

# MECHANICS МЕХАНИКА



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## Electric Discharge between a Jet Electrolytic Cathode and a Metal Anode

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### Abstract

**Introduction.** Gas discharges with liquid electrodes are considered as a promising tool for improving adhesion properties and preparing surfaces for coating application. Glow and arc discharges with electrolytic electrodes have been investigated in detail in the literature, but most studies focus on configurations with a stationary electrolyte. For “jet electrolytic cathode–metal anode” systems at atmospheric pressure, the discharge combustion modes, their stability limits, and the energy characteristics of the process are insufficiently systematized. This hinders the scalability of localized aluminum processing technologies. The objective of this study is to experimentally classify combustion modes and their stability regions, determine the electrical, spectral, and thermal parameters of the discharge, and substantiate practical modes for localized aluminum surface preparation for adhesion and coating.

**Materials and Methods.** To achieve this goal, a laboratory setup was built: a 3% NaCl jet served as the cathode, and an AMTs-40 (aluminum-manganese alloy in the RU system, ISO analog: AW-3003) aluminum plate served as the anode. The jet-anode assembly was placed in a temperature-controlled electrolytic cell with closed circulation of the solution. Typical conditions:  $U \approx 600$  V,  $v_k \approx 0.6$ – $0.7$  m/s,  $d \approx 2$  mm,  $\sigma \approx 0.10$ – $0.12$   $\Omega^{-1}$  cm $^{-1}$ . A power supply of up to 4 kV/10 A provided a wide range of settings. The diagnostics included oscillographic measurements, high-speed video recording (Casio EX-F1, 600–1200 fps), thermal imaging (FLIR A6500sc), and optical emission spectroscopy (OES) on a PLASUS EC 150201 MC spectrometer with electron density  $n_e$  estimated from Stark broadening of  $H_\alpha$ .

**Results.** Two plasma localization topologies were detected: a contact zone on the triple gas-liquid-solid line and a jet breakup region. The current was pulsed with an amplitude of 0.8–1.6 A. The spectra were dominated by the Na I doublet ( $\sim 589$  nm), the OH(A–X) bands, and the  $H_\alpha$  line; from  $\Delta\lambda_L(H_\alpha) \approx 0.64$  nm, an estimate of  $n_e \approx 6.4 \times 10^{16}$  cm $^{-3}$  was obtained. Thermal imaging maps showed a maximum effective temperature of  $\sim 47^\circ\text{C}$  at the point of contact, and an energy deposition zone elongated along the jet with a length of  $\sim 7$  mm (diameter  $\sim 2$  mm).

**Discussion.** The pulsed nature of the current with an amplitude of 0.8–1.6 A at 600 V indicates the periodic formation and breakdown of the current channel, which is typical for discharges with a nonstationary geometry of the cathode region and has been previously noted in studies on discharges with flowing jets. The estimate of the electron density  $n_e \approx 6.4 \times 10^{16}$  cm $^{-3}$  based on the Stark broadening of  $H_\alpha$  falls within the range of  $10^{15}$ – $10^{17}$  cm $^{-3}$ , characteristic of atmospheric discharges with liquid electrodes, and indicates a relatively dense plasma sufficient for effective surface activation. The dominance of Na I lines in the spectrum confirms the intense transfer of electrolyte components into the discharge gap, which is consistent with the aerosol sputtering mechanism in the near-cathode region. The compactness of the temperature spot on the anode (transverse size  $\sim 2$  mm, maximum  $47^\circ\text{C}$ ) confirms the localized nature of the energy deposition without global overheating of the component. However, the true surface temperature may be higher than the measured one due to the uncertainty in the emissivity of the growing oxide film.

**Conclusion.** A discharge between a jet electrolytic cathode and an aluminum anode at atmospheric pressure has been experimentally characterized. Two stable combustion topologies, the pulsed nature of the current, spectral markers, and a thermal energy deposition pattern are demonstrated. The results form the basis for constructing operational maps for local aluminum processing and expanding technology applications. The data obtained form the basis for constructing a map of aluminum processing modes and can be expanded through varying the flow rate, nozzle diameter, electrolyte composition, and using faster diagnostics. Future work includes standardizing the energy metrics, quantitatively decomposing the radiation sources, and scaling the methodology.

**Keywords:** jet electrode, aluminum anode, gas discharge, pulsed currents, emission spectroscopy, Balmer lines, electron concentration, thermal imaging diagnostics, surface modification

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Оригинальное эмпирическое исследование

## Электрический разряд между струйным электролитическим катодом и металлическим анодом

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### Аннотация.

**Введение.** Газовые разряды с жидкими электродами рассматриваются как перспективный инструмент для улучшения адгезионных свойств и подготовки поверхностей под нанесение покрытий. В литературе подробно изучены тлеющие и дуговые разряды с электролитическими электродами, однако большинство работ сосредоточено на конфигурациях с неподвижным электролитом. Для систем «струйный электролитический катод — металлический анод» при атмосферном давлении формы горения разряда, границы их устойчивости и энергетические характеристики процесса систематизированы недостаточно. Это препятствует масштабированию технологий локальной обработки алюминия. Цель настоящей работы — экспериментально классифицировать формы горения и области их устойчивости, определить электрические, спектральные и тепловые параметры разряда, а также обосновать практические режимы локальной подготовки алюминиевой поверхности под адгезию и покрытия.

