On the application of a discharge with liquid electrodes for polishing metal surfaces

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Abstract. The work investigates the electrical parameters of the discharge plasma with a liquid cathode and a combined porous anode. The discharge is carried out in the vertical position of the plasma column, has a volumetric multichannel structure with a pronounced diffuse structure of the electrode spots. The influence of the porous element on the stabilization of the discharge characteristics is revealed. Discharges with a liquid electrolyte cathode continue to be of great interest from the point of view of practical application and are studied in a wide range of changes in physical and geometric characteristics [1 - 4]. Discharge plasma with a liquid cathode can be most effectively used for cleaning, polishing, with simultaneous removal of fractured and relief layers, hardening, gas saturation, surface activation, improvement of mechanical and other characteristics of agricultural machinery parts. In this work, for plasma polishing, parts of the bearing assemblies of disc harrows were selected.

1. Introduction
For the first time, a gas discharge between a liquid non-metallic and a solid metal electrode was obtained and studied at the end of the last century [1]. The anode was pointed metal rods made of copper, brass, iron and coal, and the cathode was water. The discharge had a spherical shape near the water surface and moved chaotically.

One of the first attempts to explain the physical nature of a gas discharge with a liquid electrode can be considered the work of R. Davis and A. Hickling [2]. The discharge was ignited at reduced pressures between a platinum wire anode and a spiral cathode of the same material in the electrolyte. The discharge was caused by a pulse from an induction coil and burned at U = 600 V and I = 25 - 100 mA. A ballast resistance R = 2000 Ohm was connected to the circuit. In the case of l = 0.5 cm, P = 50 mm Hg, Art., the maximum power was provided at I = 0.4 A and U = 1000 V. The discharge quickly stabilized and took the shape of a cone, the top of which was located on the red-hot tip of the anode, and the base rested on the surface of the electrolyte. The cathode spot had a pink color and increased with increasing current. It was assumed that the effective current density at the cathode surface is approximately constant.

According to the physical model proposed by R. Davis and A. Hickling, the release of electrons from the surface of a liquid electrolyte is unlikely, so the current must be carried by positive gaseous ions that enter the liquid from the gas phase and are subsequently discharged. It is assumed that the main ions carrying the current, in this case, are the ions H₂ O⁺ and OH⁺. When they enter the solution, the following simple reactions can occur:
Thus, the effect of the discharge should lead to a change in the chemical composition of the electrolyte.

A discharge with a liquid nonmetallic electrode was studied in a wide range of parameters in [3]. In the case of a liquid non-metallic cathode and a solid anode, the discharge was investigated in the following range of parameters: \( P = 532 \div 105 \, \text{Pa}, \, I = 10 \div 800 \, \text{mA} \) and \( l = 1 \div 150 \, \text{mm} \) for various composition and concentration of the liquid cathode (in particular, 10% solution of NaCl and 20% solution of CuSO4 in distilled water). The authors consider in detail the geometric shape, structure and color of the plasma column of the discharge, its electrode spots and the halo formed around the plasma column. It is noted that at small interelectrode distances \( l < 4 \, \text{mm} \) from each spot formed on the electrolyte surface, separate microscopic discharges are formed. The number of microscopic discharges increases with increasing current. The plasma column expands until the entire surface of the metal anode is filled with a spot. At high currents, discharges with a cylindrical plasma column and a plasma column in the form of a cone burn simultaneously. With an increase in the interelectrode distance, the value of the current at which a discharge with a single channel in the form of a cord transforms into a volumetric form, consisting of many microdischarges, increases. With a further increase in the current, a stepwise transition to a contracted plasma column occurs. An abrupt decrease in voltage is observed on the volt-ampere characteristics of the discharge. When the metal anode is immersed in the liquid cathode, a high-voltage discharge, consisting of many microscopic discharges, also burns.

The use of porous electrodes made it possible to obtain stabilized electrical characteristics of the discharge [4-8].

The study of the electrical parameters of volumetric gas discharges [8-12] is associated with a number of difficulties. One of the reasons that impede obtaining reliable experimental data is the difficulty of maintaining a stationary discharge mode.

