Properties of plasma in case of capillary discharge interaction with metals

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Abstract. A consideration is given to the effect of capillary discharge torch on metal foils. The spectral characteristics of plasma have been measured in visible and ultraviolet ranges and plasma temperature has been determined in the area of interaction. The properties of autonomous plasma areas appearing in case of this interaction are being investigated. A study of plasma areas collision with the surface of liquid nitrogen has been presented. The motion of plasma areas in permanent electric field has been studied. A possible structure of plasma areas is being discussed.

1. Introduction
The formation of capillary discharge is accompanied by the appearance of torch of an extended plasma configuration [1, 2]. The plasma areas (PA) featuring size of 0.2–4 mm and lifetime of 0.1–1 s appear during different experiments with capillary and erosion discharges [3–5]. In order to initiate PA, the non-organic and organic substances, as, for instance, basalt wool and paraffin have been placed into discharges. After discharge discontinuation and PA extinction the microparticles have been studied, which supposedly could constitute a part of PA [5]. A torch of capillary discharge has been also used for experiments on interaction with metals [6, 7].

2. The experimental setup and spectral research
A capillary discharge has been used in interaction experiments (figure 1). A plate of plexiglas featuring thickness of 2–3 mm with capillary diameter equal to 1–3 mm has been used for a discharger, material of electrodes: graphite and copper. A power source with voltage of 250–300 V and energy content of 50–380 J was used for discharge functioning. The characteristic values in the experiments amounted to discharge current of 100–150 A, pulse duration of 5–10 ms. Metal foils of aluminum, tantalum and copper with thickness of 0.03–0.1 mm have been used for experiments.

The interaction of capillary discharge torch with metal foil results in its burning. An average quantity of evaporated material equals 0.1–5 mg. An emergence of plasma areas (PA) can be observed in the area of discharge and foil interaction (figure 1). The PA characteristic parameters are as follows: diameter 0.1–4 mm, lifetime 10 ms–0.5 s, quantity per shot – 1–20, radiation color – white, dark blue. PA motion speed is in the range of 0.1–5 m/s. In case of using aluminum and tantalum foil for PA maximum dimensions of 1–3 mm, maximum lifetime of 0.1–0.5 s and maximum quantity of 15–20 have been obtained. The photo and cine-shooting registration of luminescence has been performed by means of Nikon 1G camera (timing resolution of about 1 ms).
The capillary discharge radiation in the visible and ultraviolet ranges of electromagnetic spectrum has been investigated during work. In order to obtain panoramic spectrum, Ava Spec 2048 spectrometer (range of 200–1000 nm, resolution of 0.3 nm) has been used. The radiation timing characteristics have been investigated by means of MUM monochromator (range timing resolution of 10 ns). Figure 2a shows a capillary discharge torch radiation spectrum in case of interaction with aluminum foil (thickness of 0.05 mm). A distance between the discharger and foil amounted to about 2.1 cm. The radiation comprises lines of hydrogen atoms H\textsubscript{α} 656 nm, H\textsubscript{β} 486 nm and H\textsubscript{γ} 434 nm. The most intensive are the lines of: ion of nitrogen molecules N\textsubscript{2}\textsuperscript{+} 381…393 nm and copper atom Cu I 510.5 nm. The spectrum comprises lines of aluminum atoms Al I 309.2 nm. A characteristic time dependence of intensity of radiation of this aluminum line is shown in figure 2b. The existence of local thermal equilibrium for plasma has been supposed [8]. The temperature that amounted to value, $T = 2500\pm300$ K, has been calculated using relative intensities method along the lines of atomic hydrogen H\textsubscript{α} 656 nm, H\textsubscript{β} 486 nm. The reviewed lines H\textsubscript{α} and H\textsubscript{β} possess a widening in the range of 5–10 nm, which can be explained by the presence of the Stark effect. Therefore, the plasma concentration $n_e = (3.2\pm0.2)\times10^{16}$ cm\textsuperscript{-3} has been calculated by means of the Stark widening of these lines.