**Материалы и методы.** Для реализации поставленной цели была создана лабораторная установка: струя 3 % NaCl выполняла роль катода, алюминиевая пластина АМЦ-40 — анода; узел «струя-анод» размещён в термостатируемой электролитической ячейке с замкнутой циркуляцией раствора. Типичные условия:  $U \approx 600$  В,  $v_k \approx 0,6–0,7$  м/с,  $d \approx 2$  мм,  $\sigma \approx 0,10–0,12$   $\Omega^{-1} \cdot \text{см}^{-1}$ ; источник питания до 4 кВ/10 А обеспечивал широкий диапазон настроек. Диагностика включала осциллографические измерения, высокоскоростную видеосъёмку (Casio EX-F1, 600–1200 к/с), тепловизионную съёмку (FLIR A6500sc) и ОЭС на спектрометре PLASUS EC 150201 MC с оценкой  $n_e$  по штарковскому уширению  $H_\alpha$ .

**Результаты исследования.** Обнаружены две топологии локализации плазмы: контактная зона на тройной линии «газ-жидкость-твёрдое тело» и область распада струи. Ток носит импульсный характер с амплитудой 0,8–1,6 А. В спектрах доминируют дублет Na I (~589 нм), полосы OH(A–X) и линия  $H_\alpha$ ; по  $\Delta\lambda_L(H_\alpha) \approx 0,64$  нм получена оценка  $n_e \approx 6,4 \times 10^{16}$   $\text{см}^{-3}$ . Термовизионные карты показали максимум эффективной температуры ~47 °С в точке контакта и вытянутую вдоль струи зону энерговклада длиной ~7 мм (поперечник ~2 мм).

**Обсуждение.** Импульсный характер тока с амплитудой 0,8–1,6 А при 600 В свидетельствует о периодическом формировании и срыве токового канала, что типично для разрядов с нестационарной геометрией катодной области и ранее отмечалось в работах по разрядам со стекающими струями. Оценка электронной концентрации  $n_e \approx 6,4 \times 10^{16}$   $\text{см}^{-3}$  по штарковскому уширению  $H_\alpha$  попадает в диапазон  $10^{15}–10^{17}$   $\text{см}^{-3}$ , характерный для атмосферных разрядов с жидкими электродами, и указывает на относительно плотную плазму, достаточную для эффективной активации поверхности. Доминирование линий Na I в спектре подтверждает интенсивный перенос компонентов электролита в разрядный промежуток, что согласуется с механизмом аэрозольного распыления в прикатодной области. Компактность температурного пятна на аноде (поперечный размер ~2 мм, максимум 47 °С) подтверждает локальный характер энерговклада без глобального перегрева детали, однако истинная температура поверхности может быть выше измеренной из-за неопределённости эмиссивности растущей оксидной плёнки.

**Заключение.** Экспериментально охарактеризован разряд между струйным электролитическим катодом и алюминиевым анодом при атмосферном давлении; показаны две устойчивые топологии горения, импульсная природа тока, спектральные маркеры и тепловая картина энерговклада. Результаты формируют базу для построения режимных карт локальной обработки алюминия и расширения технологических приложений. Полученные данные

составляют основу для построения карты режимов обработки алюминиевых изделий и могут быть расширены за счёт варьирования расхода, диаметра сопла, состава электролита и применения более скоростной диагностики. Направления дальнейших работ: стандартизация энергетических метрик, количественная декомпозиция источников излучения и масштабирование методики.

**Ключевые слова:** струйный электрод, алюминиевый анод, газовый разряд, импульсные токи, эмиссионная спектроскопия, линии Бальмера, концентрация электронов, тепловизионная диагностика, модификация поверхности

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**Introduction.** Gas-discharge plasma, formed in the interelectrode gap where one or both electrodes are liquid, is a promising area of research in the fluid, gas, and plasma mechanics, as well as modern materials processing technologies [1]. One popular configuration is a system with a jet electrolytic cathode and a metal anode, in which the cathode function is performed by a flowing jet of electrolyte [2]. This design allows for the formation of a local cathode region with gas-discharge plasma and provides flexible adjustment of process parameters [3]. Local energy deposition in the cathode spot zone, effective heat removal through liquid electrodes, and rapid removal of reaction products provide the high efficiency of this configuration for local surface treatment of small-sized metal products [4], cleaning [5], burr removal, and the application of functional coatings [6].

The discharge mechanism with a jet electrolytic cathode is determined by complex interphase interactions in a three-phase “gas – liquid – solid” unit [7]. The nature of combustion and the stability of the process are significantly affected by electrical parameters (voltage, current, power, type of power supply – direct or high-frequency current) [8], jet hydrodynamics (flow rate, flow velocity, nozzle diameter, turbulence level) [9], thermal and mass transfer phenomena (evaporation, degassing) [10], chemical composition and specific electrical conductivity of the electrolyte [11], as well as the pressure and composition of the surrounding gas environment [12]. Such systems are characterized by a change in combustion modes, the occurrence of self-excited oscillations and breakdowns, as well as a pronounced nonlinearity of the volt-ampere characteristics [13]. In comparison with the discharge on a solid cathode, the structure of the near-electrode layer of a liquid cathode is specific: a key role is played by ion bombardment of the jet surface, secondary electron emission at the interface between the media, micro-splashes and microdischarges on gas inclusions, as well as electrodynamic stabilization or destabilization of the meniscus [14].

