of diffuse and bright channels. The time dependence of the bright channel intensity (curve *3* in Fig. 3) exhibits the correlation between radiation and current oscillations and further decay with the time of 100–350 ns [6]. The plasma glow after the current termination is associated with collisions of nitrogen molecules in metastable states and filling of the $C^3\Pi_u$ state [6].

Experiments in supersonic flows with Mach numbers of 1.20–1.60 have shown that the single discharge channel glow has a high intensity and duration of up to 6 μs. The high reproducibility of the glow detection results allowed comparing the dependences obtained in different time intervals under the same flow conditions. Fig. 3 presents time dependences of the discharge channel glow intensity in supersonic flows (*1*, *2*) and in still air (*3*). To make possible the comparison of the glow dynamics, the intensities have been normalized to the maximum. The intensity variations during the discharge current passage are governed by the current oscillations. Then in supersonic flows, after the current termination, in the time interval of 1500–2000 ns, there is observed a stage of a slight decrease in intensity, after which the decay proceeds within

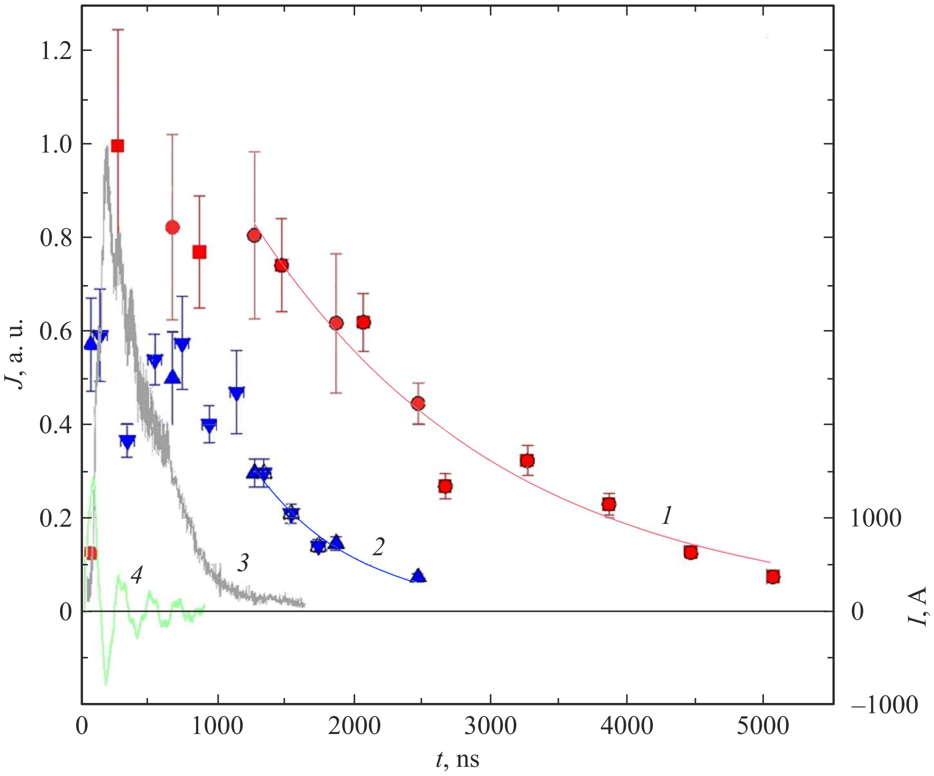

Figure 3. Time dependences of the glow intensity of discharge channels in supersonic flows (*1*, *2*) and of that of the bright channel in still air (*3*). *4* — discharge current in still air. Air density is 0.41 (*1*), 0.12 kg/m^3 (*2*–*4*). The flow Mach numbers are 1.25 (*1*), 1.46 (*2*). Each of curves *1, 2* combines results of two experiments; the lines represent exponential approximations.

2000–3000 ns (curves *1*, *2* in Fig. 3). The decay time of the discharge channel glow determined at this stage under the given experimental conditions was 800–1300 ns. This interval is several times longer than the decay time of the most intense discharge channels in still air.

The radiation dynamics of surface sliding discharges in supersonic flows was analyzed based on estimates of times of the plasma-region relaxation processes. At the electron concentration of $\sim 10^{15}\,\mathrm{cm}^{-3}$, charge recombination occurs within 10 ns. As shown by numerical calculations of gas-dynamic fields with pulsed energy deposition [7], local gas temperature in the discharge area can reach 5000–10 000 K. High temperature provides rapid relaxation of the vibrational energy (within 2–10 μs) [5]. Gas may be heated in the plasma region also due to relaxation of electronically excited states of atoms and molecules [5]. The discharge channel radiation is characterized by high intensity during microseconds; the radiation dynamics depends on the local flow density. Thus, the experiments have revealed an increase in the discharge glow duration associated with its localization into a single channel. The channel afterglow in the microsecond interval is obviously related to filling of molecular nitrogen emitting states getting formed during collisions of molecules in metastable state $A^3\Sigma_u^+$ [5,6]. The results of this study should be taken into account in developing plasma actuators for controlling high-speed gas flows with shock waves.

Acknowledgements

The study was performed using the equipment purchased in the framework of the Moscow State University Development Program.

Conflict of interests

The authors declare that they have no conflict of interests.

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