Study of arc discharges on the P-2000 facility

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Abstract. A brief review of experimental and theoretical studies of electric arc discharges and related plasma flows conducted at the P-2000 experimental setup since 2010 is presented. The main attention is paid to long discharges in open air between graphite electrodes of various shapes, both rod and plate. By optimizing the size and shape of the anode, it was possible to ensure stable burning modes of extended (up to 30 cm) electric arcs.

1. Introduction
The P–2000 facility was created at the laboratory of general hydromechanics at the Research Institute of Mechanics of Moscow State University in the early 1960s to study the structure of the plasma flow and solve various problems of interaction of the plasma flow with the channel walls, with a magnetic field and solve a number of technical problems. It combines several experimental stands located in one experimental hall and operated from a common control panel. Each stand has its own plasma source and the device under study, which is associated with a specific task investigated on it [1].

A key role in the technical formation and development of this facility belongs to Ph.D. German VO, who died suddenly in February 2018, a few days before eighty-five years.

Electric arc plasma generators - plasmatrons [2, 3] were used and are used as plasma sources on the P-2000 facility. To stabilize the discharge plasma, a number of magnetic systems have been created, which also allow studies on the stability of electric arc discharges in a magnetic field [4–7].

The main target of the research is the study of discharge instabilities and the development of methods for their stabilization, in particular, by applying external magnetic fields, matching the size and shape of the cathode and anode nodes, and the formation of developed electrode plumes.

This paper provides a brief overview of the experimental and theoretical work carried out on the P–2000 facility from 2010 to 2017, and related to the study of the stability of electrical discharges and moving electrical arcs.

The conditions for stabilizing extended electric arcs on massive anodes, obtained by the end of the current 2018, are considered.

2. Problem statement and measurement scheme
Electric arc discharges in gases are widely used in industrial technologies and devices and represent a fairly well experimentally studied object [8–12] (especially arcs stabilized by walls). However, the physical processes that determine the effects observed in experiments have not been studied enough, which makes it difficult to solve many practical problems of applying a discharge. In particular, the conditions for the occurrence of current contraction and the unsteady behavior of atmospheric arcs observed experimentally [13–15] have not been studied sufficiently. In the monographs [16, 17], the
thermal model of current contraction is developed and widely studied, as a consequence of the development of discharge instability (overheating, for example). However, in real discharges (in the presence of a gravitational field), convective currents of the interelectrode medium and heterogeneity of the structure of the discharge plasma can occur. It takes place as a result of convection development due to the presence of a volumetric heat release source in the form of Joule dissipation and the presence of magnetic fields [18].

One of the technical problems in the experimental study of extended (several cm and more) arcs is the problem of stable initiation of discharge and ensuring minimal noise to measuring circuits. In particular, when initiating a discharge in air at atmospheric pressure at interelectrode distances of 15–18 mm, oscillator voltages of more than 50 kV were required [13]. Therefore, in recent years, in the study of extended electric arcs at the P-2000 facility, discharge initiation is applied by connecting the electrodes and then extending them to the selected interelectrode distance \( l \). The typically time of separation of the electrodes in experiments is 0.1-0.2 s. The general scheme of recording video images of the discharge and the temperature of the electrodes is shown in figure 1.

![Diagram of setup scheme](image_url)

**Figure 1.** Setup scheme: 1 – video camera, 2 – electrode motion mechanism, 3 – mirrors, 4 – electrodes, 5 – arc, 6 – insulating stand, 7 – mounting clips, 8 – normal to mirror surfaces, 9 – pyrometer.

Mirrors (3) on the right and on the left are intended for taking three images of images in frames, which gives an idea of the spatial pattern of the discharge (panoramic video) [19]. An extended electric arc discharge with quasi-stationary currents in atmospheric air at graphite electrodes and in the presence of an external magnetic field, provided by a particular magnetic system (MS), is studied.

