# Generation of Gas-Discharge Plasma by an Arc Source with a Cold Hollow Cathode[1]

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**Abstract – The paper presents the results of study on generation of gas-discharge plasma by an arc source with a cold hollow cathode. The source produces plasma of density ~ $10^{10}$–$10^{11}$ cm$^{-3}$ in a volume of ~ 0.5 m$^3$ at a discharge current of up to 120 A, a discharge operating voltage of 30–40 V, and a pressure of 0.1–1 Pa. The motion of a cathode spot in crossed electric and magnetic fields inside the hollow cathode and a special cathode design make it possible to preclude almost completely the penetration of sputtered cathode material into the working chamber and to increase the lifetime of the cathode. Because the cathode spot operates at an integrally cold surface of the hollow cathode, the source allows generation of chemically active gas plasma.**

## 1. Introduction

At present low-pressure sources of high-density gas-discharge plasmas are widely employed in different technological processes. In so doing, the efficiency of a source depends both on the parameters of the plasma and on the external parameters of the discharge system. To create plasma in large vacuum volumes, arc discharges hold promise due to high discharge currents that can be reached in the continuous mode at low voltages and low pressures of the working gas. However, in a cold-cathode arc discharge the products of erosion of the cathode material (atoms and macrodroplets) come into the working space from the cathode spot. In some technological processes the ingress of the cathode material, especially, macrodroplets, is inadmissible and therefore different and sometimes rather sophisticated methods are used for their filtration [1–3].

In an arc discharge with a hollow cathode placed in an axial magnetic field, the cathode spot operates inside the hollow cathode at a surface perpendicular to the direction of the discharge operation [4, 5]. Nevertheless, in a discharge system of this type an arc suppressor at a floating potential is used to prevent the arc from being shorted over the insulator surface to the walls of the hollow anode [5]. Tests have shown that in such a system the surface of a dielectric, which separates the cathode from the hollow anode, gets "dusty" because plasma penetrates into the gap between the hollow cathode and the arc suppressor and the dielectric is damaged. This paper presents the results of tests of a plasma source with different designs of the hollow cathode.

## 2. Design of the Plasma Source

The design and principle of operation of a discharge system with three different hollow cathodes and without an arc suppressor are briefly described below. The general circuit of a hollow-cathode arc discharge is shown in Fig. 1.

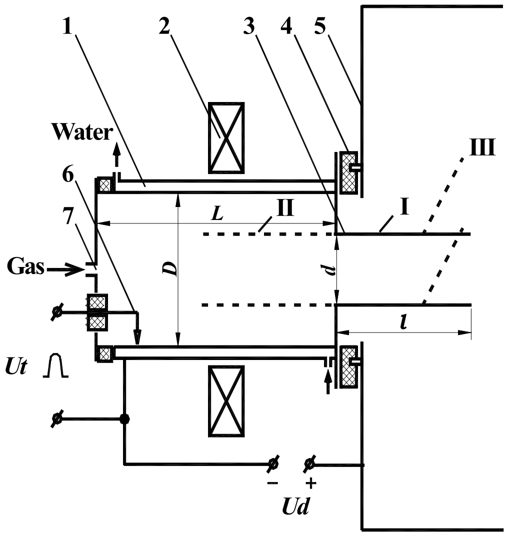

Fig. 1. Setup of plasma source: 1 – hollow cathode, 2 –magnetic coil, 3 – additional cathode, 4 – insulator, 5 – hollow anode, 6 – trigger, 7 – gas inlet

When a pulsed voltage $U_t$ = 5 kV is applied to the triggering unit, a dielectric flashover producing the primary plasma through which the anode potential penetrates into the hollow cathode occurs. The cathode spot initiated by the discharge in crossed electric and magnetic fields moves in a circular orbit over the internal surface of the hollow cathode at the maximum of the magnetic field. Ions and atoms of the sputtered cathode material are deposited on a cathode surface opposite to the cathode spot. It is known [6] that most of the droplets from the cathode spot are directed at an

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[1] The work was supported by the Russian Foundation for Basic Research, project No. 02 02 39002 and by the RF Ministry of Industry, Science and Technology, Contract No. 40.030.11.1125.

angle of 30° to the cathode surface and hence additional measures are required to preclude their penetration into the hollow anode and, primarily, due to the direct droplet flight from the cathode spot into the anode cavity.