Figure 2. Spectral measurements of the torch radiation: (a) torch radiation spectrum at interaction with aluminum foil, (b) time dependence of intensity of the line radiation Al I 309.2 nm.
3. The interaction of plasma areas with liquid nitrogen

Let us give consideration to PA interaction with a surface of liquid nitrogen \( T_N = 77.4 \) K (figure 3). An axis of capillary discharge formed an angle \( \alpha = 30-45^\circ \) with the surface of liquid nitrogen. The aluminum and tantalum foils have been used in the experiments. Following the occurrence, PA began moving in the direction towards surface of liquid nitrogen. The approach of three PA to the surface of liquid nitrogen is shown in the frame of motion-picture photography (figure 4). The dimensions of PA are 2–3 mm. The motion has taken place from the area of discharger and interaction with foil (on the right) to the area of liquid nitrogen vessel (on the left). The surface of liquid nitrogen is not registered in this picture due to high transparency of the liquid. Prior to touching the liquid nitrogen the PA featured, as a rule, nearly spherical shape and moved at the angle of about \( \alpha \approx 45^\circ \) to the liquid surface from right to left. The angular regularity of PA reflection from the liquid nitrogen surface with the initial angle of incidence \( \alpha \approx 40-50^\circ \) is shown in figure 3b. 40 interaction cases have been used. The maximum of this distribution is located close to the angle of reflection \( \beta \approx 31 \). This specific reflection can be related to PA rotary motion. The PA extinction has, as a rule, taken place inadvertently in the process of motion, or in case of contact with liquid nitrogen.

![Figure 3. The interaction of plasma regions with liquid nitrogen: (a) experimental setup: 1 – liquid nitrogen, 2 – vessel, 3 – plasma areas, 4 – discharger, 5 – metallic foil, (b) angular distribution of plasma region refraction from liquid nitrogen surface.](image)

![Figure 4. The motion of plasma areas near liquid nitrogen surface (time resolution \( \Delta t \approx 1 \) ms).](image)

4. The studying characteristics of plasma areas

In order to study the content of electric charges in the substance of plasma areas, the experiments have been conducted with the presence of electric field in the space in the range of: \( E = 10^3-10^4 \) kV/cm. Tantalum foil has been used in the experiments. A bundle of PA has been preliminarily formed by means of two diaphragms. After that PA moved in the range of cone with the angle of about \( \alpha \approx 6^\circ \) and headed towards a uniform electric field (area dimensions: \( l \approx 20 \) cm, \( a \approx 10 \) cm). The PA speed
has been in area of $v = 0.5–2.5$ m/s. A possible PA shift in the electric field has been studied. The PA path was registered by means of Nikon 1G camera. A maximum shift of PA has been observed within the limits of this angle $\alpha \approx 6^\circ$ only. Great shifts as a result of electric field effect have not been registered. It testifies to an absence of positive or negative volume charge in PA volume. Therefore, plasma, apparently, forms a structure of PA matter.

The qualitative study of PA electromagnetic radiation has been carried out. These experiments have been complicated by low intensity of radiation and presence of PA motion. A spectral prism of crystal quartz as well as interference filters in the range of 400–700 nm was used for experiments. The PA images have been registered by means of Nikon 1G camera. The measurements have shown a presence of continuous electromagnetic radiation in the range under investigation.

The edges of holes in foil can become a possible area of PA emergence. The formation of toroidal vortexes at the edges of holes is observed in hydrodynamic vortexes in gas. In view of this fact one can suppose the formation of vortex plasma structure inside of PA volume. The density of PA substance proceeding from the analyses of data of uniformly accelerated motion in the field of Earth’s gravity will amount to a value of $\rho \approx 1.5 \cdot 10^{-3}$ g/cm$^3$ and is close to air density of $\rho \approx 1.2 \cdot 10^{-3}$ g/cm$^3$ [6, 7]. In order to explain the existence of plasma configuration, including aluminum ions, a theoretical model has been built in works [9, 10]. The results of PA interaction with organic and non-organic materials testify to low PA temperature and about a specific effect mechanism [6, 7]. Some PA reflections from the surfaces of substances have been elastic and have not brought about PA destruction or extinction.

5. Conclusion
The temperature of plasma in the area of interaction of capillary discharge torch and aluminum foil has been measured in the course of experiments, which amounted to $T = 2500 \pm 300$ K. The PA motion in the permanent electric field demonstrates an absence of clearly expressed volume positive or negative charge in PA substance. In view of this fact plasma is the most likely PA structure. A reflection from the liquid surface has taken place in the experiments on PA interaction with the liquid nitrogen without vapor liberation in the place of contact and strong deformation of PA shape. These experiments of interaction of plasma areas testify to the presence of a resilient envelope preserving a shape of the area in case of external impact. In view of this fact one can admit an existence of molecular or cluster shell comprising aluminum atoms and possessing the stable interatomic links.

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