Conducted model experiments provide information on the structure of plasma armatures, an important element of various electrophysical facilities, in particular, MHD generators, electric arc...
accelerators, electrodynamic accelerators with plasma armature, and plasmatrons, [16, 20]. The efficiency and service life of such facilities essentially depends on the compactness and degree of spatial homogeneity of such armatures [21, 22].

The focus is on the visualization of processes associated with the flow of electric current using high-speed (1200÷60000 frame/s) shooting in the visible wavelength range (0.4÷0.8 microns). Additionally, pyrometric measurements of the temperature on the surface of the electrodes are carried out simultaneously, and measurement data of the discharge current and voltage on the discharge gap are recorded.

In the experiments, industrial designs of graphite electrodes were used. If necessary, they were adjusted for a particular task. Typical types of electrodes are presented in figure 2.

![Figure 2. Forms of graphite electrodes: anodes (1-6), cathodes (1); 1 - rod electrode with a hemispherical head ∅18x100 mm; 2, 3 - plate electrodes 50x70 mm; 4 - cylinder ∅60x60 mm with a contact hole; 5 - half of the cylindrical tube ∅60x60 mm; 6 - bowl (external diameter 150 mm, internal diameter 100 mm, depth 20 mm). Massive electrodes are electrodes 2-6. In the experiments performed, all the commensurate electrodes are hemispherical head rods of type 1.]

3. Studies of the instabilities of arc discharges between comparable electrodes

By task with comparable electrodes, we mean electric arc discharges between identical electrodes (plate or rod, for example). If the working surfaces of the anodes significantly (many times) exceed the working surface of the corresponding cathode, then such anodes are called massive.

Full-scale mathematical modeling of discharge electric arc processes is a rather complex (and not yet solved problem) both in the staged and in the program-algorithmic plan. This is due to the fact that processes usually matter, both in the discharge channel itself and in the electrodes and insulators and the external circuit. The greatest difficulty arises in the construction and closure of models for the transfer of charges and neutral particles in the boundary zones between dissimilar media. Finally, in
mathematical modeling, problems of availability (availability) of databases, problems of many, very different, spatial and temporal scales arise.

![Figure 3](image)

**Figure 3.** Variations in the shape of the current channel with vertically directed electrodes: (1–3) sequential video frames of current and voltage when changing from a diffuse–constricted to constricted discharge (t1 and t2 are the time points corresponding to frames 1 and 2); (4–6) sequential frames of the formation and extinction of a parallel current channel; and (7, 8) formation and evolution of the shunting arc. The anode is at the bottom, frec = 1200 frame/s [13].

The developers of MHD generators were widely aware of the fact that the current flow pattern in the channels in these devices is complex (essentially non-stationary and non-uniform). In addition, micro-arcs are formed on the electrodes.

Experiments with arcs on comparable graphite rod electrodes on a P-2000 facility (figure 3) showed that the shape of the arc (with quasi-stationary power supply modes) is not very stationary and not unique.

Meanwhile, the simplest thermal model of a discharge (when, for example, hydrodynamic processes are neglected and real plasma interaction processes with electrodes and walls are not taken into account) shows, that if there is a solution to the problem, then it is unique [23]. Accounting for the hydrodynamics model in the Boussinesq approximation showed, that the formation of current inhomogeneities in the form of convective cells in the discharge is already possible [24–26].

Theoretical and experimental studies [7] showed, that the formation of multichannel current flow patterns in air at atmospheric pressure is possible near the surfaces of graphite (with open porosity) anodes.

Along with slow-moving discharge arcs, arcs moving between rails in air and free (not limited to insulators from the sides of the railgun channel) were considered [2, 3]. It was shown, that the disordered movement of a free arc can be stabilized by the application of an external magnetic field by introducing special current loops pushing the arc at the start and pushing (“tearing”) it at the channel exit.

To study the modes of stabilization of current flow in stationary arc discharges, magnetic systems (MS) were used, creating an axial and quasi-azimuthal magnetic field (figure 4 [7]).