The practical significance of such discharges is due to the possibility of controlled modification of the microrelief and condition of the near-surface layer of the metal anode without critical thermal impact on the component. This allows for the formation of active functional groups, regulation of surface wettability, removal of oxide films and organic contaminants, initiation of nucleation sites for subsequent coating deposition, and improvement of microhardness and corrosion resistance. The localized nature of the impact is particularly relevant for small components with complex geometries, where traditional mechanical and electrochemical methods are inapplicable. For industrial production, the determination of optimal processing conditions that link discharge characteristics and electrolyte jet parameters is the critical task.

However, this area of research remains understudied. The conditions for the transition between different discharge modes, depending on electrodynamic and hydrodynamic factors, is not fully described. Mathematical models of the layer in the liquid cathode region need to be developed, taking into account the processes of vapor-gas shell generation. Systematization of the modes in the form of maps is required, where electrical characteristics (specific energy deposition per unit surface area, voltampere curves) would be compared with the final functional properties of the material. From a diagnostic perspective, the following are in demand: high-speed visualization of interelectrode processes; precision recording of voltampere characteristics and current oscillations; optical emission spectroscopy for identifying plasma composition, determination of the concentration and temperature of electrons, as well as the temperature of the heavy component.

The objective of this study is to establish the combustion modes of an electric discharge between a jet electrolytic cathode and an aluminum anode, identify the regions of their stable existence, and comprehensively determine the electrophysical, spectral, and thermal characteristics. The results obtained are aimed at developing scientifically sound recommendations for the finishing and modification of aluminum and its alloy products.

**Materials and Methods.** Ignition and stable combustion of a jet electric discharge with a liquid plasma-forming medium under localized action on a metal anode were implemented using a laboratory setup in which a flowing electrolyte jet served as the cathode and a metal plate — as the anode (Fig. 1 *a*). The jet – anode assembly was housed within an electrolytic cell (Fig. 2 *b*), equipped with systems for supplying and removing the solution, temperature control, and standard exhaust ventilation for the work area.

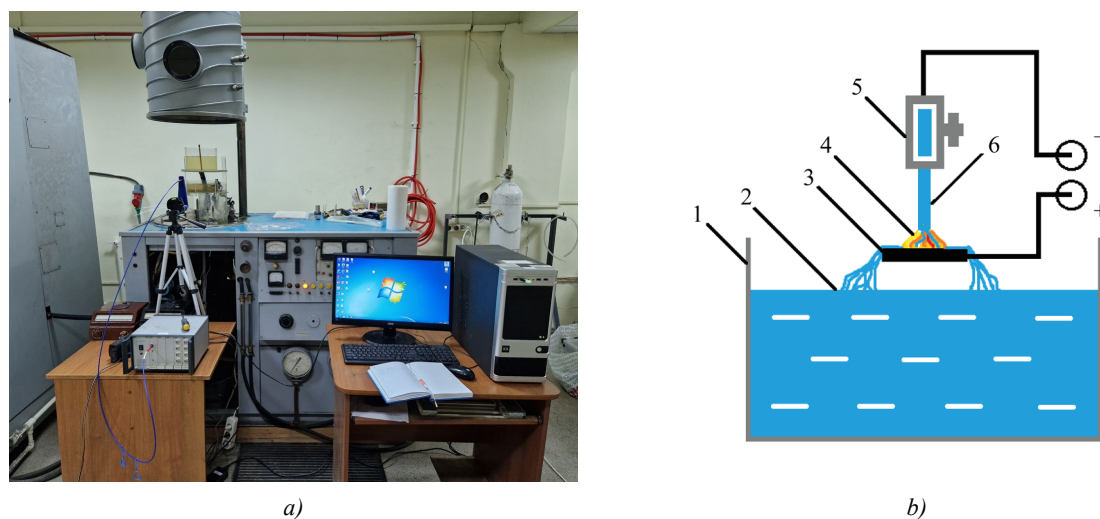


Fig. 1. Experimental setup for igniting gas-discharge plasma:

*a* — photograph of the experimental setup; *b* — functional diagram of the gas-discharge chamber for maintaining a jet discharge with a liquid cathode interacting with the surface of a metal anode, where: 1 — electrolytic cell; 2 — electrolyte; 3 — metal anode (aluminum plate); 4 — discharge combustion zone; 5 — jet feed/adjustment nozzle; 6 — electrolyte jet (cathode)

An aluminum plate from AMts-40 (ISO: AW-3003 or AlMn1Cu), secured in a cell, served as the anode. The cathode was formed by a continuous jet of a 3% aqueous NaCl solution prepared with purified tap water. Before starting, a negative potential was applied to the nozzle and the jet, and a positive potential — to the aluminum plate. The jet was generated through a replaceable nozzle; the flow rate was set using a control valve monitored by a flow gage. To ensure the stability of the solution properties, temperature control was provided: a refrigerated circulation cooler maintained the temperature within specified limits, and electrolyte was renewed in a closed loop with a coarse filter to remove mechanical impurities. Vapors and aerosols were removed from the work area by a stationary exhaust system. All current-carrying components and housing were protected by grounding.

The discharge was powered by a high-voltage source up to 4 kV with a nominal current up to 10 A and stepless control, including high-voltage and low-voltage channels. This allowed for flexible setting of voltage and current ranges, as well as powering auxiliary sensors. Current values of  $U$  and  $I$  were displayed on panel indicators and duplicated on the control PC for operational monitoring. In standard series of experiments, the parameters were: voltage  $U = 0.1\text{--}1.1$  kV; pressure  $p \approx 10^5$  Pa (atmospheric); jet velocity  $v_k = 0.5\text{--}0.7$  m/s; jet diameter  $d = 2$  mm; jet length  $l = 15$  mm;  $\nu = 0.10\text{--}0.12$  Ohm $\cdot$ cm $^{-1}$ ; temperature  $T = 12\text{--}64$  °C. The polarity of the electrodes was maintained in all modes: jet – cathode, plate – anode.

