Investigation on nanosecond surface sliding discharge in a supersonic airflow with oblique shock wave

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Abstract. We report investigations of the nanosecond surface sliding discharge in supersonic airflows with the oblique shock wave at Mach numbers of the flow 1.30-1.60 in shock tube. We show that the surface sliding discharge developed in flows as a single channel located near a zone of interaction of the oblique shock with the boundary layer on the wall of the channel. A pulse voltage of 25 kV powered the discharge; the electric current was of 1 kA. The electron concentration in the localized discharge channel was (0.7-1.4) × 10¹⁵ cm⁻³ and the electron energy was of 1.8-2.2 eV from the analysis the emission spectra. High-speed flow field shadowgraphy after the surface sliding discharge showed that the localized discharge channel generates a strong shock wave, leading to restructuring the shock-wave structure of the flow within ~100 µs and subsequent relaxation to a stationary configuration.

1. Introduction

The use of discharges as plasma actuators requires the search for effective control modes for high-speed flows [1-4]. The low-temperature plasma of surface discharges of various types can use in plasma aerodynamics to correction of the flow regime, control the laminar-turbulent transition in the boundary layer, the position of separation zones and shock waves [1-6], and the control of the processes of combustion [2, 3]. It is necessary to study the regimes of the development of discharges under the conditions of various types of flows, which may include shock waves [1, 5, 6]. Shock waves and compression waves are also formed during the development of nanosecond discharges, which can have a significant effect on the flow [3, 6, and 7].

Nanosecond distributed surface sliding discharge (plasma sheet) can be used as plasma actuator to influence the flow [4, 6]. Discharge channels sliding along the dielectric surface form a plasma layer comparable in thickness with the boundary layer of a supersonic flow in a shock tube (~ 0.5 mm). Diagnostics of discharge plasma is an integral part of the study, since the registration of the parameters and characteristics of plasma actuator is necessary to assess the qualitative and quantitative effects on the flow [1, 2, 4-6]. Using emission spectroscopy methods allows estimating the discharge characteristics [5, 7-9]. The aim of the work was to study the development of a surface sliding discharge of nanosecond duration in a supersonic airflow with an oblique shock wave at Mach numbers 1.30-1.60 in the shock tube channel. The parameters of the discharge plasma such as the electron density and energy were determined by processing the measured discharge current and
radiation spectra. The structure of the flow field after the discharge was investigated by high-speed shadow imaging.

2. Experimental Setup
The experiments were carried out in a shock tube with a discharge chamber with a cross section of $24 \times 48 \text{ mm}^2$ [4-6]. Two opposite walls of the discharge chamber were the plane-parallel quartz glasses within a length of 17 cm. A plane shock wave diffracted at a small obstacle (a rectangular parallelepiped) located on the lower wall of the discharge chamber in experiments. The quasi-stationary flow developed with an oblique shock wave reflected from the upper wall of the chamber and interacting with the boundary layer (Fig. 1a). A surface sliding discharge with a width of 30 mm, and a length of 100 mm in the direction of flow was initiated on this surface. Supersonic homogeneous airflows with the Mach numbers of 1.30-1.60 behind the shock waves (M=2.8-4.2) was characterized by a velocity of 750-1060 m/s, a density of 0.25-0.35 kg/m$^3$, and a duration of 300-400 μs. Using the signals of piezoelectric pressure sensors in the shock tube channel, the velocity of the shock waves was measured and synchronization of the processes in the experiments was provided.

Figure 1. The flow structure in the discharge chamber with an obstacle (a); photo images of the discharge in motionless air (b) and in the supersonic airflow with oblique shock wave (c). Density is 0.10 kg/m$^3$; low Mach number is 1.33. The electric circuit of surface sliding discharge (d): 1 – high-voltage electrode, 2 – grounded electrode, 3 – dielectric; C – capacitor; S – spark gap switch (controlled); U – high voltage.