The results of experiments [6] have shown that a magnetic compression field of a rod MS (2 in figure 4) can stabilize the discharge in a fairly wide range of parameters (figure 5).
Figure 4. Discharge circuits with axial 1 and quasi-azimuth 2 external magnetic fields superimposed: 3 - electrodes, 4 - arc with current I, 5 - cylindrical coordinate system (z, r, φ), 6 - coils of solenoidal or rod magnetic systems with currents Im [7].

Figure 5. Diagram of the influence of an external magnetic field on the discharge burning modes: I - discharge self-quenching region, II - unsteady arcs, III - transition region, IV - quasistationary arcs.
It can be seen in figure 5 that as the current (Im) increases in MS to 1 kA or more, destabilization and rapid discharge quenching are observed (point V); \( l \) is the interelectrode distance, \( R \) is the radius of the core MS; powering the MS and the discharge - sequentially, from one source; currents of the unperturbed discharge and MS are directed oppositely; current ratio MS and arc \( Im / I = 1 \) (I — IV); powering the MS and the discharge from independent sources, \( Im / I = 4 \) (V) [6].

It turned out that the traditional method of stabilizing arcs using an axial external magnetic field (1 in figure 4) also works, but when the magnetic field exceeds a critical value, the screw instability of the discharge develops [13, 14, 7].

The use of the considered MS made it possible to obtain a stable burning of open vertical air arcs up to interelectrode gaps of the order of 15 cm (1 in figure 6).

A further increase in the length of the stable arc was associated with the use of massive anodes.

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**Figure 6.** Video frames of discharges: 1 - rod anode with end hemisphere; 2 - a continuous plate anode (along with the main diffuse current binding, a covert spot is formed in a circular orbit); 3 - flat anode with a hole (220 V / 100 mm), plasma anode mode with two spots along the periphery; 4 - cylindrical trough, circular movement of the spot; 5 — cylindrical trough — two anode streams; 6 - anode - conical bowl, plasma anode mode; video recording frequency frec = 4000 frame / s (1-3) and frec = 1200 frame / s (4-6).
4. Studying the possibility of stabilizing arcs on massive anodes

The instability of the electric discharge in the zone of the rod (hemispherical at the end) anode required to conduct discharge experiments with anodes of different shape and size in order to identify their optimal forms. A line of anode electrodes was developed (figure 2).

The first decision in this direction was to increase, by an order of magnitude, the geometric dimensions of the anode.

Firstly, it should improve the processes of short circuit on it of an electric (especially strong) current, as the working surface of the anode increases. As a result, it can accept all electrical current without significantly increase its density.

Secondly, this allows to remove the increased thermal load on the anode, characteristic of the rod anode (with a hemispherical contact surface), comparable in size with the cathode.

Third, (as shown by pyrometric measurements), a massive anode reduces the level of temperature fluctuations of the anode surface, which are more intense in the case of size-comparable electrodes.

One of the typical classical forms of the electrode is a plate form with a flat, contact discharge plasma, surface. The large surface of the anode leads to a change in the distribution of the intrinsic magnetic field of the arc in the zone of contact of the discharge with an extended anode. Indeed, the current spreading in the massive electrode body is more uniform compared to the current spreading in the narrower rod electrode (the average current density falls). This results in a decrease in the level of variations in the magnetic field strength at the anode surface. In addition to the factors noted above, reducing the heat load can also reduce anode erosion. This reduces the concentration (particles and vapors) of the anode material in the discharge gap and their pressure on the discharge channel.

The disadvantages of massive anodes are, in particular, their higher cost compared to small anodes. However, the main disadvantage of massive anodes is the difficulty of interaction with the cathode jet. The reflection (rebound) of this jet from their surface is, as a rule, uncontrollable. This shifts the anode reference zone of the discharge in an arbitrary direction, up to the exit of the reference spots on the side surface of the electrode. Thus, a strongly non-linear, destabilizing discharge, gas-dynamic perturbation of the plasma cord of the arc appears.

