Experimental research of sliding surface distributed nanosecond discharge in supersonic air flow

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Abstract. Results are presented from the experimental study of the spatial structure and spectrum of the nanosecond distributed sliding surface discharge (plasma sheet) in quiescent air and in a supersonic and transonic gas flow behind a plane shock wave. Discharge investigations were carried out in air flow with velocities up to 1600 m/s within density range of 0.08-0.40 kg/m3. Different structures of plasma glow were observed for the laminar and turbulent flow regimes in the boundary layer. Analysis of the obtained images clearly shows that character of the glow of the discharge changes with change of the boundary layer structure. The analysis of the experimental data shows that the radiation spectrum of sliding surface discharge changes in gas flow after a shock wave

1. Introduction

A great number of papers devoted to different approaches of non-equilibrium plasma flow control in aerodynamics have appeared recently [1, 2]. Applications of plasma to flow control involve managing flow detachment or attachment to the surface, which results in managing lift and drag force of the airfoil.

A sliding surface discharge (plasma sheet) is the distributed formation of parallel channels, sliding on a dielectric surface. Such discharges are used as plasma electrodes, UV radiation sources in gas-discharge and excimer lasers [3, 4]. The development of the channels of a sliding discharge is characterized by high values of the electric field. The growth rate of the channels is ~106 m/s. Breakdown of a gas layer near a dielectric surface is accompanied by an abrupt increase in the current (as much as several kA) and the formation of bright channels [3-5]. It is this phase of a high-current discharge that determines the energy input into the surface gas layer. Initiation of the plasma sheet in the gasdynamic flow allows providing the pulse energy deposition in a boundary layer region [5, 6]. The electric discharge energy is converted into gas heating, molecule rotation, vibration, ionization, and electron excitation.

Research of discharge plasma and gasdynamic flow interaction should be done for the high speed flow control possibility analysis. The pulse surface discharge can strongly influence the gasdynamic flow structure. Shock waves arise in a flow field as a result of quick energy input [5, 6]. It is important to study plasma-dynamic characteristics of the sliding discharge in air flow for a better understanding of the fundamental problems in the physics of nonequilibrium plasma and the optimal solution of engineering problems.

The analysis of spatial structure of a luminescence and spectral characteristics of radiation of the distributed sliding surface discharge in a supersonic and transonic gas flow behind a shock wave was a research objective.
2. Experimental Set-up

A detailed description of the experimental set-up has been presented in [5, 6]. A special discharge chamber mounted with a shock tube was used for the experiments (figure 1). The rectangular cross-section of the discharge chamber was the same as that of the shock tube ($48 \times 24$ cm$^2$). The shock tube allowed plane shock waves, with transonic and supersonic flows behind them, to be generated with Mach numbers up to 5. Plasma sheets were initiated on two opposite walls of the discharge chamber at a distance of 24 mm from each other. Two other walls of the experimental discharge test section were quartz glasses; 170 mm in length (see figure 1).

In order to organize a plasma sheet, the special electrode configuration was used with discharge gap dimensions of $30 \times 100$ mm$^2$ [5]. A high-voltage pulse applied to the discharge gap, was transmitted from the main capacity to the high-voltage electrode of the discharge chamber by means of a spark-gap controller. Experiments were carried out at 25 kV pulse voltage. A reduced electric field was realized at parameter $E/N = 500-1000$ Td, where $E$ was the electric field strength and $N$ was the gas number density. The current parameters were measured using a special current shunt. Pulse discharge time was about 200 ns, which was much less than the characteristic gasdynamic time in the shock tube (~10 μs). The discharge current reached a maximum of 1-2 kA during the first 50 ns of the discharge development. The current pulse signals showed that the main energy deposition in the discharge occurred during the time ~ 100 ns.

Plasma sheets in air flow were initiated after the shock wave left the discharge area. The signal from the piezoelectric gauge of pressure started the spark-gap controller through timing electronics. Plasma sheet glow was registered integrally and with nanosecond resolution by digital cameras. The exposure time during integral recording was equal to discharge glow time. A Nanogate-2 ICCD camera (spectral response 380-800 nm) was used to determine spatial-temporal characteristics of the discharge. Special digital image processing was then used to determine space characteristics of the surface discharge in the flow. Spectrometer AVASpec-2048FT (174-1100 nm) was used for the spectral analysis of discharge glow.

Discharge glow investigations were carried out in motionless air and in air flow with velocities up to 1600 m/s within density range 0.08-0.40 kg/m$^3$. Flow Reynolds numbers were in the $(4.5-12.5) \times 10^3$ range. The thickness of the plasma layer in motionless air, measured from the emission intensity profiles in the plane of the plasma sheet, decreased from 0.8 to 0.4 mm with density increasing. The plasma layer thickness in air flow was about 0.4 mm [5].

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**Figure 1.** Experimental set-up: 1 – Discharge chamber; 2 – Discharge area (black colour corresponds to electrodes); 3 – Photo camera; 4 – ICCD camera; 5 – Pressure transducer; 6 – Timing electronics; 7 – Spark-gap controller; 8 – Image PC.
3. Experimental Results

Space and time distribution analysis of surface discharge glow was carried out in the supersonic and transonic gas flows with flow Mach numbers up to 1.6 after the plane shock waves (Mach numbers up to 4.5).

Glow evolution analyses revealed, that the time of discharge current (200 ns) and the time of discharge glow were close (300 ns). However, gasdynamic time in the shock tube was much longer than the time of the discharge radiation. Thus, flow shifted 0.3 mm during registration time of the discharge glow. The structure of the high-speed flow didn’t change during integral glow registration.