The pulse voltage applied to the electrodes of the sliding discharge was 25 kV (Fig. 1 d). When a voltage pulse was applied to high-voltage electrode, a displacement current was generated on the
surface of dielectric which value was determined by the voltage and the voltage growth rate. When the voltage exceeded the breakdown value for a given discharge gap, a set of channels developed over dielectric surface (see Fig. 1 b). The experiments were performed at the positive polarity of the high-voltage electrode. The discharge current was 1 kA; its duration did not exceed 500 ns. The discharge current, emission spectra, and spatial characteristics of the radiation were analyzed. The discharge spectra and radiation were recorded through quartz glasses of the discharge chamber. Spectra were measured over the range 200-1100 nm using AvaSpec-2048 spectrometer. Special shunt recorded the discharge current. Photo cameras recorded the radiation of the discharge. The supersonic airflow shifted less than 0.5 mm during the registration of the discharge current and the radiation.

Shadow images of the gas-dynamic flow field after the discharge were recorded with a high-speed camera with a frame rate of up to 150,000 fps and exposure time 1 μs. The high-speed shadow imaging was used to study the flow pattern evolution before and after the discharge. The laser beam (532 nm) was formed by the optical system of shadow visualization and directed perpendicular to the glasses of the discharge chamber [4, 6].

3. Experimental results

3.1. Discharge characteristics

In experiments, a pulsed surface sliding discharge developed in supersonic flows as a single channel located near the zone of interaction of oblique shock with the boundary layer (Fig. 1 c). The discharge glow in stationary air distributes over the entire length of the discharge gap (Fig. 1 b). The discharge glow is localized in the region of reflection of the oblique shock wave from the upper channel wall in the supersonic flow (Fig. 1 c). Photo image of the discharge looks like a narrow, intensive emitting compact strip with a width of less than 10 mm. The discharge current has a large maximum and a lower attenuation decrement in the supersonic flow with an oblique shock wave by compared to the current in a homogeneous medium (Fig. 2 a).

Figure 2 a shows measured optical emission spectra from a surface sliding discharge in motionless air and in a supersonic flow. The bands of molecular nitrogen (C₃Π_u → B₃Π_g transition) mainly contributes radiation in the range 200-500 nm. The spectra indicated combinations of a continuum radiation and strong atomic line emissions due to the presence of oxygen, nitrogen, hydrogen. The intense peak was the hydrogen Balmer series alpha line (Hα) at 656 nm. In the infrared region, the distinct lines could be observed due to atomic oxygen, with the strongest emission at 777 nm. The continuum is present in the spectra in the range from 200 to 900 nm.

Figure 2. a) Discharge current waveforms in motionless air (1), in homogeneous airflow (2) and in airflows with oblique shock waves (3, 4). The flow Mach number is 1.55; density is 0.13 kg/m³; b) Emission spectra in the airflow with oblique shock wave (1) and in motionless air (2). The flow Mach number is 1.37; density is 0.10 kg/m³.
The emission spectra of a sliding surface discharge in supersonic flows were processed. The electron concentration in the localized discharge channel, calculated from the Stark broadening of the hydrogen line H$_\alpha$, was $(0.7-1.4)\times10^{15}$ cm$^{-3}$, which is 3-5 times higher than in still air. A digital processing of the continuum part of measured spectra was carried out. From a comparative analysis, the profile of the continuum part of the emission spectrum of the discharge for different conditions has a maximum in the region from 410-450 nm.

The continuum radiation from the discharge plasma originates from the ions and neutral atoms that undergo interactions with free electrons [8, 9]. Free-free transitions are due to bremsstrahlung and bremsstrahlung in collisions of electrons with ions in a Coulomb field. To calculate the spectral emissivity of bremsstrahlung, the formula was used [9]:

$$dJ_\lambda = C_1 \frac{n_e n^+}{kT_e^{1/2}} \exp\left(-\frac{hc}{\lambda kT_e}\right) d\lambda,$$  

where $C_1$ is a constant, $n_e$ and $n^+$ are the concentrations of electrons and positive ions, $h$ and $k$ are the Planck and Boltzmann constants, $c$ is the speed of light, $T_e$ is the electron temperature. Mostly emit quanta with energy $h\nu \approx kT$. Theoretical maximum of bremsstrahlung depends on the energy of the electrons, and of 70-400 nm for electron energies of 1.5-10 eV. By properly analyzing the bremsstrahlung, the electron energy can be experimentally estimated for discharge plasma.