Note that graphite has a very high reflection coefficient in the infrared region. Therefore, on a long flat anode, a large reflecting surface is formed for the radiation incident from the discharge channel. With a vertical orientation of the discharge with the upper location of the cathode, this can lead to additional heating of the air adjacent to the surface of the already hot, heated currents flowing in it, the anode, and the formation of heated air due to gravitational convection. Such flows will contribute to the stabilization of the anode torches and jets.

In experiments with a flat anode, it was found that in arcs with a length of up to 70 mm, the anode stream is suppressed by the cathode stream. At the same time, anode spots with torches arise and extinguish spontaneously, and migrate along the surface of the anode (graphite 50x70mm) (2, 3 in figure 6).

One of the ways to divert a falling cathode jet is to use a massive extended anode in the form of a cylinder (the cathode jet falls on the side surface of a cylinder 60 mm in diameter and 60 mm long). Experiments have shown that a massive cylindrical anode (like a flat anode) retains a stabilizing effect on the discharge. In this case, the cathode jet can bend around its surface and leave the discharge zone. This approach made it possible to realize a stabilized vertical discharge with a length of 90 mm.

Another possible form of a massive anode may be a hollow form in the form of a half of a cylindrical tube. In this case, there may be an additional factor of stabilization of the discharge. Indeed, the concave cavity of the electrode can keep disintegrating plasma at the anode longer due to its heating, both by the current flowing and by the radiation reflected from the walls of the trench. At the same time, the falling cathode jet now has the ability to freely exit through its open ends. In the experiments performed, the formation of a stable zone of a decomposing low-temperature plasma was recorded in the flute cavity. This zone reduces the intensity of the anode torches and maintains a uniform (diffuse) mode of combustion of the discharge. At such an anode (cavity 60 mm long, with a radius of 30 mm) it was possible to obtain a stable vertical discharge length 130 mm (5 in figure 6).
A natural continuation of the use of profiled massive anodes is the cup-shaped profile of the electrode surface. The optimal size and profile of such anodes are the subject of study. It seems that they significantly depend on the discharge current and the interelectrode gap. In a series of experiments, graphite porous anodes with an entrance diameter of the funnel-shaped cavity of 100 mm and a diameter of the entire anode of 150 mm were used. At such an anode, it was possible to stabilize a vertical discharge with a length of 300 mm (like 6 in figure 6). In this case, the stabilization by the magnetic field was not applied.

Let us consider in more detail the achieved extended discharge on a massive graphite anode. Note the features of the exit of the interelectrode distance \(l\) to the desired value \(l^*\) (figure 7).

\[ l(t) \]

Figure 7. Qualitative picture of the change in time \(t\) of the interelectrode distance \(l\): \(l^*\) is the specified gap, \(t^*\) is the time to establish the necessary gap.

The change with time of the image of the arc cord when initiating a discharge and in stationary mode is shown in figure 8.

Figure 8. Stabilization of an extended vertically oriented discharge on a massive cup-shaped anode: \(l = 300\) mm; video frames are directed from left to right in increasing time; registration frequency \( \text{freq} = 1200\) frame / s; the anode - below.
The recorded waveforms are shown in figure 9.

![Oscillograms of current (I), arc voltage (U) and temperature (T) in the middle of the anode: output to a stable arc mode.](image)

**Figure 9.** Oscillograms of current (I), arc voltage (U) and temperature (T) in the middle of the anode: output to a stable arc mode.

![Video image of a stable arc](image)

**Figure 10.** The video image of a stable arc:

1 = 300 mm, I = 700 A, U = 200 V;
1 - cathode jet,
2 - a column of an air arc of atmospheric pressure,
3 - area of discharge in the medium of an evaporation cloud of particles from an electrode,
4 - supporting anode spots,
5 - anode streams.