On this basis a plasma source with a hollow cathode consisting of two cylindrical parts of different diameters was proposed. The diameter of the main cathode was 110 mm and its length was 200 mm. The diameter of the additional cathode (*d* = 5 cm), which was connected to the main cathode and placed either inside it or inside the hollow anode, was equal to the diameter of the arc suppressor hole. The length of the additional cathode was chosen experimentally from the condition of stable initiation and operation of the discharge and in order to obtain parameters of the plasma in the hollow anode which would be optimal for surface modification. To minimize the penetration of droplets into the hollow anode, experiments were performed with a stainless steel cathode. In these experiments, there were three configurations of the hollow cathode – a rectilinear additional cathode and an additional cathode bent at an angle of 60° (they were placed inside the hollow anode) and an addiction cathode located inside the main cathode (Fig. 1).

## 3. Results and Discussion

The studies have shown that as the length of the rectilinear additional hollow cathode $\ell$ is varied in the range from 5 to 15 cm the external parameters of the discharge (namely, the discharge current and the discharge operating voltage) are nearly invariant. However, with a length in excess of 20 cm the discharge operation becomes unstable owing to impeded penetration of the anode potential into the hollow cathode. Therefore all further investigations were performed with additional cathodes of lengths 10 cm.

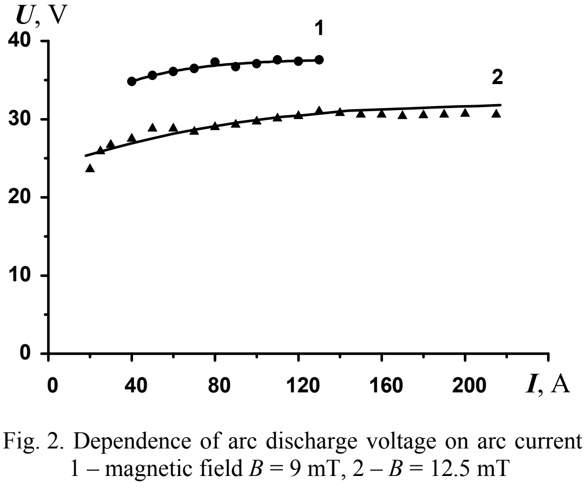

Fig. 2. Dependence of arc discharge voltage on arc current. 1 – magnetic field *B* = 9 mT, 2 – *B* = 12.5 mT

Figure 2 shows the current-voltage characteristics of the discharge operation in Ar at two values of the magnetic field. At a constant gas pressure and magnetic field, there is a characteristic independence of the discharge operating voltage from the discharge current, no matter what the location and configuration of the additional cathode is. Increasing the magnetic field causes an increase in discharge operating voltage and the region where the discharge displays the current stability of operation grows smaller. The most appreciable effect on the discharge characteristics is exerted by the magnetic field.

Figures 3a, b show the discharge operating voltage and the discharge current versus the value of the magnetic field. In the range of average values of the discharge current the discharge operating voltage increases and as the magnetic field is varied in the range from 6 to 14 T the discharge currents decreases by ~ 30% according to a near-linear law. With higher magnetic fields extinction of the discharge takes place.

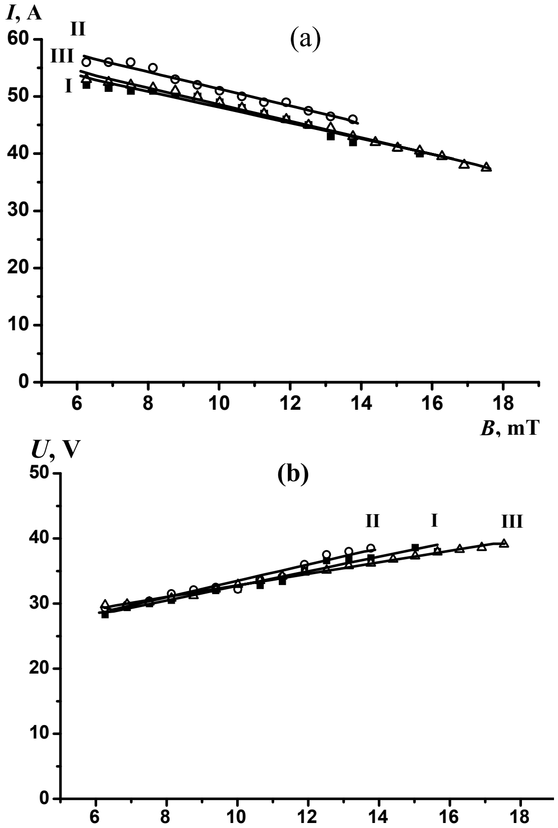

Fig. 3. Discharge current (a) and discharge voltage (b) vs. magnetic field

As one would expect (Fig. 4), an increase in pressure causes an increase in discharge current and a decrease in discharge operating voltage.