The diagnostic complex included mutually complementary methods of visualization, thermal and electrical control, as well as optical emission spectroscopy.

1. High-speed video recording of the torch and near-electrode structure dynamics was performed using a Casio EX-F1 camera at 600 and 1200 fps. The camera was mounted on a tripod approximately 300 mm from the discharge zone. Data transfer and initial processing were performed on a PC using HX Link and Movavi Video Editor 14 Plus software. The recording made it possible to capture the shape and oscillations of the cathode jet, as well as the evolution of the anode spot.

2. A FLIR A6500sc thermal imaging camera (640×512 pixels; 3.6–4.9  $\mu$ m) calibrated with a multi-wavelength pyrometer was used to map the temperature field on the anode surface and in the vicinity of the cathode jet. This compensated for changes in effective emissivity associated with the formation and growth of an oxide film on the aluminum. Thermogram analysis was performed using the ALTAIR v5.91.010 software package.

3. Current and voltage pulsations were recorded using GDS-806S and GOS-6030 digital oscilloscopes. A photodiode discharge radiation sensor connected to the oscilloscope was used to synchronize electrical signals with optical events. This approach ensured that ignition timing, transitions between combustion modes, and surges were correlated with visually observable changes in the flame.

4. Optical emission spectroscopy was performed on a PLASUS EC 150201 MC fiber-optic spectrometer in the range of 195–1105 nm. The radiation was collected by a collimator brought to the combustion zone at a distance of 100–200 mm. The instrumental function was calibrated using a SIRSH 6–100 source; the instrumental width was  $\Delta\lambda_g \approx 1$  nm. The spectra were compared with the NIST database. The electron concentration (based on the broadening of  $H_\alpha$ ) was estimated from the profiles of the Balmer series hydrogen lines.

A set of tools and modes provided representative, reproducible measurements and comparison of electrical, spectral, thermal and visual characteristics of a jet discharge with a liquid cathode and local impact on the surface of a metal anode.

**Research Results.** The photographs (Fig. 2) show that with the polarity “jet electrolytic cathode — aluminum anode”, the discharge at  $U = 600$  V,  $p = 10^5$  Pa and jet velocity  $v_k = 0.6$  m/s, is localized in two characteristic areas: 1 — in the zone of direct contact of the jet with the surface of the anode (Fig. 2 *a*), and 2 — in the region of jet breakup (Fig. 2 *b*).

In the first case, a near-electrode light-emitting region is formed, tied to the “contact spot” and the “gas-liquid-solid” triple cross-section line. In the second case, glow and microdischarge events occur at the necks and droplets of the disintegrating jet, where the surface curvature and localized gas inclusions enhance the field and reduce the effective gap length.

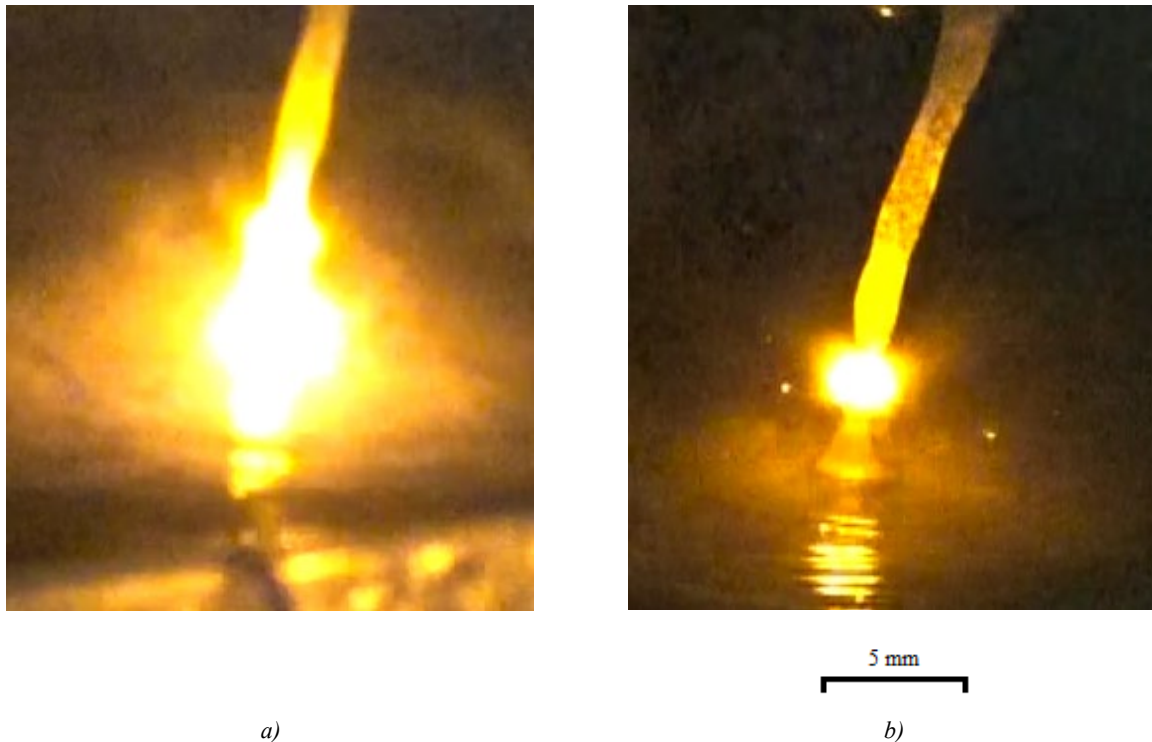


Fig. 2. Jet electric discharge between a jet anode and an aluminum cathode at  $U = 600$  V,  $I = 1.6$  A,  $p = 10^5$  Pa,  $v_k = 0.6$  m/s: *a* — at the interface between jet and metal surface; *b* — in the jet breakup zone

