# Gas flow influence on streamer-to-leader transition in surface barrier discharge in air at atmospheric pressure

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**Abstract**. The experimental results on study of a sinusoidal surface barrier discharge (SBD) in airflow at different velocities are presented. Influence of gas flow velocity and its orientation on plasma structure of SBD is established and the conditions providing transition of SBD from the streamer mode to the mode with surface leaders (SL) are found out as well. It is shown the formation of the SL in SBD happens owing to thermal effects associated with a local gas heating in both the bright current spots disposed at the sharp edge of high-voltage electrode and thin current channels (streamers) originated from these spots. It was revealed that gas flow with a high velocity directed against the propagation of surface streamers leads to destruction of the bright anode spots and elimination of the SL (but not the streamers) on a barrier surface. However the gas flow with the same velocity but opposite direction leads to regular disposition of the bright current spots at the edge of high-voltage electrode and regular spatial structure of the thin current channels (streamers and leaders) originated from the current spots. It was found out that gas flow of any orientation leads to diminishing the gas temperature in the plasma channels compared to that in SBD in gas at rest.

## 1. Introduction

The sinusoidal SBD is an alternating current gas discharge which generates a thin layer (or sheet) of non-thermal plasma tightly adjoining the barrier surface. In fact, the SBD is a capacitor with a variable capacitance, and one of the capacitor plates of this capacitor is a thin non-stationary plasma sheet periodically forming on a barrier surface. The spatial configuration of a thin plasma sheet formed at each half-cycle depends on the specific experimental conditions. For instance, plasma sheet can be homogeneous (diffusive regime of SBD) or consist of many thin current filaments (streamer regime of SBD). The streamer regime goes over into so called leader regime, if the electric power feeding the SBD increases. In this regime, plasma sheet is heavily non-uniform - only a few bright current channels (surface leaders) are observed on the barrier. The both diameter of leader and its brightness exceed analogous streamer parameters. The formation of surface leaders in SBD is not always a desirable process. At present the level of knowledge about the processes forming the surface leaders is obviously insufficient. It is known only that the formation of low-current surface leader in SBD differs strongly from the formation of high-current volume leader in the spark [1-3]. The alternating current gas discharge is characterized by that the plasma processes happened in preceding half-cycle can influence the processes in subsequent half-cycle. An alternating current gas discharge is characterized by the fact that the plasma processes which happened in the previous half-cycle can influence plasma processes in the subsequent half-cycle. This dependence can be called as a short "memory" of SBD which is determined by time of decaying the plasma structures created in the previous half-cycle. Both the current spots on HV electrode and non-stationary current channels on barrier provide a strongly inhomogeneous energy deposition into gas adjoining the barrier and into barrier as well. This circumstance leads to non-uniform and gradual (during many periods) warming up of the barrier, HV electrode and gas. The decay time of thermal structures formed in SBD is defined by heat conductivity processes which are slower in comparison with a recombination of plasma structures. This is a reason why thermal structures in SBD keep themselves for many periods and influence slow evolution of plasma structures in subsequent periods. The influence of long-living thermal structure on the surface plasma structure in SBD can be called as a long "memory". This report presents the results on experimental investigation of plasma structures (streamers and leaders) of SBD in air at atmospheric pressure and influence of gas flow on the long memory of SBD.

