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PHYSICAL INVESTIGATIONS OF A HIGH-CURRENT VACUUM ARC DISCHARGE

G. A. Dyuzhev and S. M. Shkol'nik UDC 537.5

The experimental data on the processes at the electrodes and in the interelectrode gap of a high-current vacuum arc discharge that were accumulated by different researchers are systematized. A critical analysis is conducted on the essentially static discharge models proposed earlier. A dynamic model of a two-component plasma is described and substantiated, which, in the opinion of the authors, better explains the current results of experimental studies into this type of electric discharge than the static models.

In distinction from many other types of electric discharge, such as, for example, an arc with a glowing cathode, glow-discharge, HF-discharge, etc., a high-current vacuum arc discharge (HCVAD) until recently was little studied as a physical object. Interest in HCVAD is due to the wide potentials of its application in technology (switching devices, spark gaps, etc.) [1]. The history of the research encompasses more than one decade, but interest in HCVAD particularly rose in the last decade, when it became quite obvious that far from all technical problems can (and practically) be solved using solid-state switching devices.

Usually, physical studies were conducted with plane-parallel geometry electrodes (the ends of cylinders of diameter D of a few centimeters, interelectrode gap of $H \sim 1$ cm, $D/H >> 1$). The range of currents is from a few hundred to several thousand amperes. The main efforts were concentrated on studying processes at the electrodes. In addition to the traditional interest in cathode processes for a vacuum arc when studying HCVAD, a good deal of attention is devoted to anode phenomena, since an increase in the discharge current above some so-called critical current leads to contraction of the discharge in the anode region and the formation of an anode spot. The spot causes strong erosion and a definite prolongation of the recovery of the electrical stability after extinction of the arc. Clarification of the conditions and the causes of the formation of the anode spot is one of the main directions of research into HCVAD. Integrated characteristics were investigated for along time, volt-ampere characteristics have been measured, streak photography of the discharge has been done, the thermal flux to the electrodes, the temperature, and the rate of erosion of the electrodes were determined, etc. [2-5]. Beginning with the middle of the seventies, papers began to be published on the measurement of parameters of the plasma in the interelectrode gap [6-9].

Several different models of HCVAD, and correspondingly explanations of the causes of the formation of the anode spot, were proposed as the basis of the studies that were performed [10]. These models combine the idea that the interelectrode gap is filled with a column of homogeneous plasma (the concentration of which is proportional to the discharge current), based on a set of spots scattered chaotically over the cathode. In the diffuse mode (without the anode spot) the anode is treated as a passive element, almost completely absorbing the flux of plasma incident on the anode (Fig. 1 [11]). Thus, all models are essentially static. The distinction of the models appears only when examining the question of the character of the ion motion: a) the directional speed of the plasma from cathode to anode is much greater than that of the thermal motion [11]; b) the directional speed is less than (or comparable) to the thermal speed of the ions [12]. (Note that in the latter case, it is still unclear what the mechanism is for the loss of momentum by the plasma jets, emanating at high speed from the individual cathode spots.)

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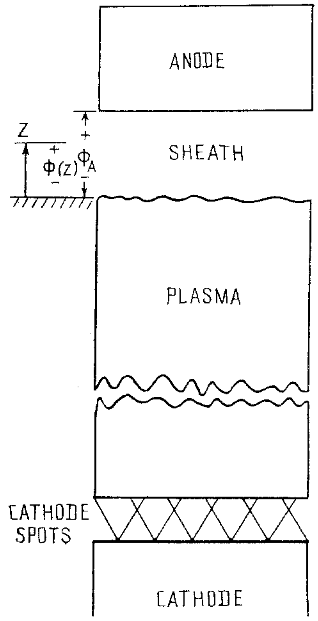

Fig. 1

In a series of papers, experimental results were obtained which did not fit into the HCVAD model described above [13-16]. The studies performed in recent years have definitely showed the deficiencies of the static models. Below we describe the current understanding of cathode processes and processes in the interelectrode gap of HCVAD and the dynamic model of a two-component plasma that is based on these ideas. In conclusion, in the light of the aforementioned understanding of processes in the plasma of the interelectrode gap, we evaluate the conditions and the causes of the formation of an eroded spot on the anode.

Cathode Processes. It is known that on clean surfaces for sufficiently high currents and durations of the arc glow, so-called thermal spots are formed [17]. The characteristic current passed by one spot $I_s \sim 10^2$ A, in particular, for copper $I_s \sim$ 75 A [18]. (Note that the discharge itself cleans the surface most effectively. According to the data of [19], a few pulses of current $I \sim 1$ kA and duration of $\sim 10^{-3}$ sec is sufficient for initial cleaning of a copper electrode of a few cm in diameter. If after cleaning, the cathode is maintained in a vacuum even for a prolonged time, for subsequent cleaning one pulse is sufficient.)