The characteristic yellow color of the torch in both cases is primarily due to the intense emission of the sodium resonant doublet ( $\approx 589$  nm), which arises from the evaporation/aerosol emission of Na-containing components from the jet of 3% NaCl solution in the near-cathode zone and their subsequent dissociation-excitation in the discharge volume. The contribution of continuous radiation from heated aerosol particles and local oxide inclusions can impart an orange-yellow hue at moments of peak energy deposition, but remains secondary to the Na lines.

The current oscillograms (Fig. 3) at a fixed voltage of  $U = 600$  V demonstrate the pulsed nature of the conductivity: the current is realized in series of pulses with an amplitude of about 0.8–1.6 A. This intermittent structure corresponds to the alternation of stages of amplification and attenuation of electron emission at the gas-liquid interface and the periodic “switching” of the conductivity channel between two geometries — “a spot on the surface of the metal electrode” and “in the jet breakup zone”.

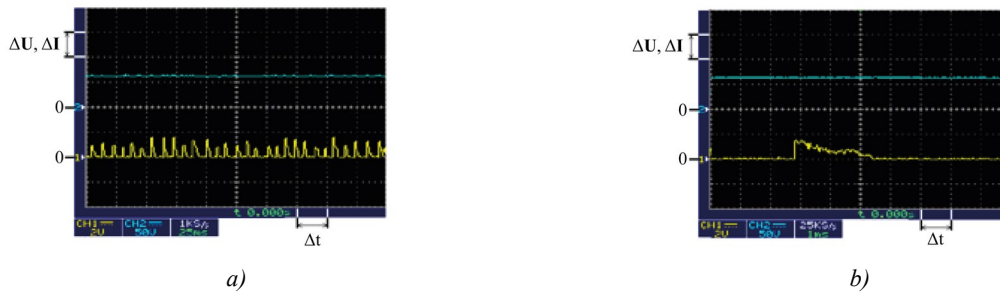


Fig. 3. Oscilloscope images of discharge current and voltage oscillations between the jet cathode and aluminum anode:

*a* — at  $p = 10^5$  Pa,  $\Delta U = 500$  V,  $\Delta I = 2$  A,  $\Delta t = 25$  ms;

*b* — at  $p = 10^5$  Pa,  $\Delta U = 500$  V,  $\Delta I = 2$  A,  $\Delta t = 5$  ms

Hydrogasdynamic processes, including the formation of gas bubbles, the emergence of convective currents, as well as the specific flow characteristics and jet velocity — along with accompanying variations in the interelectrode distance and cathode spot geometry — cause fluctuations in current density and electromagnetic field strength. These phenomena are recorded on the oscillogram as characteristic pulsed regions (Fig. 3).

Electrical signals obtained using an oscilloscope are compared with optical recordings of the discharge glow. It is found that current pulses correlate temporally with the occurrence of intense radiation in the combustion zone. This indicates that rapid microevents in the near-cathode region are crucial in initiating the pulses, transforming the conditions for the formation of the cathode layer and triggering microdischarges toward the anode.

In this electrode configuration, the following mechanisms of charged particle formation can act as sources of primary electrons for avalanche ionization and subsequent ionization in the volume: (1) secondary electron emission from the surface of the liquid cathode under the impact of bombardment by positive ions and fast neutral particles; (2) field emission from highly curved areas where the field strength increases locally; (3) photoelectron emission from the surface of the jet under the action of radiation from the discharge volume; (4) emission from gas bubbles adjacent to the cathode, where the reduced effective work function and field concentration facilitate the injection of electrons; (5) detachment of electrons from negative ions in the near-electrode layer.

Figure 4 shows the plasma emission spectrum of a discharge between a jet electrolytic cathode and an aluminum anode, with identified bands and lines.

Bands OH (A→X), are recorded, as well as the atomic lines H I, Na I, N I and K I. The presence of an intense resonance doublet Na I ( $\approx 589.0/589.6$  nm) is consistent with the visually observed yellow color of the flame: sodium enters the discharge zone from a 3% NaCl solution via evaporation from the near-cathode region, after which it is excited in the plasma volume.

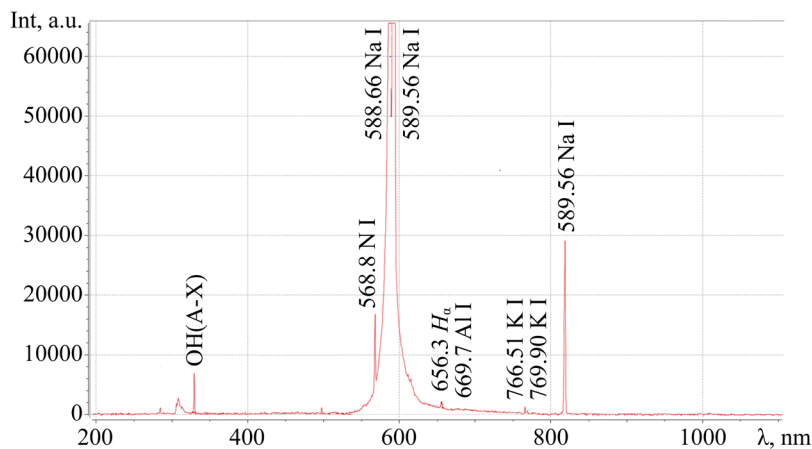


Fig. 4. Emission spectrum of the discharge plasma between the jet cathode and the aluminum anode with identified spectral lines