## 2. Experimental setup

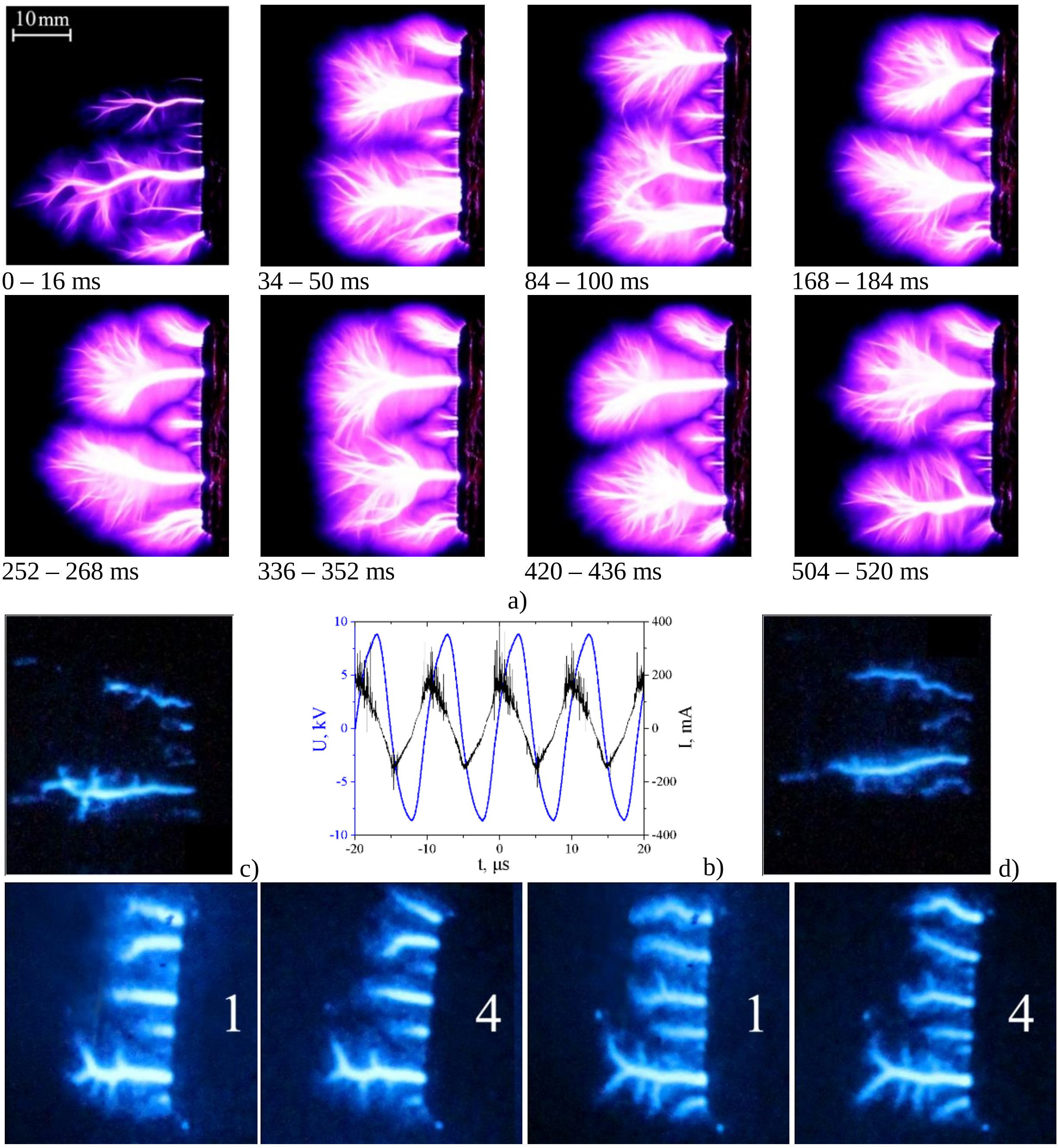
The sinusoidal SBD influenced by gas flow was organized on a ceramic plate (dielectric permittivity $\varepsilon$=9) with sizes of 60x60x1.5 mm$^3$. The electrodes were made of aluminum foil with thickness of 50 μm. High-voltage (HV) electrode looks like a rectangular strip with sizes of 35x35 mm$^2$, the angles of which are rounded. HV electrode has been pasted on top side of the barrier plate. The strip was oriented perpendicularly to a gas flow and disposed at the edge of the plate upstream. The HV electrode was partly covered with a dielectric so that only narrow part (3x35 mm2) of its surface is open. The grounded electrode with sizes of 35x35 mm$^2$ has been pasted on bottom side of the barrier plate. The upper edge of the grounded electrode was shifted by 2 mm downstream relatively the edge of HV electrode. The grounded electrode was fully covered with a dielectric.

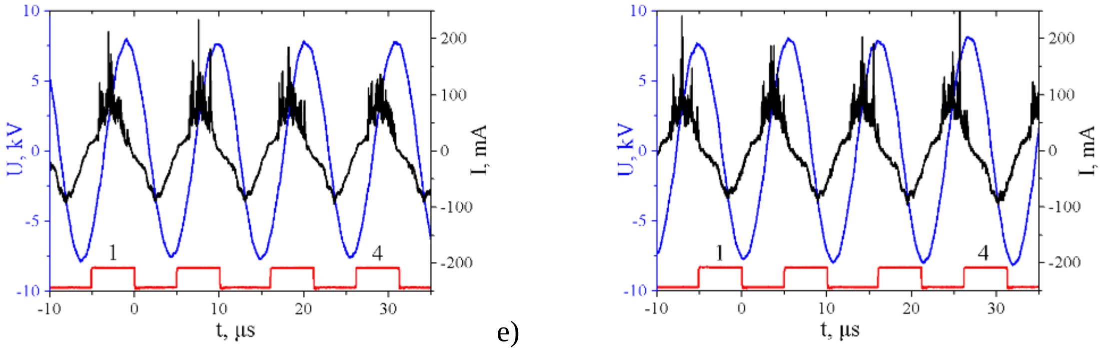
The subsonic jet of air was flat and had the cross-section of 48x2 mm$^2$, i.e. the wide stream of air was able to cover all plasma area on a barrier. The flat air jet was directed either along a barrier surface or at angle 90$^0$ and 45$^0$ to the barrier surface. In the first case, the jet can be directed in two directions - along the movement of the plasma channels (streamers and leaders) and in opposite direction. The magnitude of gas velocity in jet was measured by thermo-anemometer Testo-510. In the experiments gas velocity was varied within limits of 0-80 m/s.