By varying the electron energy in the theoretical dependence (1), one can estimate it by comparing the theoretical and the experimental spectrum. The bremsstrahlung spectra were calculated for electron energies of 1-10 eV (Figure 3). The spectra were normalized to the intensity of wavelength $\lambda=280$ nm in the region of which the experimental continuum least overlaps with the bands. The experimental data are in good agreement with the calculation of the continuum in the region of 200-300 nm and 750-900 nm. In the region of 300–750 nm, the bands of the second positive system of molecular nitrogen and atomic lines overlap the continuum. Accordingly, under the assumption that the continuum is due to bremsstrahlung in collisions of electrons with ions, the average electron energy in the discharge plasma was evaluated to be 1.8-2.2 eV.

3.2. **Gas dynamics flow after the discharge**

The dynamics of the gas flow after the surface sliding discharge was studied by high-speed shadowgraphy. The experiments showed the quasi-stationary supersonic flow during 100-500 $\mu$s after...
diffraction of a plane shock wave on an obstacle. The gas dynamics flow in the channel contained an oblique shock wave that interacted with the boundary layer on the upper wall of the discharge chamber (Fig. 1a, 4a). Shadow visualization of the flow field after the discharge showed that localized discharge channel generates a strong shock wave (Fig. 4b, c).

Numerical simulations were performed to determine the structure of the flow in the channel after the diffraction of plane shock wave on an obstacle under experimental conditions. The flow in the channel of the shock tube was modeled by the solution of unsteady two-dimensional Navier-Stokes equations for a viscous compressible gas [10]. A perfect gas model was used with a constant adiabatic index (γ=1.4) and a Prandtl number Pr=0.72. Numerical calculations of the flow field in the channel showed that the formation of the shock-wave structure near the obstacle occurs within 90-110 μs, and the duration of the quasi-stationary flow is 200-400 μs. A low-density zone with or without flow separation is formed upon the interaction of an oblique shock wave with a boundary layer on the channel wall (Fig. 4d, e). The flow separation region is shown on an enlarged scale in Fig. 4d. The minimum density in the flow separation region was 40-60% of the incident flow density [11].

Figure 4 The sequences of shadow images (a-c, time interval is 10 μs); the calculated density field with the velocity vector field (d) and the calculated field of local Mach number (e); the photo image of discharge glow in a flow, registered through an optical filter (405 nm). The density is 0.11 kg/m³, the flow Mach number is 1.47.

The density distribution affects the development of nanosecond discharges due to dependence of the reduced electric field $E/N$ on the local density. Increased conductivity (or the concentration of electrons) in the low-density areas leads to a change in the geometry of the current and the radiation of a nanosecond discharges in the gas-dynamic flows [5, 6, 11]. The surface sliding discharge is
concentrated near the zone of interaction of inclined shock wave with the boundary layer in the form of the single discharge channel with a width of less than 10 mm. Figures 1c and 4f show photo images of intense discharge channels in supersonic airflows with an inclined shock wave in the discharge chamber. The fast energy release near the inclined shock wave changes the gas parameters in this area and leads to the generation of blast-type strong shock wave. The shock wave drifts along the streamlined surface and moves away from the surface, decelerating and losing energy. The motion of shock wave leads to restructuring shock-wave structure of the flow within ~100 µs and subsequent relaxation to a stationary configuration.

4. Conclusions
The surface sliding discharge of nanosecond duration in supersonic airflows with oblique shock wave in a channel is studied. An analysis of the discharge current and the radiation of the discharge is carried out in supersonic flows with Mach numbers 1.30-1.60. The radiation spectra and the discharge current were registered at the pulsed voltage of 25 kV, and an electric current ~1 kA. The oblique shock wave interacted with the boundary layer, forming a separation region with a lower density. The local reduced electric field was higher in the zone of the interaction of the inclined shock wave with the boundary layer and the surface sliding discharge was localized in single discharge channel. The electron concentration in the discharge channel was (0.7-1.4) × 10^{15} cm^{-3} and the electron energy was of 1.8-2.2 eV. High-speed imaging of the flow field after the discharge showed that the localized discharge channel generates a strong shock wave. It is established that the duration of nonstationary action of the generated shock wave exceeds the discharge-pulse duration and can reach up to 100 µs. Thus, it is possible to use surface sliding discharge as plasma actuator in pulse mode to restructuring the shock-wave structure of the high-speed airflow.

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