This stationary discharge mode \((U = 200 \, \text{V}, \, I = 700 \, \text{A})\) lasts about 1 s, and then the discharge circuit was deliberately disconnected. The temperature of the anode surface did not exceed 1800°C.
The video image of the discharge gap is shown close-up in figure 10. It is seen that the arc pillar is smooth. Only in the short zone near the surface of the massive electrode are three anode spots and two small plumes.

It should be noted that the achieved result of stable burning of an extended discharge was obtained with a consistent rate of separation of $V_d = 300 \text{ mm} / 0.9 \text{ s} = 333 \text{ mm} / \text{s}$. Significantly higher $V_d$ speeds can “blow out” the arc burning with limited possibilities of discharge voltages at the P–2000 facility: $U < U^* < 750 \text{ V}$.

However, the slow modes of separation of the electrodes can be dangerous. Indeed, consider one of the pictures of such a slow expansion: $V_d = 200 \text{ mm} / 0.7 \text{ s} = 286 \text{ mm} / \text{s}$ (figures 11, 12).

![Figure 11. Picture of plasma channel disintegration of the discharge channel and arc self-extinguishing with an abnormal initial delay of the mechanism of separation of the electrodes: $l = 300 \text{ mm}$; video frames are directed from left to right in increasing time; registration frequency $f_{\text{rec}} = 1200 \text{ frame} / \text{s}$.

![Figure 12. Oscillograms of current (I), arc voltage (U) and temperature (T) in the middle of the anode: self-extinguishing of the arc discharge in case of insufficient electrode acceleration rate (see Figure 11).](image)

It can be seen that the delay of the sliding mechanism at its start led to the heating of the anode to $2200 ^\circ \text{C}$ (figure 12). This led to the pollution of the interelectrode gap plasma by the erosion products of the massive electrode (figure 11). As a result, the discharge gap resistance sharply increased to more than 500 V and the discharge went out.
5. Conclusion
As a result of investigations of processes in low-temperature plasma of extended stationary arc discharges in atmospheric air between graphite electrodes, along with the traditional (corded) form of discharge, other current flow modes were studied: diffuse (distributed) and diffuse cord [15]. Regimes of current oscillations due to the interaction of the cathode and anode jets, the occurrence of plasma and solid particles from locally overheated anode surface were detected. The formation of local closed areas of increased brightness (“plasmoids”) moving from the anode along the discharge column with their gradual resorption in the interelectrode gap was observed near the anode surface. Quantitative data were obtained on current flow modes with separation of plasma clouds from the arc column and discharge modes with the formation of local anode gas-dust and gas-plasma inhomogeneities of the discharge structure. Their speed of movement and size were evaluated. For a horizontal discharge, the modes of oscillations of the current cord in the vertical direction were studied [13].

The formation and development of multichannel discharges was studied, the modes of oscillation of discharge channels in a field of gravity were investigated, and new data on the development of screw-shaped arc instability were obtained [7]. The possibilities of stabilizing the motion of arcs when an external magnetic field is applied are studied [2, 3]. The results obtained at the P-2000 setup can be used in the development and optimization of plasma facilities, in particular, to stabilize unstable modes of arcing and to provide distributed discharge modes. One of the areas of application of the investigated plasma jets may be electric discharge initiation of detonation, for example, by injection of plasma jets into the detonation volume.

A study was conducted of extended electric arcs in a free air atmosphere between graphite electrodes — the core cathode and massive anodes of various shapes. With the use of massive (many times larger cathodes in size) anodes, stable burning modes of extended (up to 30 cm) vertical electric arcs with a current strength of up to 700 A have been achieved. The formation and development of multichannel arc discharges and their helical structures have been studied in a free inter-electrode air environment. The principal possibility of stabilizing the directional movement of a free electric arc between rails (without using traditional stabilizers, side insulators [20]) using an external magnetic field from specially oriented and located current loops is shown.

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