SBD was powered with sinusoidal voltage of 100 kHz in a form of the wave packets of variable duration from 0.1 to 2 s. The voltage amplitude was varied from 2 to 12 kV. The current and voltage waveforms of SBD were recorded by Tektronix TDS-520 and Tektronix DPO-2024 oscilloscopes. Based on these data the electric power of SBD was calculated. The image of plasma structure of SBD averaged over many periods of sin voltage was taken by digital camera Canon EOS 550D. Dynamics of fast development of SBD in a single half-cycle was studied with use of the multi-frame and fast camera LV-03, the frames of which with exposure time of 100 ns were synchronized with current and voltage of SBD. The optical spectrum of SBD plasma radiation was registered by a fiber-optical spectrometer AvaSpec-2048FT with the spectral resolution of 0.1-0.2 nanometers. The translational and vibration temperatures of nitrogen in the SBD plasma sheet were determined from processing of spectra of the second positive system of $N_2$.

## 3. Experimental data and discussion

The set of photos presented in figure 1a shows slow evolution of plasma structure formed on a barrier of high-frequency SBD in air at rest. This evolution is traced from the very beginning of the wave packet till its end in 0.5 s. The exposure time of each picture is equal to 16 ms. It means that the image on each photo is formed by overlapping of 3200 instant images of SBD in the half-cycles following one after another. The behavior of SBD current in a positive and negative half-cycle is shown in figure 1b by example of four periods from the whole wave packet. Note that the average electric power of SBD is high enough and equal to 210 W. Due to that the formation of the surface leaders roaming on a barrier surface happens quickly, as a rule, in 30-50 ms (see figure 1a). However the stabilization of spatial localization of the electrode spots and bright surface leaders originated from these spots takes place approximately in 200 ms after application of the wave packet to the SBD. Figures 1c and 1d show instant images of long-lasting SBD in the beginning of negative and positive half-cycle respectively. Exposure time of each shot is 100 ns. Figures 1e and 1f show images averaged over single positive and negative half-cycle respectively. In this case exposure time of each shot is 5 μs. All images are synchronized with appropriate oscillograms of current and voltage shown below.



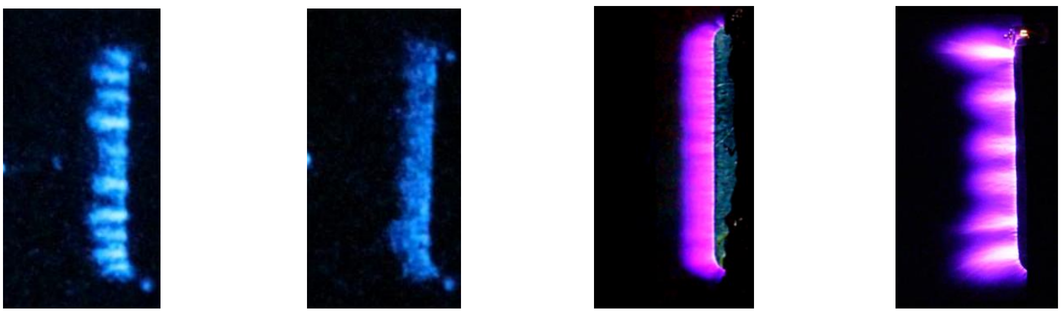



e) f)

**Figure 1.** a) Evolution of the SBD plasma structure in ambient air at rest. Each image is the overlapping of 3200 instant images of SBD in the positive and negative half-cycles following one after another. Time is counted from the beginning of imposing of a sin wave packet. The time interval corresponding to each photo is given below. b) The current and voltage waveforms of SBD. c) and d) The instant images of SBD with the exposure time of 100 ns; the pictures were taken in the beginning of positive (c) and negative (d) half-cycles. e) and f) The images of SBD averaged over appropriate positive (e) and negative (f) half-cycle respectively; the exposure time of each shot is 5 µs; all images are synchronized with I, U oscillograms; the appropriate marks numbered as 1 and 4 are shown below.