The discharge in the horizontal plane is technically easier than in the vertical position. In this work, the vertical spatial orientation of the discharge is considered. The lower electrode is a liquid electrolyte cathode, the upper one is a porous electrolyte anode. The discharge between two liquid electrodes is investigated.

2. Materials and methods

As a result of studying the interaction of the discharge with samples of high-carbon chromium steel grade ShKh6, the basic modes of polishing the working surface were established. It was revealed that the decrease in roughness is maximum when processing with heat fluxes in the range from \( 7.4 \, \text{W} \cdot \text{m}^{-2} \) to \( 8.2 \, \text{W} \cdot \text{m}^{-2} \).

The value of the studied profile with a possible arithmetic mean deviation \( \text{Ra} \) was chosen as the response function. Independent factors that significantly affect the surface roughness are taken: heat flux density and interelectrode distance.

3. Experiment

Figure 1 shows an experimental installation.
Figure 1. Schematic of the experimental installation. 1 - power supply, 2 - electrolytic bath, 3 - upper electrode, 4 - porous element, 5 - controller, 6 - digital oscilloscope, 7 - recorder.

The lower electrode is presented in the form of an electrolytic bath with a connection to the negative pole of the power source. There is no electrolyte circulation as it was unnecessary. The upper electrode is combined, with a porous element with a diameter d. The main functions of this electrode are: supplying liquid to the discharge area, continuous circulation of the electrolyte, adjusting the interelectrode distance, ensuring a constant flow rate and heat flux through the electrolyte. Thus, the intensity of evaporation was regulated, providing a stable heat flux from the discharge to the liquid.

A digital oscilloscope and a recording device were used to assess the pulsations of electrical parameters and plot the current-voltage characteristic.

4. Experimental results and their analysis

For setting up a two-factor experiment, a symmetric compositional plan Bk was chosen [13]. Factors intervals and levels of variation are presented in table 1.

Table 1. Factors, intervals and levels of variation.

| Variable factors         | Coded designations, $x_i$ | Variation interval, $\Delta_i$ | Factor levels |
|--------------------------|---------------------------|-------------------------------|---------------|
| Heat flux density, kW • m-2 | $x_1$                     | 0.4                           | 8.2 7.8 7.4   |
| Interelectrode distance, mm | $x_2$                     | 1                             | 4 3 2         |

The levels of the factors are chosen in such a way that their optimal values, taking into account the existing restrictions, fall into the center of the variation interval.

Factors were encoded using a well-known technique [14] (table 2). According to this technique, a response function was constructed (figure 2, 3) for a two-factor experiment and a coded regression equation was obtained (1).
Table 2. Matrix for planning the experiment and the results of the experiments.

| No. | Natural values of factors | Coded values of factors | Response $R_a$ |
|-----|--------------------------|------------------------|---------------|
|     | Heat flux density $q$, V/m², $X_1$ | Interelectrode distance $\ell$, mm, $X_2$ | $x_1$ | $x_2$ |
| 1   | 8.2                      | 4                      | +1 | +1 | 0.65 |
| 2   | 7.4                      | 4                      | -1 | +1 | 0.59 |
| 3   | 8.2                      | 2                      | +1 | -1 | 0.51 |
| 4   | 7.4                      | 2                      | -1 | -1 | 0.49 |
| 5   | 8.2                      | 3                      | +1 | 0  | 0.41 |
| 6   | 7.4                      | 3                      | -1 | 0  | 0.45 |
| 7   | 7.8                      | 4                      | 0  | +1 | 0.35 |
| 8   | 7.8                      | 2                      | 0  | -1 | 0.38 |
| 9   | 7.8                      | 3                      | 0  | 0  | 0.31 |

$$y = 0.031 + 0.010x_1 + 0.035x_2 + 0.010x_1x_2 + 0.170x_1^2 + 0.105x_2^2,$$

Figure 2. The surface of the response, the dependence of the surface roughness index $R_a$ on the heat flux density $Q$ and the interelectrode distance $\ell$ in natural values of the factors under study.
The resulting regression equation was tested by Fisher’s criterion for adequacy. The hypothesis about the statistical significance of the obtained regression coefficients by Student’s t-test was also tested. As a result, all the regression coefficients were statistically significant. Using the method of searching for the extremum of the function, it was determined that the extremum points of the response surface have the coordinates: $x_1 = -0.0024; x_2 = -0.0166$.