Figure 2 presents the images of nanosecond surface discharge glow. The registered integral plasma sheet glow shows the discharge structure in motionless air (figure 2 a). One can see that the discharge has a quasi-planar structure and consists of a set of channels. The plasma sheet region is uniformly filled with straight-line diffuse channels, with the presence of brighter channels. Greater diffuse distribution of plasma glow was observed after the shock wave in transverse (relative to the propagation direction of the discharge channels) air flow. Some channels were curved (figure 2 b, c). An analysis of the experimental patterns showed clearly, that discharge glow character changes with the changing of the flow boundary layer structure. The structure of the boundary layer flow could be determined by the obtained images of the plasma discharge glow.

The sliding surface discharge radiation in the visible and ultraviolet spectral region was determined generally by the $2^+$ system of nitrogen corresponding to $\text{N}_2 (\Sigma^+ \Pi_u \rightarrow \Pi^0 \Pi_g)$ transition (figure 3). One can see typical atoms lines of hydrogen, oxygen and nitrogen in the spectra. The long-wave part of the spectrum was more intensive in supersonic flow after the shock wave in transverse (relative to the propagation direction of the discharge channels) air flow. In this case the discharge was initiated in heated air behind the shock wave front. The vibrational temperature was determined from relative intensities of emission lines of $2^+$ system of nitrogen with the sequence $\Delta \nu = -2$. The distribution of energy over vibrational degrees of freedom with a reasonable degree of accuracy appears the Boltzmann distribution. The vibrational temperature was equal to $(3400 \pm 400)$ K in motionless air (gas density $0.11$ kg/m$^3$) and $(3900 \pm 400)$ K in supersonic gas flow behind the shock wave (Mach number 3.6; gas density $0.11$ kg/m$^3$, temperature 1000 K).

The distribution of the plasma discharge radiation intensity corresponds to the instant distribution of gas density due to the strong dependence of radiation intensity on local value of reduced electric field $E/N$ and due to the short time of the discharge. Consequently the heterogeneity of density near the surface influences on the character and the geometry of the sliding surface discharge development.

Figure 4 presents the main flow elements behind the shock wave in the shock tube. The thickness of the boundary layer in the shock tube channel increases from zero at shock wave front. The boundary layer becomes turbulent at certain distance from shock wave front. The thickness of the laminar boundary layer was about 0.5 mm in supersonic flow.

One can see that, immediately behind the shock-wave front, the glow has a diffuse homogeneous and smooth character, without visible discontinuities (figure 4, on the left). At a certain distance from the shock-wave front, the character of the glow exhibited a change; i.e., the glow became inhomogeneous, showing chaotic structures and separate curvilinear channels (figure 4, on the right). An analysis of images in the flow yielded convincing evidence that the character of the glow was altered due to a modification of the boundary layer structure, which changed from laminar (behind the shock-wave front) to turbulent. Laminar and turbulent zones were distinctly visible. Homogeneous area of the glow corresponds to laminar boundary layer and heterogeneous area (curved channels) visualizes turbulent one [6]. The turbulent medium turns out to be ionized and contains plasma structures, with their scale corresponding to the turbulence scale.
Figure 4. Flow diagram for the shock-tube channel: (1) front of the propagating shock wave; (2) laminar region in the boundary-layer flow; (3) turbulent region in the boundary-layer flow; (4) integral glow of the plasma sheet (the flow Mach number is 1.2 and the gas density is 0.19 kg/m³).

On the other hand the discharge initiation essentially affects the flow structure. The pressure and temperature of the surface thin gas layer increases during one microsecond due to fast energy input. Consequently perturbations propagate away from the plasma sheets [5, 6]. However, insofar as the discharge-glow duration is many times shorter than the characteristic times of gas-dynamic processes in the shock wave tube, the structure of the near-surface flow layer remains unchanged during the discharge-glow time.

Due to the strong dependence of radiation intensity on local value of reduced electric field E/N and due to the short time of the discharge compared with gas dynamics times the distribution of the plasma discharge radiation intensity does correspond with the instant distribution of gas’ density. This makes it possible to get spatial calibers typical for laminar and turbulent flow areas of boundary layer by
relevant mathematical analysis of the spatial distribution of discharge glow. The spectrum of frequencies and amplitudes of discharge glow intensity in supersonic boundary layer varies for different types of flow (see figure 5). In the laminar flow there aren’t any specialized structures, while in the turbulent boundary layer there are some characteristic structures with the size of 3-5 mm. Sliding-windows method was used for image processing and investigation of the fractal dimension. The investigated picture is covered by random-radius circles and mass for each circle is counted due to chosen criteria. As a result, we have got the fractal dimension of the image in the flow as tangent of mass-radius dependence. The fractal dimension of the discharge glow images changes from 1.8 in the laminar boundary layer to 1.9 in the turbulent boundary layer.

4. Conclusions
The investigation of the sliding surface discharge of nanosecond duration in the supersonic and transonic flow behind the shock wave was carried out. Our studies have demonstrated that the type of boundary layer affects the character of discharge channels developed across the flow. The thickness of the plasma sheet was about 0.4 mm that is an order of a thickness of a boundary layer. The turbulence in the boundary layer results to the formation of curvilinear channels due to the appearance of inhomogeneities of density and the ionization coefficient. We have got spatial calibers typical for laminar and turbulent flow areas of boundary layer by relevant mathematical analysis of the spatial distribution of discharge glow. Also fractal dimensions were counted for images of laminar and turbulent flows. In the parameter range under study, the radiation spectra of the sliding surface discharge changed in the supersonic flow. It was shown that the long-wave-line part of spectrum is more intensive in supersonic flow after the shock wave. It was found out that the distribution of energy over vibrational degrees of freedom is represented by Boltzmann distribution.

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