Such spots are sources of high-speed jets of strongly ionized plasma [20]. As theoretical calculations show [21, 22], most of the energy of the jet is collected in the immediate vicinity of the cathode at a distance of a few spot radii r_0 ($\sim 10^{-2}$ cm), and at a distance of a few tens of radii ($\sim 10^{-1}$ cm) (when the concentration of the plasma drops due to expansion of the jet) collisionless dispersion of the ions begins, accelerating to $v > 10^6$ cm/sec.

A high-current vacuum arc discharge can be considered as a discharge with a current $I >> I_s$, i.e., a discharge at the cathode of which many spots function simultaneously. The fundamental experimental fact for HCVAD, which was not given the proper attention for a long time, is the ordered position of thermal spots on the cathode that was first observed in [13]. The spots form a ring, the radius R of which increases with time. Inside and around the ring, only random spots can form and die off. The rate of expansion and the maximum radius of the ring are determined by the shape and amplitude of the current pulse [23]. If the current and the duration of the discharge are large enough, then the spots, reaching the edge of electrode are maintained mostly on the edge or runs off to the side surface. The plasma jets from the spots flow outside the interelectrode gap. New spots are not formed at the end. The burning of the discharge becomes unstable.

Since in a vacuum arc the plasma forming materials are only the products of the erosion of the electrodes, for a current less than critical for the formation of an anode spot for the cathode described above, ordered positioning of spots on the surface of the cathode and their motion should obviously be reflected on the state of the plasma in the interelectrode gap.

Processes in the Interelectrode Gap. As early as [15] a definite correlation was noticed between the motion of emission centers over the cathode and the dynamics of the plasma in the interelectrode gap. Movable spherical probes were used for the diagnostics of the plasma in [15]. The discharge was fed by a rectangular current pulse ($I < 8$ kA, $\tau < 2$ msec). However, this work did not garner sufficient attention. In the overwhelming majority of both preceding and subsequent papers, a sinusoidal

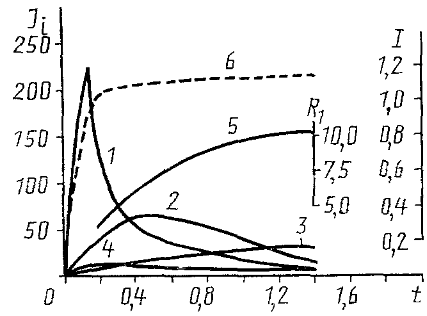

Fig. 2. High-current vacuum arc discharge with copper electrodes D = 20 mm, H = 6 mm (probe measurements were done at a distance of h = 5 mm from the cathode; ion current to the probe reflected to the cathode (1, 2, 3) and to the anode (4)): 1) probe on the axis of the discharge r = 0; 2) r = 5 mm; 3) 10; 4) 0; 5) variation of the radius of the cathode spot ring (according to streak camera results) as a function of time R = R(t); 6) oscillogram of the discharge current pulse. J, mA; 1, kA; t, msec, R_1 = mm.

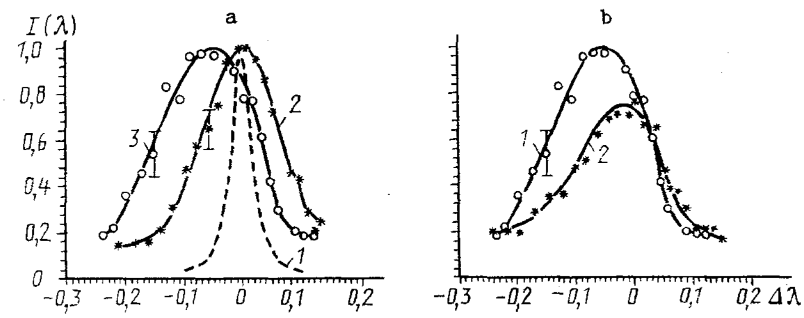

Fig. 3. High-resolution spectroscopic measurements in a HCVAD with copper electrodes (Cu II, λ = 4555.9 Å, rectangular current pulse I = 1200 A of duration τ = 1.5 msec, time resolution of Δt = 100 μsec); a) measurements through t = 500 μsec from the beginning of the discharge: 1) contour of the studied line in the an LT-2 spectral lamp with a hollow copper cathode; 2) transverse contour of the studied line; 3) longitudinal contour; b) measurements along the axis of the discharge: 1) t = 500 μsec, 2) 1000. I, arbitrary units; $\Delta\lambda$, Å.

current half-wave was used, the duration of which corresponded to f = 50 Hz. The time-dependence of the plasma parameters was maximized by their current dependence.