The instrumental broadening was estimated using the optically thin line K I (769.9 nm); the minimum half-width of the narrow lines was  $\Delta\lambda_G \approx 1.0$  nm and was then taken as the Gaussian component of the instrumental function. The observed line profiles were approximated by a Voigt contour; the Voigt ( $\Delta\lambda_F$ ), Lorentzian ( $\Delta\lambda_L$ ) and Gaussian ( $\Delta\lambda_G$ ) half-widths were related using approximation [15]:

$$\Delta\lambda_F \approx 0.5346 \cdot \Delta\lambda_L + \sqrt{0.2166 \cdot \Delta\lambda_L^2 + \Delta\lambda_G^2}.$$

From it,  $\Delta\lambda_L$  was found with known  $\Delta\lambda_F$  and  $\Delta\lambda_G$ , thereby eliminating the contribution of instrumental broadening.

For line  $H_\alpha$  (656.28 nm), the measured half-width of the Voigt profile was  $\Delta\lambda_F(H_\alpha) = 1.38$  nm. Taking into account the instrumental component, the Lorentz half-width was obtained as  $\Delta\lambda_L(H_\alpha) \approx 0.64$  nm. The electron concentration  $n_e \approx 6.4 \times 10^{16} \text{ cm}^{-3}$  was calculated using temperature-dependent coefficients.

This electron density is typical for atmospheric pressure, where the linear Stark broadening of hydrogen lines dominates.

In this series,  $H_\beta$  (486.13 nm) was not detected due to the low signal-to-noise ratio in the channel and exposure adjustment for the bright yellow lines Na I, which does not prevent  $n_e$  from  $H_\alpha$ .

Table 1

Summary Spectral Parameters for Estimating  $n_e$  from Line  $H_\alpha$

| Parameter                   | Value                                        | Note                                              |
|-----------------------------|----------------------------------------------|---------------------------------------------------|
| $\Delta\lambda_F(H_\alpha)$ | 1.38 nm                                      | Voigt contour half-width                          |
| $\Delta\lambda_L(H_\alpha)$ | $\approx 0.64$ nm                            | Lorentz component (without instrument broadening) |
| $n_e$                       | $\approx 6.4 \times 10^{16} \text{ cm}^{-3}$ | Stark broadening estimation of $H_\alpha$         |

The combination of observed bands and lines confirms the mixed nature of plasma formation (air + electrolyte sputtering products). The yellow color of the flame is due to the dominance of Na I lines, and an estimate based on the broadening of  $H_\alpha$  yields an electron concentration of approximately  $10^{16} \text{ cm}^{-3}$  under the conditions studied.

Thermographic analysis of the discharge zone. In the thermograms (Fig. 5), the origin of coordinates is the position corresponding to the contact area of the jet electrolytic cathode with the aluminum anode (“gas-liquid-solid” line).

At this point, the maximum effective temperature is recorded at  $T = 47^\circ\text{C}$ . As the electrode moves toward the source of the electrolyte jet, that is, along the jet, the temperature decreases within the first 7 mm, indicating a plasma region elongated along the jet, approximately 7 mm in length and with an effective transverse dimension of 2 mm. Outside the plasma region, the temperature profile declines exponentially to the ambient temperature. As the electrode moves toward the aluminum anode, the temperature also drops sharply to  $22^\circ\text{C}$ . This profile asymmetry is explained by the high thermal conductivity of aluminum and its effective heat dissipation into the component volume, as well as by intensive convective cooling by the adjacent electrolyte. The temperature “spot” on the anode surface is compact and confined to the contact zone. This corresponds to the pattern of directed energy deposition from the discharge elongated along the cathode jet.