It should be noted that in this system stable initiation and operation of the discharge obtains at higher pressures, as compared to a discharge system with an arc suppressor, and the pressure dependence of the discharge operating voltage and discharge current is also more pronounced in the range of pressures $1 \cdot 10^{-2}$–$1 \cdot 10^{-1}$ Pa. At low magnetic fields there is no plane portion of the dependence typical for a discharge with an arc suppressor [7].

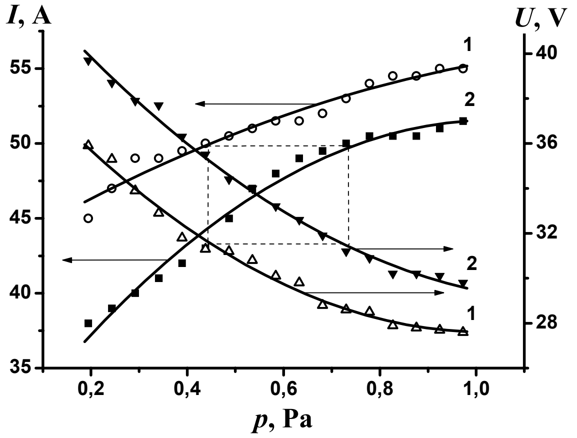

Fig. 4. Dependences of discharge current and discharge voltage on gas pressure. 1 – magnetic field $B = 9$ mT, 2 – $B = 12.5$ mT

High magnetic fields are required to hold the cathode spot on the surface of the main cathode. At low magnetic fields the cathode spot goes onto the external surface of the additional cathode with an abrupt increase in current and in cathode erosion. The undesirable decrease in discharge current and the increase in discharge operating voltage can be compensated by a buildup of the gas pressure.

As evident from Fig. 4, at a level of 50 A the discharge current remains invariant under changes of the magnetic field $\Delta B = 3.5$ mT, providing the pressure is increased by $\Delta p_1 = 0.27$ Pa. It is notable that in these conditions not only the discharge current is constant, but also the discharge operating voltage as well ($U_d = 31$ V), i.e., the discharge power is automatically kept constant.

The observed dependence of the discharge current on the magnetic field can be explained as follows. During the operation of the arc in the crossed fields the increase in magnetic field and, consequently, in cyclotron frequency causes a decrease in plasma conductivity in the hollow cathode, which coincides with the sense of the electric field in the near-cathode region of the discharge. In strong magnetic fields ($\omega >> \nu$), the plasma conductivity can be presented in the form

$$\sigma_m = \sigma_0 \frac{\nu^2}{\omega^2}, \tag{1}$$

where $\sigma_0 = e^2 n_e / m\nu$ is the plasma conductivity in the absence of the magnetic field, $\omega = eB/m$ is the cyclotron frequency, $\nu = n_g \sigma_{ea} v$ is the rate of electron collision with neutrals. Here $e$, $n_e$, $m$ are, respectively, the charge, density, and mass of an electron and $n_g$ is the neutral density, $v$ and $\sigma_{ea}$ are the velocity and the section of elastic collision of an electron. As the magnetic field is increased the discharge current and the discharge operating voltage do not vary, providing the plasma conductivity coincident with the electric field sense remains constant. As follows from equation (1), this condition is fulfilled, if the collision rate of electrons leaving the cathode and gas molecules increases by the law

$$\frac{\nu_1}{\nu_2} = \frac{\omega_1}{\omega_2} = \frac{B_1}{B_2}. \tag{2}$$

Because the collision rate is related to the gas pressure as [8]

$$\nu = 5.93 \cdot 10^7 \sqrt{E} \cdot P \cdot p. \tag{3}$$

where $E$ is the energy of an electron (eV), $P$ is the probability of collisions (cm$^{-1}$ · Torr$^{-1}$), $p$ is the pressure of the working gas (Torr), the collision rate can be increased by increasing the pressure in the hollow cathode. When calculating the pressure dependence of $\nu$ one should take into account that the pressure in the main cathode, where electrons collide, differs from the experimentally measured pressure in the vacuum chamber due to the pressure difference that occurs during the gas passage in the additional cathode. Calculation shows that the pressure in the hollow cathode is five times higher than the pressure in the vacuum chamber.

