The research of interaction of the capillary discharge with metal foils

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Abstract. The properties of capillary discharge under its interaction with various metal foils are analysed. Spectral composition of capillary discharge jet is investigated. Upon jet interaction with metal foils, plasma domains occur. The properties of glowing plasma domains, which occur in a constant magnetic field, are analysed. The possible internal structure of plasma domains is analysed.

1. Introduction
Upon adding organic and inorganic matters to the erosive discharge, glowing plasma domains occur. The lifetime of these domains is up to 1 sec \[1-3\]. In this version of capillary discharge, a construction with a thin channel in the dielectric and one electrode closing the capillary is used \[4,5\]. Resulting from the current, which passes through the capillary, intense metal evaporation, takes place and intense plasma jet emerges in the outlet of the capillary. Upon interaction of the capillary discharge with aluminum foil, plasma domains separated from the discharge area occur. The lifetime of these domains is up to 0.5 sec \[6\]. Taking into account these circumstances, we decided to investigate the properties of these plasma domains and their possible internal structure.

2. Experimental setup
In order to obtain the capillary discharge, we used a dielectric arrester (plexiglass, 3-4 mm thick). The diameter of little hole - the capillary was equal to 1-3 mm. A capacitor battery was used as a power supply unit (voltage 200-250 V, energy 100-250 J). The discharge was ignited by a high voltage pulse. As a result, a plasma jet with cylindrical form occurred. The jet length was equal to 8-12 cm, the jet diameter was equal to 3-5 cm. The discharge current was equal to 80-140 A, the pulse duration was equal to 6-10 ms. Nikon 1 J1 camera was used for video- and photo recording of discharge characteristics (temporal resolution 1 ms).

Interaction of the capillary discharge with metal foils was investigated with the help of experimental setup, which is shown in figure 1. Near the discharger (1), at a distance of 1.0-3.0 cm from the capillary, a thin metal foil (4) was located in the holder (material: aluminum, tantalum, copper, brass, 0.05-0.1 mm thick). The jet (2) interacted with this foil. Initial shape of jet is shown as dotted line. As a result of interaction of jet with metal foil, the jet length decreases. Resulting from the interaction, plasma domains (5) occurred and maintained horizontal motion. The dimensions of plasma domains were equal to 0.1-3 mm, their lifetime was equal to 0.02-0.5 s. There were about 1-20 plasma
domains during one shot. The velocity of plasma domain motion was equal to 0.5-8 m/s. Their glowing characteristic color was white or blue. As a rule, they usually moved in the direction of jet propagation in a cone with an angle of about 120°.

Figure 1. Experimental setup, which was used for analysis of interaction of the capillary discharge with metal foils: 1 - discharger, 2 - capillary discharge jet, 3 - holder, 4 - metal foil, 5 - plasma domains, 6 - barrier, 7 - spectrometer

3. Spectral measurements
We decided to measure temperature and plasma concentration in the area of interaction between capillary discharge jet and metal foil. The spectral methods were implemented. Ava Spec 2048 spectrometer (spectral range 200-1000 nm, spectral resolution 0.3 nm) was used for obtaining of electromagnetic radiation panoramic spectrum. The temporal characteristics were investigated with the help of MUM monochromator (spectral range 200-800 nm, spectral resolution 0.2 nm) and FEU-85 photoelectron multiplier (time resolution 5 ns). The image in figure 2(a) shows the discharge spectrum obtained where the jet interacts with tantalum foil. The discharge spectrum was registered perpendicularly to the jet axis at the distance \( x \approx 2.2 \) cm from the capillary.

Figure 2. Results of spectral measurements, conducted during the interaction of capillary discharge jet with tantalum foil: (a) discharge spectrum; (b) temperature distribution along the jet axis (line 1 – interaction occurs; line 2 - without the interaction)

Of the highest intensity are the lines of atomic copper, Cu I 521.8 nm; atomic tantalum, Ta I 482.5 nm and 335.8 nm; \( \text{N}_2^+ \) molecular nitrogen ion, 378...390 nm. The atomic hydrogen lines of Balmer series \( \text{H}_\alpha \) 656 nm and \( \text{H}_\beta \) 486 nm have the lower intensity. We supposed that local thermal equilibrium takes place in the jet plasma. In this case the method of relative intensities of spectral lines can be used. By means of the atomic hydrogen lines \( \text{H}_\alpha \) and \( \text{H}_\beta \), we calculated the temperature in the area of interaction between capillary discharge jet and metal foil. The foil was located at the distance \( x = 1.8-2.4 \) cm from the capillary, temperature range was equal to \( T = 1000-2200 \) K. We obtained two temperatures (figure 2(b)): under the jet interaction with the tantalum foil (line 1) for the foil located at
the distance $x=1.8-2.4$ cm from the capillary; without the interaction (line 2). The maximum plasma temperature, $T=7800\pm300$ K, takes place near the capillary. The hydrogen lines, $H_\alpha$ and $H_\beta$, have essential broadening $\Delta\lambda=5-12$ nm that might be attributed to Stark effect. We calculated the plasma concentration in the interaction area according to the Stark $H_\alpha$ and $H_\beta$ line broadening. At the distance $x=2.1$ cm, the plasma concentration was equal to $n_e=(1.4\pm0.2)\cdot10^{16}$ cm$^{-3}$.