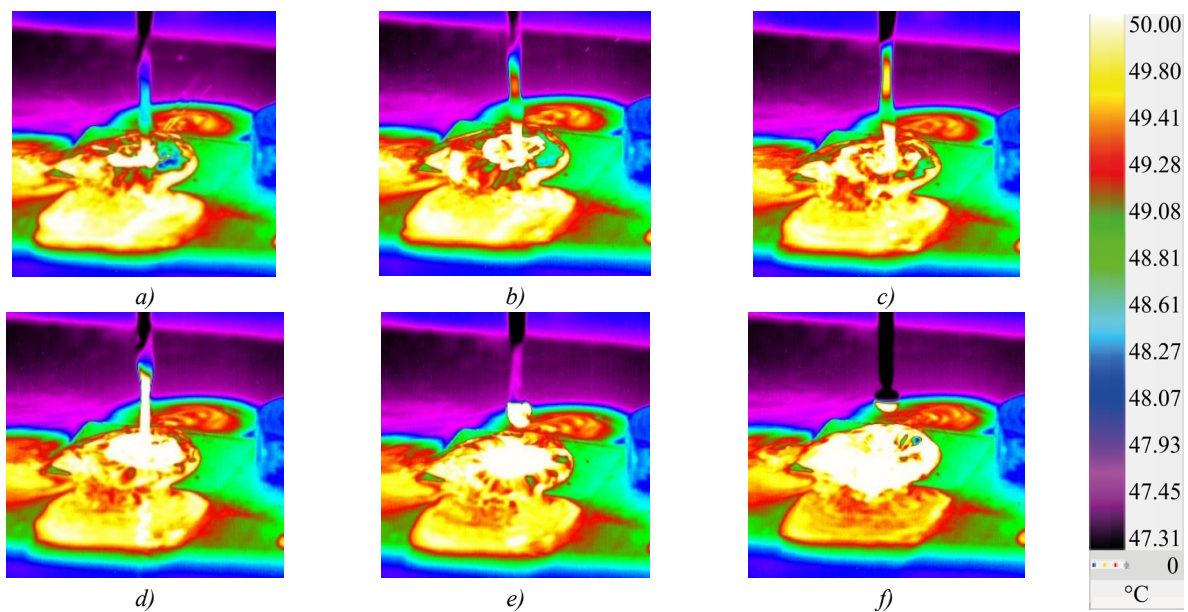


Fig. 5. Dynamics of temperature distribution of the jet electrolytic cathode (thermograms,  $t = 0-5$  s,  $\Delta t = 1$  s): a — 0 s; b — 1 s; c — 2 s; d — 3 s; e — 4 s; f — 5 s

**Discussion.** Based on the data obtained, it follows that plasma structures are localized in two areas of the system: (1) — in the area of contact of the jet electrode with the surface of the workpiece, and (2) — in the zone of thinning and disintegration of the jet electrode.

In the first case, the maximum energy deposition from the discharge is localized in the area of the cathode spot on the surface of the metal anode. In the second case, it shifts toward the constriction and disintegration region of the jet electrode, where the surface geometry and the vapor-gas gap enhance the electromagnetic field. This behavior of the jet electrode explains the changes in conductivity and, consequently, current fluctuations in the range of 0.8–1.6 A at a voltage of approximately 600 V.

The pulsed nature of the discharge combustion is due to the interrelationship between the electrical parameters of the discharge, the cathode layer, and the jet hydrodynamics. The dynamics of the jet flow, accompanied by the formation of localized areas of constriction and jet breakup, causes a non-stationary change in the geometry of the cathode region and a change in the electric field strength. Under these conditions, short-term microdischarges are formed in the vapor-gas region between the anode and cathode which show themselves as successive current pulses that correlate with the discharge plasma glow. The initiation of these pulses is determined by the combined contribution of various electron emission mechanisms, including secondary emission under ion bombardment, field emission, and electron injection into the plasma volume from the surface of the near-cathode layer.

Analysis of the emission spectra indicates the combined nature of the gas-discharge plasma, formed by both ambient air components and elements dislocated from the electrolyte. Intense radiation is recorded at the Na I line in the region of approximately 589 nm, which determines the predominance of the yellow color of the discharge combustion. The detection of the bands OH (A–X) and line  $H_\alpha$  indicates the occurrence of gas-phase processes involving hydrogen and hydroxyl radicals. The electron concentration, estimated from the Stark broadening of line  $H_\alpha$  ( $\Delta\lambda_L \approx 0.64$  nm), is  $n_e \approx 6.4 \times 10^{16} \text{ cm}^{-3}$ .

Thermographic measurements show the formation of a localized heating zone on the surface of the metal anode with a maximum temperature of approximately 47°C. The spatial asymmetry of the temperature field is due to the high thermal conductivity of aluminum, which provides intense heat transfer into the bulk of the material and convective cooling from the electrolyte. The recorded temperature values do not determine the mechanism of aluminum surface activation. The change in the properties of the surface layer is realized due to the nonequilibrium effect of gas discharge plasma, including a flow of charged particles, active chemical components, and local electric fields in the anode region, and not as a result of thermal destruction of oxide film  $\text{Al}_2\text{O}_3$ .

From the point of view of practical implementation, the process is characterized by the presence of stable regime regions determined by a set of electrical parameters (voltage, current), hydrodynamic characteristics of the jet (speed, diameter, length of the gap) and the electrical conductivity of the solution.

Limitations of the study include the finite spectral resolution of the equipment used ( $\sim 1$  nm), which imposes restrictions on the interpretation of narrow lines and makes line  $H_\alpha$  preferable for estimating electron concentration. An additional factor is the fixed electrolyte composition (3% NaCl), while changes in ionic composition and pH can significantly affect excitation kinetics and the thermal balance of the system. These circumstances determine the directions of further research.

Inspection of the treated aluminum anode surface reveals the formation of a localized impact zone with no signs of melting. This indicates the gentle nature of the plasma-liquid action, ensuring surface cleaning while maintaining the component geometry. Quantitative assessment of changes in roughness, wettability, and micromechanical properties requires further experimental analysis.

From an applied perspective, the established pulsed reactions and the presence of two stable electric discharge combustion modes create the prerequisites for controlled changes in energy deposition through varying the jet parameters and electrical characteristics. This enables a transition from gentle surface cleaning modes to controlled modification of surface morphology without significant thermal impact on the material, which is important for the development of compact technological solutions for the preparation of aluminum surfaces for coating deposition and ensuring adhesion.