The condition of conservation of the plasma conductivity under changes of the magnetic field in the hollow cathode can conclusively be presented in the form

$$\frac{\nu_{k1}}{\nu_{k2}} = \frac{p_{k1}}{p_{k2}} = \frac{B_{k1}}{B_{k2}}, \tag{4}$$

where $\nu_{k1}$ and $\nu_{k2}$ are the rates of elastic electron collisions and $B_{k1}$ and $B_{k2}$ are the magnetic fields in the hollow cathode. The rates of elastic collision calculated by formula (2) $\nu_{k1} = 2.3 \cdot 10^8$ s$^{-1}$, the cyclotron frequency $\omega_1 = 1.6 \cdot 10^9$ s$^{-1}$, and the ratio of the magnetic fields without accounting for demagnetization $B_1/B_2 = 0.72$. In the experiment the equality of the discharge currents at a level of 50 A is retained (Fig. 4) as the external magnetic field is changed by $\Delta B = 3.5$ mT and the pressure by $\Delta p_\kappa = 1.1$ Pa. In so doing, $p_{k1}/p_{k2} = 0.58$. When allowing for demagnetization of the external field by the Hall current which is $\omega/\nu$ times higher than the discharge current, the ratio of the actual magnetic fields $B_{k1}/B_{k2} = 0.63$. Taking into account the complicated dependence of the collision probability on the electron energy, the calculated and experimental relations agree with theoretical and experimental results obtained at lower discharge currents in [9] and may be thought as adequately reflecting the dependences of the discharge current on the magnetic field, which are associated with a change in the plasma conductivity in the crossed electric and magnetic fields.

Visual observations show that at equal discharge currents, but with different configurations of the hollow cathode, there are some differences in the form and intensity of the discharge glow in the hollow anode. Therefore one would expect a change in the plasma parameters and in the number of droplets penetrating into the hollow anode. The results of measurements of the plasma parameters with the plane probe at a discharge current $I_d = 50$ A, pressure $p_{\mathrm{Ar}} = 4.4 \cdot 10^{-1}$ Pa, and magnetic field $B = 9$ mT are presented in the table below (types of the additional cathode in the table corresponds to Fig. 1). For comparison there are also the parameters of the discharge plasma with an arc suppressor.

Table I. Parameters of the plasma in the hollow anode

| Type of the additional cathode | I | II | III | with arc suppressor |
|---|---|---|---|---|
| Plasma density, $10^9$ cm$^{-3}$ | 5 | 4 | 4 | 9 |
| Plasma temperature, eV | 3 | 3 | 2 | 4 |
| Plasma potential, V | 3 | 3 | 3 | 4.5 |
| Floating potential, V | –11 | –11 | –10 | –14 |
| Operating voltage, V | 35 | 35 | 35 | 26 |
| Number of droplets, pieces/mm$^2$ | 40–50 | 5–6 | 1–2 | 100–200 |

It can be seen from the table that with equal lengths of the additional cathode and different configurations of the hollow cathode the plasma parameters in the working volume of the vacuum chamber are nearly constant. Increasing the discharge current two times (from 50 A to 100 A) leads to an increase in plasma density by a factor of 1.7 and an increase in its temperature by a factor of 1.5. The average number of droplets presented in the table was determined at three target points upon 30-min operation of the source with different types of the additional cathode. As can be seen, the most preferable version is the cathode system with a curvilinear additional cathode directed inward the hollow anode. With this system, the number of macrodroplets penetrating into the hollow anode is minimum. In so doing, no droplets of diameter larger than 0.7 μm were found at the targets. The effect of the magnetic field on the droplet fraction reaching into the hollow anode was also studied. A twofold increase in magnetic field and, consequently, an increase in the speed of rotation of the cathode spot in the hollow cathode decreases approximately two or three times the number of macrodroplets at the targets, all others factors being equal. In all likelihood, this is due to the fact that local regions of the hollow cathode are less heated because of the higher velocity of the cathode spot at the surface of the hollow cathode.

## 4. Conclusion

At a constant gas pressure and magnetic field, the operating voltage of a cold-hollow-cathode arc discharge does not depend on the discharge current in a wide range of its variation (30–120 A) and on the configuration of an additional cathode with a length of no greater than 20 cm. The increase in arc operating voltage and the decrease in discharge current with increasing the axial magnetic fields are associated with a drop of the plasma conductivity coincident with the sense of the electric field in the near-cathode region of the discharge. The enhancement of the elastic collision rate of electrons by increasing 1.7 times the gas pressure in the hollow cathode may compensate for the increase in voltage and decrease in discharge current as the magnetic field is increased from 9 mT to 12.5 mT (by a factor of 1.4).

Reasoning from optimal parameters of the plasma in the working volume and from minimum penetration of the droplet fraction into the hollow anode, the configuration with a curvilinear additional cathode directed inward the hollow anode appears to be most acceptable, since the number of droplets penetrating into the hollow anode in this case is minimum with the plasma parameter in the hollow anode held constant.

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