4. The investigation of plasma domain characteristics
At first we registered plasma domain characteristics which occurred as a result of interaction between jet and aluminum foil. As a result of interaction between plasma domains and vertical plexiglass barriers, the plastic domain elastic reflection occurred. In some cases drastic damping of plasma domain motion was registered. We assumed that plasma domains have totally formed structure and elastic shell. The occurrence of plasma domains, which took place as a result of interaction with tantalum foil, had some special characteristics. The number of plasma domains greatly increased, their dimensions used to increase too. In some cases up to 3 spherical plasma domains occurred (2-3 mm diameter). In other cases domains with smaller dimensions (0.1-1 mm diameter) and irregular shape occurred. The image in figure 3 shows the motion of plasma domains, which have dimensions in the range of 3 mm and are surrounded by a halo, and the motion of 17 plasma domains, which have smaller dimensions.

![Figure 3. Photo of plasma domains (t=6.8 ms after discharge initiation, time resolution is equal to 1 ms)](image)

The process of plasma domain splitting in the smaller domains is quite unusual. This process occurs spontaneously or as a result of plasma domain interaction with barriers. The new small domains move independently and exist for some time. The process of mutual interaction of two domains, which are located at a distance that is equal to several domain dimensions, is also very interesting. This interaction is complex and cannot be reduced to the predominance of attraction or repulsion.

In the area, inside of which moving plasma domains occurred, magnetic field was formed. The magnet with magnetic induction $B=500-700$ Gs was located at a distance $l=7-15$ cm from capillary discharge, at an angle $\alpha=0-90^\circ$. Plasma domains, which occurred as a result of interaction between the jet and the foil, moved toward the magnet. The velocity of plasma domain motion $v$ was equal to 0.5-1.5 m/s. Some domains interacted with magnet surface. The change of plasma domain motion trajectory under the influence of magnetic field also took place. The results of series of experiments, which were conducted under different trajectories of plasma domain motion towards magnetic field, were investigated. Obtained results show that there is no volume positive charge or volume negative charge inside the plasma domain. Taking into account these circumstances, we can assume that plasma domain should have a plasma structure.

Now we have to analyze which phenomena can occur as a result of plasma domain occurrence. Plasma domains occur during an interaction between the capillary discharge jet and metal foil (tantalum or aluminum). If we use tantalum foil, temperature in the interaction area is $T=1000-2200$ K, electron concentration is $n_e=(1.2)\cdot10^{16}$ cm$^{-3}$. Degree of ionization of the capillary discharge jet is $\alpha=(1.1-1.8)\cdot10^{-3}$. Let’s assume that plasma domain characteristics are close to characteristics of the capillary discharge jet. Let’s propose that aluminum oxidation reaction, which takes place inside the
domain, is an energy source. The physical model of plasma near-spherical domain with added aluminum atoms is presented [7]. This model shows that decrease of near-spherical domain charge is caused by drift motion of ions through the plasma domain surface. Energy loss occurs when ions and electrons of plasma domains and air molecules are recombined. The above-mentioned experiments show that plasma domains have a stable internal structure. That is why we can assume that plasma vortex can be generated. During the interaction of the capillary discharge jet with the foil, the most likely areas of plasma domain occurrence are edges of the hole, which was made in the foil. Some studies show that toroidal vortices and other stable vortices can be generated on the edges of holes or on the edges of plates. Plasma domain can have lower viscosity that is why we can assume that such vortex can be generated inside such domain. So we can assume that vortical plasma structure can be generated inside the plasma domain volume.

5. Conclusion
The following data were obtained as a result of this study. As a result of interaction of the capillary discharge with metal foils, plasma domains occur. The dimensions of these domains are up to 3 mm, their lifetime is up to 0.5 sec. Plasma domains have an elastic structure. This phenomenon was confirmed during their interaction with vertical and horizontal dielectric barriers. The velocity of plasma domain motion is equal to 0.1-5 m/s. Trajectories of plasma domain motion are usually parabolic, in some cases vertical motions can occur. The characteristics of interaction of plasma domain with barriers and the characteristics of plasma domain motion in magnetic field show that plasma domain has a totally formed internal plasma structure. This structure can be vortical.

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