**Conclusion.** An experimental study on an electric discharge in a jet electrolytic cathode–aluminum anode system at atmospheric pressure was performed. Two plasma localization topologies were established: a contact zone on the triple line and a jet breakup region. In both cases, the current was pulsed with an amplitude of approximately 0.8–1.6 A. Optical emission spectroscopy confirmed the mixed nature of the plasma (air + electrolyte sputtering products), and the dominance of the Na I doublet, while an estimate based on the broadening of  $H_\alpha$  yielded the electron concentration

$n_e \approx 10^{16} \text{ cm}^{-3}$ . Thermal imaging data indicated a maximum effective temperature of approximately 47°C on the contact side, and an energy deposition zone approximately 7 mm long, elongated along the jet. It was shown that the pulse triggering mechanism was due to electromechanical feedback between the cathode layer and the jet hydrodynamics. Possible sources of primary electrons included secondary, auto-, and photoemission, as well as emission from gas microcavities. In practice, this allowed for targeted selection of modes (jet velocity/diameter, electrical conductivity, voltage) for delicate activation, cleaning, and microtexturing of aluminum surfaces. Prospects for further research include standardization of energy metrics, quantitative decomposition of the contributions of radiating components, and expansion for constructing process maps.

The presented results form the physical basis for subsequent quantitative analysis of surface quality and construction of operational maps for plasma-liquid processing of aluminum products.

## References

1. Haixia Wu, Wei Ye, Wang Shen, Quanfa Zhao. Tetracycline Degradation in the System of Peracetic Acid Activation by Liquid Discharge Plasma. *Separation and Purification Technology*. 2025;354(2):128783. <https://doi.org/10.1016/j.seppur.2024.128783>
2. Kovačević VV, Sretenović GB, Obradović BM, Kuraica MM. Low-Temperature Plasmas in Contact with Liquids—A Review of Recent Progress and Challenges. *Journal of Physics D: Applied Physics*. 2022;55(47):473002. <https://doi.org/10.1088/1361-6463/ac8a56>
3. Vasilev M, Conlon P, Bohl D, Thagard SM. The Effect of Discharge Frequency of a Gas–Liquid Plasma Reactor on Bulk Liquid Transport and Removal of Organic Contaminants. *Plasma Chemistry and Plasma Processing*. 2022;42(4):759–783. <https://doi.org/10.1007/s11090-022-10246-2>
4. Srivastava T, Simeni MS, Nayak G Bruggeman PJ. Self-organized Patterns at the Plasma–Liquid Anode Interface in a Helium Glow Discharge: Temporal Development and Mechanisms. *Plasma Sources Science and Technology*. 2022;31(8):085010. <https://doi.org/10.1088/1361-6595/ac83ed>
5. Bruggeman P, Garrick SC, Kushner MJ, Locke BR, Gardeniers JGE, Graham WG, et al. Plasma–Liquid Interactions: A Review and Roadmap. *Plasma Sources Science and Technology*. 2016;25(5):053002. <https://doi.org/10.1088/0963-0252/25/5/053002>
6. Kashapov N, Kashapov R, Kashapov L. Influence of the Electrolytic Cathode Temperature on the Self-Sustaining Mechanism of Plasma-Electrolyte Discharge. *Journal of Physics D: Applied Physics*. 2018;51(49):494003. <https://doi.org/10.1088/1361-6463/aae334>
7. Yutong Yang, Bing Sun, Shaohua Sun, Xiaomei Zhu, Jinglin Liu. Heterogeneous Liquid Discharge Cracking of n-hexadecane as a Heavy Oil Model Compound: A Way to Generate Plasma in Liquid Hydrocarbons at Low Voltage. *Journal of Analytical and Applied Pyrolysis*. 2024;177:106348. <https://doi.org/10.1016/j.jaap.2024.106348>
8. Akishev YuS, Grushin ME, Karalnik VB, Monich AE, Pan'kin MV, Trushkin NI, et al. Generation of Nonequilibrium Plasma in Heterogeneous Atmospheric-Pressure Gas–Liquid Media and Demonstration of Its Sterilization Ability. *Plasma Physics Reports*. 2006;32(12):1142–1152. <https://doi.org/10.1134/S1063780X06120087>
9. Barinov YuA, Shkolnik SM. Discharge with a Liquid Non-metallic Cathode (Tap Water) in Atmospheric-Pressure Air Flow. *Technical Physics*. 2016;86(11):155–158. <https://doi.org/10.21883/jtf.2016.11.43833.1833>
10. Sirotkin NA, Titov VA. Experimental Study of the Liquid Cathode Heating and Transfer of Its Components to a Gas Phase under Action of a Direct Current Discharge. *Applied Physics*. 2016;(6):25–31.
11. Averin KA, Lebedev YuA, Shakhmatov VA. Some Results of Studies of a Microwave Discharge in Liquid Heavy Hydrocarbons. *Applied Physics*. 2016;(2):41–45.
12. Gaisin AIF, Gaisin FM, Zheltukhin VS, Son EE. High-Frequency Discharge with a Jet Electrolytic Electrode. *Plasma Physics Reports*. 2022;48(1):48–54. <https://doi.org/10.1134/S1063780X22010068>
13. Gaisin AI, Kayumov R, Kuputdinova A, Mardanov R. Plasma–Liquid Recycling of Metal Powder for 3D Printing. *Physics and Chemistry of Material Treatment*. 2023;(1):37–44. <https://doi.org/10.30791/0015-3214-2023-1-37-44>
14. Petryakov SYu, Mirkhanov DN, Gaisin AF, Basyrov RSh, Kashapov NF. DC Discharge between a Metal Anode and a Liquid Non-metallic Cathode. *Journal of Applied Mechanics and Technical Physics*. 2022;63(5):20–32. <https://doi.org/10.15372/PMTF20220502>
15. Ochkin VN. *Low-Temperature Plasma Spectroscopy*. Moscow: Fizmatlit; 2006. 472 p. (In Russ).

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