Extrusion of a nanosecond surface discharge plasma near a dielectric ledge

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Abstract. The presence of a dielectric ledge along the pulse discharge propagation led to a redistribution of the pulsed surface (plasma sheets) discharge glow. Discharge glow on the surface without the ledge, was uniform and lasted no more than 200 ns. Two plasma channels with increased glow intensity were observed near the rectangular ledge placed in the discharge area. The duration of these longitudinal plasma channels increased and lasted for about 0.9 μs (at a voltage of 25 kV and a density of 0.03 – 0.18 kg/m³). A nine-frame nanosecond camera recorded the evolution of the plasma glow. The dynamics of the flow induced by the pulse surface discharge was recorded using a high-speed shadow imaging during 40-50 μs after the ignition of the discharge.

1. Introduction
Flow control is an actual problem to improve the aerodynamic characteristics of the aircraft. Active and passive flow control methods allow reducing the drag on the surface, buffeting elimination, fuel combustion intensification. The active methods of flow control include plasma control of the flow. Different types of electrically driven plasma actuators for flow control have been investigated in the last years [1-3]. Plasma actuators can be used to control internal flows, to control the structure of shock waves and their interaction with the boundary layer, to influence the noise characteristics and flow fluctuations [1, 2, 4]. The modification of a flow field with the plasma actuators can change the characteristics of flows as a result of the plasma interaction with the gas medium and with the streamlined surface. For high-speed flow control, the surface sliding discharge of nanosecond duration could be used [1, 2, 5]. Sliding surface discharge (plasma sheet) forms a plasma layer of ~0.5 mm thickness [2, 6]. Pulse surface discharges with durations of ~300 ns produce shockwave and thermal action on high-speed flows [1, 2, 6, 9].

Plasma actuators can be located on various sections of the streamlined surfaces of channels, including steps, ledges, cavities, bevels, etc. [7-11] In particular, localized plasma actuators located near the nozzle edge of a laboratory jet have recently demonstrated that they have sufficient control powers to significantly excite the jet downstream [11]. A plasma actuator of this class, which in this case is sunk in a small cavity near the nozzle edge, causes intense local heating. It is shown that the cavity, for preventing plasma blow-off by the high-speed flow, is necessary for its action. Thermal expansion inside the cavity leads to the release of fluid from it, which violates the boundary layer and the mixing layer located downstream. We have taken a simple rectangular element for modeling and analyzing the local energy supply.
In this work, characteristics of surface sliding discharge are investigated near a dielectric ledge in a form of rectangular parallelepiped mounted on the lower wall of the discharge chamber. The flow field after the discharge is recorded by high-speed shadowgraphy. Knowledge of the mechanism of surface interaction with gas-discharge plasma and the dynamics of discharge flow near the solid dielectric makes it possible to determine optimum regimes of the discharge-assisted effective control of gas flows.

2. Experimental setup

In this paper, we study the effect of the wall geometry on the spatial distribution of the plasma of a nanosecond surface sliding discharge (plasma sheet) [2, 6], and on the post-discharge flow in a discharge chamber with a rectangular cross-section of $48 \times 24 \text{ mm}^2$ (see Figure 1(a)). Two high-current discharges were initiated on the upper and lower walls of the chamber at a distance of $24 \text{ mm}$ from each other. Each plasma sheet was initiated between a pair of copper electrodes $100 \text{ mm}$ long, $100 \text{ mm}$ thick, formed on dielectric plates. The area of each plasma sheet was $100 \times 30 \text{ mm}^2$. The plasma sheets were connected through a capacitor $C_1$, charged to a voltage of $25 \text{ kV}$, via a triggering unit as shown in the electrical scheme (see Figure 1(b), when $C_1=2270 \text{ pF}$, $R_2=R_3=1 \text{ k}\Omega$, $R_1=100 \text{ M}\Omega$).

A dielectric ledge (Polyamide 6) with a size of $48 \times 6 \times 2 \text{ mm}^3$ was mounted on the bottom wall of the channel (see Figure 1(a), white rectangle). The discharge current waveforms, shown in Figure 1(c), were recorded using a back-current shunt. A black rectangle (see Figure 1(b)) indicates the place of the shunt, and the points around it are the points, the potential difference between which we see on the current waveform (see Figure 1(c)) and, according to which the current strength was determined. A calibrated low-inductive back-current shunt with a bandwidth of $1 \text{ GHz}$, made to order, was inserted into the circuit of the grounded electrode. The shunt was connected by a BNC cable to the Tektronix TPS 2014 oscilloscope with a bandwidth of $100 \text{ MHz}$.

![Figure 1](image.png)

**Figure 1.** (a) Experimental setup; (b) Electrical scheme of the discharge; (c) typical current waveform; (d) Dependences of the maximum current amplitude (squares) and current duration (triangles) with the dielectric ledge, on the density in still air.
There were the dependencies of the maximum discharge current $I_{\text{max}}$ and its duration on the density in still air in the figure 1(d). The discharge current is $800 – 1200$ A and decreases with increasing density in accordance with an increase of the discharge gap resistance. Figure 1(d) shows, that the increase of the discharge current duration is connected with an increase in density and decrease of current amplitude. This is due to the fact that with increasing density the value of the reduced electric field $E/N$ decreases, which leads to a decrease in the ionization rate and an increase in the time required for the required electron concentration.