These coordinates were used to determine the optimization parameter and construct the response surface equation in canonical form. The coefficients of the canonical equation are obtained with the same signs. This means that the surface has the shape of a paraboloid of revolution, and the value of the response function is the smallest and is located at the point with the above coordinates.

The interpretation of the results obtained showed that the minimum surface roughness will be at a heat flux density of 7.79 kW • m$^{-2}$ and an interelectrode distance of 2.83 mm.

5. Conclusions
A multichannel structure of the discharge was obtained; the points of attachment to the anode and cathode are diffuse. The area of the electrode spots depends on the current. The use of a porous electrode gives a number of advantages: the pulsations of the current and voltage are substantially smoothed, which in turn affects the stability of the discharge; the diffuse nature of the electrode spots made it possible to significantly increase the discharge volume; the upper limit of the current variation is much higher, since there are no limiting factors such as overheating, oxidation and destruction of the solid electrode.

As a result of setting up a two-factor experiment according to a symmetric compositional plan of the $B_4$ type, the optimal parameters of the process of plasma surface polishing were determined.

References
[1] Plante G 1875 Recherches sur les phenomenes Produits dans les Liquides par de Courants Electriques de Haute Tension C.R. Hebd. Seances Acad. Sci. 80 1133-7
[2] Davies R A and Hickling A 1952 J. of chemical Society 9 3595-602
[3] Son E E, Gaisin F M and Shakirov Y I 1993 Glow Discharge with Liquid Electrodes (Massachusetts Institute of Technology, USA)
[4] Tazmeev Kh K and Tazmeev B Kh 2003 Porous elements in plasma generators with a liquid electrolytic cathode Inzhenerno-fizicheskii zhurnal 76(4) 107-14
[5] Tazmeev B Kh 1999 Electric discharge with an electrolyte cathode and its electrical characteristics Bulletin of the Kazan State Technical University 4 71-6
[6] Tazmeeva R N and Tazmeev B Kh 2014 Experimental study of mass entrainment of a liquid electrolyte cathode under the influence of a gas discharge *Applied Physics* **1** 35-7
[7] Tazmeev G K, Timerkaev B A, Tazmeev K K *et al.* 2017 *Journal of Physics: Conference Series* **789** 012060 DOI 10.1088/1742-6596/789/1/012060
[8] Tazmeev K K, Arslanov I M, Tazmeev G K and Tazmeev B K 2019 *Journal of Physics: Conference Series* **1393** 012061 DOI 10.1088/1742-6596/1393/1/012061
[9] Tazmeev G K, Tazmeeva R N and Tazmeev B K 2020 Gas discharge between two liquid electrolyte electrodes *Journal of Physics: Conference Series* **1588** 012050 DOI 10.1088/1742-6596/1588/1/012050
[10] Tazmeev R N and Tazmeev B K 2019 Development features of the plasma flow in the gas discharge with the liquid electrolyte cathode *Journal of Physics: Conference Series* **1328** 012074 DOI 10.1088/1742-6596/1328/1/012074
[11] Tazmeev K K and Tazmeev B K 2016 Some features of horizontally oriented low-current electric arc in air *Plasma Physics Reports* **42** 86-90 DOI 10.1134/S1063780X16010153
[12] Tazmeev K K and Tazmeev B K 2015 Low-current electric arc in the open air between the end of the cathode and long vertical anode *Journal of Physics: Conference Series* **652** 012038 DOI 10.1088/1742-6596/652/1/012038
[13] Novik F S and Arsov Ya B 1980 *Optimization of metal technology processes by methods of planning experiments* (M.: Mechanical engineering; Sofia: Technique)
[14] Tazmeev B K and Tsybulevsky V V 2021 In search of optimal mode of plasma polishing of surface of agricultural machinery parts when using a discharge with liquid cathode *Journal of Physics: Conference Series* **1870**(1) 012017