The use of spherical probes in [15] "smeared" the effect which much more distinctly appeared when using "single-side" probes (Fig. 2 [24]). The results cited in the figure show that the distribution of the plasma in the interelectrode gap of the HCVAD is inhomogeneous and nonstationary, the dynamics of the plasma distinctly correlate with the motion of the ring of cathode spots; the ions in the immediate vicinity of the anode retain high speeds of directional motion. Analysis of the results of high-resolution spectroscopic measurements performed in [25] lead to similar conclusions. The authors of this paper measured the spectral line contours of copper ions, the shape of which was determined by the Doppler effect, along (longitudinal contour) and across (transverse) the axis of the discharge (Fig. 3). In fact: I) the significant shift of the longitudinal contour relative to the transverse (the center of which coincides with the position of the undisplaced line in the spectrum of a special spectral lamp) indicates the presence of the high rates of directional motion of the ions from the cathode to the anode and on the inadequacy of the suggestion in [12] regarding the purely thermal character of the motion of the ions in the interelectrode gap of the HCVAD to explain the results of the measurements; 2) the obvious impossibility to superpose the contours by a displacement along the horizontal axis, the different shape of the contours indicates the fallacy in the concepts of [11] regarding the presence

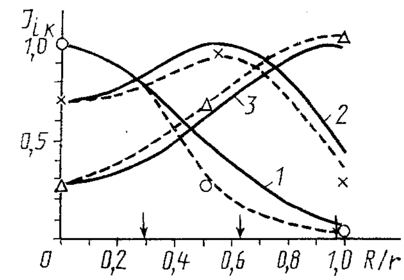

Fig. 4

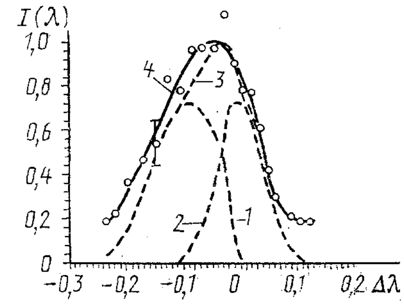

Fig. 5

Fig. 4. Comparison of calculated and experimental radial distributions of the current density of cathode ions J_{ci} at different points in time (I = 1200 A, D = 20 mm, H = 6 mm): solid curves pertain to calculations, dashed curves pertain to experiments; 1) R/H = 0.5, 2) 1.1, 3) 1.7. The arrows denote the radius of the cathode spot ring at the corresponding points in time.

Fig. 5. Comparison of the measured and calculated contours (Cu II λ = 4555.9 Å): Curves refer to calculations, points refer to experiments; 1) calculated profile of the emission line of cathode ions; 2) of anode ions; 3) sum of the contours; 4) convolution of the calculated contour with the instrument function (the standard procedure of the method of least squares was used for the optimization).

of axially symmetric homogeneous flow of ions in the interelectrode gap; 3) strong deformation of the "blue" wing of the longitudinal contour with time for a constant discharge current indicates significant changes in the parameters of the plasma with time and, correspondingly, that static models of HCVAD are unsatisfactory [10].

Extremely important for the development of the correct representations of the processes in the interelectrode gap is the sharp increase in the emission of an atomic line on approach to the anode that was noted in [25]. It indicates that in the diffuse form of a discharge for a current significantly below critical for the formation of an anode spot, the anode is not a passive electrode, but a source of atoms which are effectively ionized in the immediate vicinity of its surface, since the electron temperature in the HCVAD is quite high ($T_e \sim 3$ eV [26]). The retention of ions of the cathode jets of high directional motion speeds right down to the surface of the anode suggests that the emission of atoms from the anode takes place as a result of sputtering of its surface (ion–atom emission), which is quite effective in the case of copper for energies of the incident atoms of $E_i > 50$ eV [27].

The accumulation of probe [24] and spectroscopic [25] measurements are satisfactorily explained in the framework of the dynamic model of a two-component plasma. It is assumed that fast ions fly away from the cathode spots along a linear trajectory on a background of slow chaotically moving ions of anode origin. The cathode spots are situated in a ring which expands with time. This also determines the dynamics of the plasma.

Such qualitative ideas were extended and refined by a series of propositions (for example, regarding the angular distribution of the ion current density form the cathode spot, the character of the ion excitation and deexcitation processes, the absence of reabsorption of the radiation, etc.), based on the data existing in the literature. After this numerical calculations were conducted, comparison of the results of which with experiment showed that the proposed model satisfactorily describes the dynamics of the plasma (Fig. 4) and allows one to determine the energy characteristics of both groups of ions, and even the ratio of concentration of fast and slow ions on the axis of the discharge at different points in time (Fig. 5). Note that the value for the mean energy of directional motion of fast cathode ions ($E_{ci} \approx 50$ eV) and temperature of the slow anode ions ($T_{ai} \approx 4.5$ eV) obtained in this manner substantiate the validity of the basic propositions of the model, since they agree with known data on the energies of ions in the cathode jet from an isolated spot [20] and the average energy in the spectrum of ion-atom emission [28], respectively.