The discharge radiation and flow was studied near the ledge. Experiments have been carried out in quiescent flow conditions at 15-110 Torr air pressure, 0.03 – 0.18 kg/m$^3$ air density. The integral discharge glow was recorded using a Canon EOS 550D photographic camera and the duration of the discharge glow was the exposure time $0.2 – 1.5$ μs, which was the glow time of the discharge and depended on the density of the gas medium. High-speed recording of the discharge radiation with a nanosecond resolution with an exposure of $0.1$ µs and a pause of $0.1$ µs was carried out, which made it possible to acquire the pulsed surface discharge glow evolution (see Figure 2(b)). For this, ICCD camera K011 BIFO was used in the mode of a nine-frame scan of the recorded image; it has its own response delay time (error) from 0 to 1.3 ns from the moment of receiving the triggering signal. The spectral sensitivity range of the camera's photocathode is 370-850 nm. The camera was synchronized by a discharge trigger pulse, which was simultaneously received by the camera. Integral and ICCD images of plasma sheets were obtained by cameras directed toward the center of discharge chamber. A high-speed camera (resolution $256 \times 144$, shutter 1 mcs) captured series of consequent shadowgraphy images at a rate of 150 000 frames per second (see Figure 2(c)). The gas-dynamic flow was investigated with a $1.0$ μs exposure during the 40 – 50 μs after initiation of the discharge.

Figure 2. Experimental setup and examples of images obtained from optical research methods (a) integral imaging, (b) 9-imaging by ICCD camera, (c) the high-speed camera, shadow imaging (the sample images shown correspond to a density of $0.12$ kg/m$^3$).

3. Result and discussion
The glow of the discharge from the upper plasma layer was rather uniform over the range of the studied pressure (15 – 110 Torr). On the other wall, it was found that the presence of a dielectric element on the electrodes led to a change in the localization of the discharge. The integral images of the lower plasma layer showed an inhomogeneous distribution of the glow as in Figure 3 (left). There was an increased intensity of radiation in the areas adjacent to the ledge on both sides; these areas of glow were symmetrical when recorded from the front viewing point. Along the ledge, two symmetrical intense plasma areas were observed, the brightness of which increased with increasing gas density/pressure (from 0.03 kg/m$^3$ to 0.18 kg/m$^3$).
The integral images of the discharge glow reveal the spatial distribution of the discharge plasma (see Figure 3, left). The dynamics of the discharge-induced flow was studied using high-speed shadow imaging during the first 45-50 µs after the discharge (see Figure 3, right).

The fast conversion of the electrical energy of a high-current discharge into heat led to the formation of shock waves and a high-speed flow. The flow induced by these plasma channels of pulsed discharge along the ledge included a curved shock-wave configuration, in contrast to the flow away from the ledge or from the same surface without the ledge.

![Integral shooting vs Shadow shooting](image)

**Figure 3.** (left) glow of a pulsed discharge in the presence of a ledge – integral photo image of the glow; (right) a post-discharge flow after the initiation of a pulsed surface sliding discharge – shadow flow pattern: at an air density of 0.12 kg/m³.

The nine-frame ICCD camera K011 BIFO allowed us to study the evolution of the glow of plasma sheets and channels along the ledge (Figure 4). The sequences of frames given in the work were obtained with the same intensity registration setting; the background was subtracted during processing. The first frame in the sequence was considered to be a frame with a non-zero intensity. Consecutive images were obtained at the same exposure and sensitivity of the recording equipment.

![Evolution of plasma glow](image)

**Figure 4.** (a) Image of a dielectric ledge in the discharge chamber; (b-c) Evolution of the plasma glow of a pulsed discharge at an air pressure of 19 Torr (density 0.03 kg/m³) and (d-e) at an air pressure of 115 Torr (density 0.18 kg/m³). Nanosecond shooting with an nine-frame ICCD camera with an exposure time of 100 ns and a pause of 100 ns.
Figure 4 shows a diagram (Figure 4 (a)) and images of the evolution of the glow at a gas density of 0.03 kg/m³ (b-c) and 0.18 kg/m³ (d-e). The images are presented for the same times after the initiation of the discharge (0.0 – 0.1 µs and 1.0 – 1.1 µs). The glow of the upper plasma sheet lasted up to 0.2 µs, while the discharge plasma near the dielectric ledge continued to emit the glow to 0.5 µs (see Figure 4(c)) exponentially. Figure 4 (d-e) shows images of the discharge glow at a still gas density of 0.18 kg/m³. The surface discharge glow completely ends up to 0.2 µs, and then the glow contracts near the protrusion, as in the first case Figure 4 (b-c). The attenuation of bright channels lasted up to 1.9 µs.

4. Conclusion

It is shown that the presence of a dielectric ledge along the propagation of a pulsed surface sliding discharge led to its glow redistribution. The duration of the glow of two longitudinal plasma channels near the ledge was up to 1.9 µs (at 0.18 kg/m³ and a voltage of 25 kV) in optical range, while the plasma sheets glow lasted for less than 0.5 µs at a density of 0.03 kg/m³. In this case, the discharge glow decreases exponentially. The pulsed supply of electrical energy from the discharge was accompanied by gas-dynamic disturbances of the medium. The results indicate that the discharge current and energy were redistributed over the surface in the presence of a dielectric ledge. The high speed flow induced by these plasma channels of pulsed discharge along the ledge included a curved shock-wave configuration, in contrast to the flow from the similar surface discharge without the ledge (on the upper wall).

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