Close examination of the images presented in figure 1 leads to the conclusion that in the case of long-lasting SBD the localization and configuration of bright plasma structures (anode and cathode current spots on HV electrode and surface leaders on a barrier) approximately repeat each other in every positive and negative half-cycles through many periods of a sin voltage. This feature can be called as long memory. However, the numerous thin and less bright surface streamers surrounding the leaders are subject to more frequent change of their configuration, especially those which are localized around the leader head. Note that leaders in each half-cycle do not appear simultaneously: at the beginning the large leaders develop from the most bright electrode spots and then the smaller ones arise. Another important feature of steady sin SBD sounds as follows: due to existence on a barrier of the residual plasma formed at the previous half-cycle (short memory) there is no necessity to involve any additional ionization mechanisms like photoionization of gas in order to provide the propagation of positive surface streamers and leaders.

Gas flow appreciably influences the plasma structure of SBD. For example, fast airflow directed against movement of the plasma channels breaks large anode and cathode current spots. In this case, numerous and irregular small anode spots and regular small cathode spots happen in positive and negative half-cycles respectively (see pictures 2a and 2b). Hereat the surface leaders disappear (there are only surface streamers). Total area of a barrier occupied by plasma sheet becomes smaller.

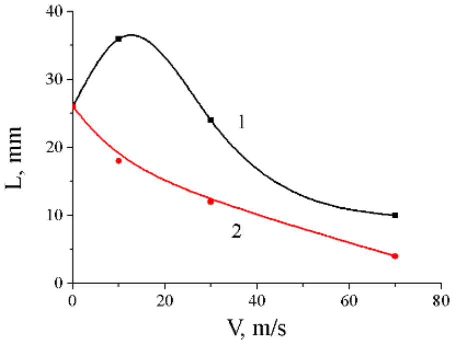


a) b) c) d)

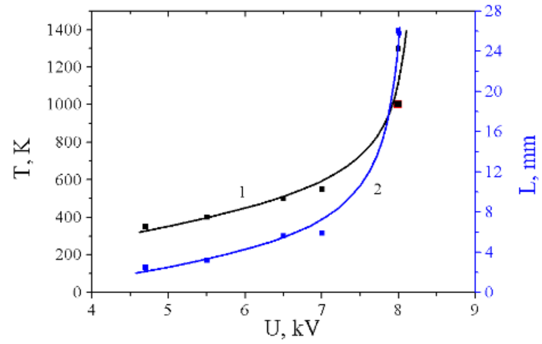
**Figure 2.** The images of SBD in fast airflow at different direction of gas flow velocity. V=70 m/c. a) and b) airflow is directed against movement of the plasma channels; negative (a) and positive (b) half-cycles; exposure time is 5 µs. Airflow is directed against (c) and along (d) movement of the plasma channels; exposure time is 16 ms.

Figures 2c and 2d present the images of SBD in fast airflow directed against (c) and along (d) the movement of the plasma channels. These photos were taken with long exposure time (15 ms) and their images were formed due to overlapping of many instant images of SBD. In the (c) case, small electrode current spots and streamers originated from these spots are not localized and slowly and chaotically migrate on a surface within limit of their small spatial period. This is a reason why plasma sheet in picture 2c looks like a homogeneous discharge but in fact this is not the case (see, for instance, the instant image 2a). In the (d) case, the leaders are not destroyed. The number of cathode spots and leaders are less and they are regularly distributed with a large spatial period. Besides, the chaotic migration of these spots and leaders in transverse direction is slow and happens within the limits which are smaller compared to their spatial period. This is a reason why the periodical structure of SBD in pictures 2c and 2d is kept even if they are taken with a long exposure time. In this case there is a long memory which is not destroyed by even fast airflow directed along the plasma channels. Short memory in spatial structure of SBD exhibits itself in negative half-cycles. This memory is determined by cathode spots and therefore cannot be destroyed by airflow of any direction.

Gas flow influences total length and translation temperature of streamers and leaders. The dependence of total length of streamers and leaders on airflow velocity is shown in figure 3a. Curves 1 and 2 in this figure correspond to velocity directed along (1) and against (2) the movement of the plasma channels. In the first case there is a non-monotonic dependence on velocity. At high velocities, the higher velocity, the shorter plasma sheet. There is a correlation between gas temperature in streamer and its possibility to transform into leader. The threshold for appearance of leader in SBD corresponds to the amplitude of sin voltage U ≈ 8 kV. At this amplitude, the gas temperature in streamer sharply grows up approximately to 1200 K and streamer transforms into leader which appreciably increases own length (see figure 3b).



a)



b)

**Figure 3.** a) The dependence of total length of plasma channels on airflow velocity; curves 1 and 2 correspond to velocity directed along (1) and against (2) the movement of the plasma channels.
b) The dependence of gas temperature in plasma channels (1) and total length of plasma channels (2) on the amplitude of sin voltage for SBD in ambient air at rest.

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**References**

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