Anode Processes. In stationary models with a homogeneous plasma, the anode is treated as a passive collector, the anode potential drop (AD) is assumed to be positive (or close to zero). The possibility of the existence of a negative anode drop is not considered in the overwhelming majority of papers. The formation of the spot is treated as an evolutionary process (growth of the current – growth of the thermal flux to the anode – increase of its surface temperature – intense vaporization), and the threshold character of the processes is ignored even though it is obviously manifested in experiment [10].

Detailed analysis of the models of the formation of the anode spot, based on the concept of a homogeneous plasma column in the HCVAD, performed by the authors of [29], showed these models to be unsatisfactory. The model proposed in [29] as an alternative to the evolutionary processes assumed the existence of an negative anode drop in the diffuse mode and related the formation of the spot with the development of an instability of the anode region when the sign of the anode drop changes [30]. The model permitted satisfactory explanation of numerous experimental facts. Later, the existence of a negative anode drop in the diffuse form of the discharge was experimentally confirmed [26]. There was a significant difficulty with the model of [29]: it remained in the framework of ideas about a homogeneous plasma, and they were unable to find the cause of the change of sign of the anode drop with increasing current.

The dynamic model described above reduces these problems. As was already stated, the shape and the amplitude of the current pulse determine the rate of expansion of the ring of spots on the cathode, and with it the dynamics of the plasma in the interelectrode gap as well. As the ring expands, the ratio of the ion current, "intercepted" by the anode, to the total current from the cathode spots decreases. In addition, depletion of the preaxial region by cathode ions occurs (Fig. 3b, 4). This fact is especially interesting, since it can lead to local change of the sign of the anode drop in the preaxial region, which means it can lead to a loss of stability of the preanode layer in this region relative to the formation of an anode spot [30]. Not excluded is the fact that the anode spot forms for negative anode drop on the majority of the area of the anode. The existing data on the rate of expansion of the ring of cathode spots [23] shows that under the conditions of the discussed experiments (sinusoidal half-wave current pulse, f = 50 Hz, electrode diameter D of several centimeters) for discharge currents close to critical, $2R \sim D$, i.e., the aforementioned effects are substantial.

Apparently, slow ions of anode origin play an important role in the formation of the anode spot, since their concentration in the anode region is comparable to the concentration of fast ions, however, this question still remains open and requires further research.

NOTATION

I, discharge current, I_s, current passed by one spot; D, diameter of the electrodes; H, length of the interelectrode gap; h, coordinate in the interelectrode gap; R, radius of the spot ring on the cathode; r, radial coordinate; τ, pulse length, T_e, electron temperature, J_i, ion current to the probe; J_{ci}, cathode ion current density, E_{ci}, energy of directional motion of the cathode ions; T_{ai}, temperature of the anode ions.

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INVESTIGATION OF THE THREE-DIMENSIONAL STRUCTURE OF A RF CAPACITANCE DISCHARGE

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UDC 537.74

The author analyzes experimental methods of investigating the three-dimensional structure of an RF capacitance discharge (RFCD), methods which would simply and reliably determine specific features, in particular: 1) the fact that near-electrode layers exists, and the degree to which processes occurring there affect the plasma discharge parameters; 2) the singularity of each RF discharge shape, weak and concentrated, and the causes and conditions for transitions between them: and 3) the mechanism for forming a discharge structure normal to the current direction, and the possibility of simultaneous ignition of both types of RF discharge in one interelectrode gap.

The RF capacitance discharge in the pressure range from tenths to hundreds of torr and frequency of the RF field from 10^6 to 10^8 Hz is one of the simplest, most reliable and efficient plasma sources in the most diverse fields: in plasma chemistry [1, 2], in plasma technology [2-4], in new laser technology [5-7], etc. Hence there is great interest in methods of obtaining, investigating and applying it.

A particularly fruitful matter for understanding the physics of the RF discharge, the mechanism by which its structure is formed, and also for the numerous applications of RFCD has been the perception of the important role of the near-electrode layers of the space discharge (NLSD) and the secondary emission processes occurring there. It was explained in [8] that there are various forms of RFCD: weak and strong, differing in the phenomena occurring in the NLSD, and for this reason there are qualitatively different spatial structures for the same external conditions: pressure and gas type, size of interelectrode gap, similarity of the RF voltages on the electrodes. For example, the discharge current density in transition from the weak discharge

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